# On Life Cycle Assessment in the built environment: from conventional sustainability to regeneration and glocal architecture.

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*"He who hasn't tasted bitter things hasn't earned sweet things."*
*— Gottfried Wilhelm Leibniz, Discourse on Metaphysics and Other Essays*

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# Abstract

The building industry is well known for being attached to traditional practices. Conventional building materials and methodologies usually collide with the optimum solution in terms of sustainability and energy efficiency. Because of the pressing concern of climate change, nations are forcing every industry sector to implement sustainability measures. Those measures include reducing carbon emissions, avoiding the overgeneration of waste, and preventing the emission of toxic gasses. However, the building sector is still reluctant to change. The stakeholders involved in a construction project need to be certain, not only that the new materials and technologies implemented are going to be sustainable, but also that they would be able to perform long-term. That requires an intensive study of both new and conventional materials.

The overarching idea of this thesis is to analyze the role of Life Cycle Assessment (LCA) as a project decision-making tool. LCA is a methodology to conduct a sustainability analysis of any human activity. This work is constructed in three levels, the study of building materials individually, the constructions, such as façades and partitions, and finally, the whole building. As the chapters progress, the focus of the study zooms out from the particularities associated with materials until arriving at the study of the life cycle of buildings. Chapter one corresponds with the first level. In this chapter, several composite boards with bio-epoxy resin and natural fibers are compared to plasterboard in terms of their environmental impact and mechanic characteristics. In the case of constructions, this thesis analyzes some important aspects related to their performance, such as acoustic and thermal insulation. Without at least a competent performance in those parameters, constructions composed of new sustainable materials cannot be considered alternatives to the conventional solutions. In chapter 2, several partition typologies combining the biocomposites and new and conventional acoustic absorbents are compared in terms of their environmental impacts and their airborne acoustic insulation. The third chapter, which also deals with constructions, analyzes the use of façade panels built using rice straw waste from the Albufera park in Valencia and compares it to the most common façade typology in Valencia, the double-layered brick wall. The study assesses the airborne acoustic insulation and the thermal transmittance of the straw construction experimentally. The hygrothermal performance of this material is also analyzed. The last chapter deals with the environmental impacts of buildings as a whole by comparing a European reference wood house in different locations in Europe. The environmental impacts of this house are studied over its whole life cycle in Munich, Ljubljana, Portorož, Madrid, and Valencia to understand how barriers towards regenerative sustainability change depending on location.

When it comes to the results, the first chapter indicates that the bio-epoxy composites proposed can be a sustainable alternative to plasterboard by reducing the environmental impact by around 50%. The second chapter shows that replacing the plasterboard and the mineral wool in a drywall partition with the bio-composites and a sheep wool acoustic absorbent can reduce carbon emissions by almost 60%. The third chapter highlights the importance of finding ways of using the rice straw from the Albufera park as a raw material. Moreover, the rice straw façade analyzed demonstrated to be not only beneficial for the environment (avoids the emission of 52 kg of $CO_2e$ to the atmosphere per square meter), but also perfectly adequate to be a sustainable alternative to the most common façade typologies in Valencia in terms of acoustic, thermal and hygrothermal performance. Because of the environmental benefits of its use and the fact that it is a proximity material, the rice straw façade panels can be considered a glocal material. The last chapter shows that conventional sustainability measures, such as a wooden frame and high thermal insulation, are not enough to successfully build neither regenerative nor Nearly Zero Emissions Buildings (NZEB). The use of bio-based materials, designing towards passive efficiency, and new technologies are necessary to reach regenerative sustainability.

Overall, the results emphasize the need to use LCA as a decision-making tool during the project stage of a building. LCA is the only tool that can provide an accurate representation of the influence a building will have on the environment over its lifespan.

# Resumen general

La industria de la construcción es conocida por su reticencia a alejarse de las prácticas tradicionales. Las prácticas y materiales convencionales a menudo difieren de la solución óptima en lo que a sostenibilidad i eficiencia energética se refiere. Debido a la amenaza del cambio climático, las naciones de todo el mundo están creado nuevas regulaciones para obligar a los sectores industriales a adaptarse a un nuevo paradigma de sostenibilidad. Esas regulaciones incluyen medidas como la reducción de las emisiones de carbono, evitar la generación masiva de residuos y detener la emisión de gases tóxicos. Sin embargo, la reticencia al cambio del sector de la construcción es un gran obstáculo. Los profesionales involucrados i los promotores necesitan la seguridad no solo de que los nuevos materiales son más sostenibles, sino también de que serán capaces de mantener sus propiedades durante un periodo largo de tiempo. Para poder afirmar que un material cumple esos requerimientos es necesario llevar a cabo un estudio intensivo de sus propiedades.

La idea general de esta tesis es estudiar el papel que el Análisis de Ciclo de Vida (ACV) puede jugar como una herramienta para la toma de decisiones durante la fase de proyecto de una obra de construcción. El ACV es una metodología que permite el cálculo de los impactos ambientales de cualquier actividad humana. Este trabajo está construido en tres niveles, el estudio de materiales de construcción individualmente, las soluciones constructivas y por último el conjunto del edificio. A medida que los capítulos progresan, el foco del estudio se aleja desde las particularidades asociadas con los materiales hasta llegar al estudio del ciclo de vida de los edificios. El capítulo uno corresponde con el primer nivel. En este capítulo, varios biocomposites que contienen resina bio-epoxi se comparan con la placa de yeso laminado en términos de sus impactos medioambientales y sus propiedades mecánicas. En el caso de las soluciones constructivas, esta tesis analiza, además de los impactos ambientales, otros parámetros relevantes, tales como el comportamiento acústico y térmico. Sin un comportamiento adecuado en esos aspectos. las soluciones constructivas sostenibles no pueden considerarse una alternativa a las convencionales. En el caso del capítulo 2, se comparan varios tipos de particiones que combinan los biocomposites estudiados en el primer capítulo con absorbentes acústicos convencionales y no convencionales en términos de sus impactos medioambientales y su aislamiento a ruido aéreo. El tercer capítulo continúa tratando las soluciones constructivas. En este caso se analiza el uso de paneles de fachada formados a partir de residuo de paja de arroz generada en el parque natural de la Albufera. Una fachada compuesta por estos paneles se compara a una fachada de doble hoja de ladrillo. El estudio lidia con la comparación de sus impactos ambientales, su aislamiento a ruido aéreo y su transmitancia térmica. Además se analiza el comportamiento higrotérmico de la fachada de paja. El último capítulo compara los impactos ambientales de una casa de madera pensada para ser una referencia de la media europea en cinco ciudades diferentes. Las ciudades estudiadas son Munich, Ljubljana, Portorož, Madrid, and Valencia. El propósito es comprender como las barreras hacia la sostenibilidad regenerativa cambian dependiendo de la ubicación.

En referencia a los resultados, el primer capítulo indica que los composites propuestos pueden ser una alternativa sostenible a la placa de yeso laminado al reducir un 50% su impacto ambiental. El segundo capítulo muestra que reemplazar la placa de yeso laminado y la lana mineral de las particiones por los biocomposites y con un material basado en residuo de lana de oveja puede reducir las emisiones de carbono un 60%. El tercer capítulo señala la importancia de encontrar manera de utilizar la paja de arroz de la albufera como materia prima. Además, la fachada de paja de arroz analizada demuestra no solo ser beneficiosa para el medio ambiente (evita la emisión de 52 kg de $CO_2$ eq. por metro cuadrado), sino también demuestra ser una alternativa adecuada en términos de su comportamiento acústico, térmico e higrotérmico. Debido a los beneficios ambientales que el uso de los paneles de paja supone para el medio ambiente, la paja de arroz puede ser considerada como un material glocal. El último capítulo muestra que las medidas de sostenibilidad convencional, como el uso de la madera en la estructura y el aumento del aislamiento, no son suficientes para llegar a construir edificios regenerativos ni de emisiones de carbono neutras (NZED). El uso de materiales de base biológica, un correcto diseño y nuevas tecnologías enfocadas a la eficiencia energética son fundamentales para alcanzar el objetivo de la sostenibilidad regenerativa.

En general los resultados enfatizan la necesidad de utilizar el ACV como una herramienta para la toma de decisiones en fase de proyecto de un edificio. El ACV es la única metodología capaz de ofrecer una representación fiable de la influencia que un edificio tiene sobre el medio ambiente.

# Resum general

La industria de la construcció és ben coneguda per la seva reticència a allunyar-se de les pràctiques tradicionals. Les pràctiques i materials convencionals sovint difereixen amb la solució òptima en termes de sostenibilitat i eficiència energètica. Degut a la amenaça del canvi climàtic, nacions de tot el món estan creant noves regulacions per obligar als sectors industrials a adaptar-se a un nou paradigma de sostenibilitat. Eixes regulacions inclouen mesures com la reducció de les emissions de carboni, evitar la generació massiva de residus i detenir la emissió de gasos tòxics. La reticència al canvi del sector de la construcció es un gran obstacle, però. Tant els professionals involucrats a la obra com els promotors necessiten tindre la seguretat no sols de que els materials són més sostenibles, sinó també de que seran capaços de mantenir les seves propietats per un període llarg de temps. Per poder afirmar que un material compleix eixos requeriments es necessari du a terme un estudi intensiu de les seues propietats.

La idea general d'aquesta tesi es estudiar del paper que l'Anàlisi de Cicle de Vida (ACV) podria jugar com a ferramenta per a la pressa de decisions durant la fase de projecte d'una obra de construcció. El ACV és una metodologia que permet el càlcul dels impactes ambientals de qualsevol activitat humana. Aquest treball està construït en tres nivells, el estudi de materials de construcció de manera individual, les solucions constructives i per últim l'edifici com a conjunt. A mesura que els capítols progressen, el focus s'allunya des de les particularitats dels materials fins arribar a l'estudi del cicle de vida dels edificis. El capítol 1 es correspon amb el primer nivell. En aquest capítol. diversos biocomposites formats amb resina bio-epoxi es comparen amb la placa de guix laminat en termes dels seus impactes ambientals y les propietats mecàniques. En el cas de les solucions constructives, aquesta tesi analitza, a més dels impactes ambientals, uns altres paràmetres rellevants, com el comportament acústic i tèrmic. Sense un comportament adequat en eixos aspectes, una solució constructiva composada de materials sostenibles no pot ser considerada una alternativa al mètodes de construcció convencional. En el cas del segon capítol, diversos tipus de particions que combinen els biocomposites estudiats en el primer capítol amb absorbents acústics convencionals i no convencionals en termes dels seus impactes ambiental i el seu aïllament a soroll aeri. El tercer capítol continua analitzant solucions constructives. En aquest cas s'analitza l'ús de panels de façana composats de residu de palla d'arròs generada al parc natural de l'Albufera de València. Una façana composta d'aquestos panells es compara amb una façana de doble fulla de maó. L'estudi tracta la comparació dels seus impactes ambientals, el seu aïllament acústic i la transmitància tèrmica. A més s'analitza el comportament higrotèrmic de la façana de palla.L'últim capítol compara els impactes ambientals

de una casa de fusta pensada com una referència de la mitjana europea en cinc ciutats diferents. Les ciutats estudiades són Múnich, Liubliana, Portorož, Madrid, and València. L'objectiu es comprendre com les barreres cap a la sostenibilitat regenerativa canvien depenent de la ubicació del edifici.

En el referent als resultats, el primer capítol indica que els compòsits proposats poden ser una alternativa sostenible a la placa de guix laminat al reduir un 50% el seu impacte ambiental. El segon capítol mostra que reemplaçar la placa de guix laminat i la llana mineral de les particions amb els biocomposites i amb un material basat en residu de llana d'ovella pot reduir les emissions de carboni un 60%. El tercer capítol senyala la importància de trobar maneres d'emprar la palla d'arròs de l'Albufera com a matèria prima. A més, la façana de palla d'arròs analitzada demostra ser no sols beneficiosa per al medi ambient (evita la emissió de 52 kg de $CO_2$ eq. per metre quadrat), sinó també demostra ser una alternativa adequada en termes del seu comportament acústic, tèrmic i higrotèrmic. L'últim capítol mostra que mesures de sostenibilitat convencional, com emprar estructura de fusta i augmentar l'aïllament, no son suficients per arribar a construir edificis d'emissions neutres de carboni (NZEB). L'ús de materials de base biològica, un correcte disseny i noves tecnologies enfocades a l'eficiència energètica són fonamentals per arribar a la sostenibilitat regenerativa.

En general, els resultats emfatitzen la necessitat d'utilitzar el ACV com a una ferramenta per a la pressa de decisions en la fase de projecte d'un edifici. El ACV és l'única metodologia capaç d'oferir una representació fiable de la influència que un edifici te sobre el medi ambient.

# Introduction

This Ph.D. thesis is divided into four different chapters corresponding to four journal articles. The overarching theme that connects all of them is the environmental evaluation of new bio-based building materials. This environmental evaluation is performed through the Life Cycle Assessment (LCA) methodology. The study is structured in three levels. The first level corresponds to the study of materials individually, the second is the study of the materials as part of a construction, and the third level is a study of the whole building. The first level corresponds to chapter one, the second level to chapters two and three, and the third level to chapter four. The chapters can be summarized as follows:

The first chapter deals with the development and the comparative Life Cycle Assessment of new kinds of bio-epoxy boards designed to be a sustainable alternative to gypsum plasterboard. The bio-composites contain bio-epoxy resin as the matrix and different natural fibers as the filler. The LCA analyzes how the environmental impacts of the bio-composite board change depending on the natural fiber used and compares them to the ones generated by gypsum plasterboard.

The second chapter starts analyzing constructions. It uses the composite boards analyzed in the first chapter to form partitions and compares them to partitions using gypsum plasterboard. The conventional drywall partitions are compared with new typologies using the mentioned bio-composites. Besides the bio-composites, two different acoustic absorbers are studied as alternatives to mineral wool. One of them is made from residues obtained from the sheep wool industry, and the other is manufactured from recycled cellulose. The life cycle and the airborne acoustic transmission of the different combinations of the mentioned materials are compared. The airborne acoustic transmission is studied through a simulation due to the importance this parameter has con building partitions. Through this study, it is possible to assess the contributions of each element on the environmental impacts of the partition. It also gives an accurate representation of the influence that replacing each element has on acoustic performance.

The third chapter deals with a different kind of construction. It focuses on the study of building façade panels composed of rice straw waste generated in Valencia. Rice cultivation in the Albufera Park is deeply rooted in the Valencian culture. However, rice cultivation generates around 90000 tons of rice straw annually after the harvest. The management of that straw as waste arises considerable environmental problems. In this chapter, the most common waste straw management practices and how they affect the local and global environments are studied. A rice straw façade panel was analyzed as an alternative to conventional brick façades, probably one of the most common façade typologies in the region. Using the straw to build the panels avoids the impacts generated by the standard waste management practices. The article compares the environmental impact, the acoustic performance, and the thermal transmittance of the rice straw panels with a conventional brick wall. This way it is possible to determine the suitability of these panels as a sustainable façade typology. As a final note, the article briefly discusses the idea of glocal building materials as the combination of having a benefit both locally and globally.

The fourth chapter deals with the environmental impacts that occur over the lifespan of a building. It analyzes the life cycle of a European average wooden single-family house and deals with the concept of regenerative sustainability. The aim is to determine which are the existing barriers to regenerative architecture and how those barriers change depending on the location. The environmental impacts of the model house were compared in five different locations in Europe: Munich, Ljubljana, Portorož, Madrid, and Valencia.

The combination of these four case studies allows for an understanding of how the environmental impacts change from the most primary construction elements to the combination of all of them over the life span of a building.

## Historic perspective on buildings and the environment

Buildings dramatically affect the way we live by shaping the landscape around us. As our cities and buildings reach a higher level of sophistication, examining how it affects us and our surroundings gets more and more important. This situation is not new by any means; humans have always had a tense relationship with the environment. From the first settlements thousands of years ago, human ingenuity has allowed us to shape the materials in our surroundings into shelters. That kept our ancestors safe from adverse climate conditions, predators, and even other human tribes. However, soon enough, they realized that the interior spaces they were creating had an enormous potential that went way beyond their imagination at the time. Buildings used to practice religious rites, workshops, and even academies started to populate communities. As their craft improved, they even built roads, and even bridges to connect different settlements. This development led to an alteration in the surrounding environment that sometimes led to the degradation of ecosystems. Generally, this alteration was minor when compared to the massive scale of the planet. There were exceptions to this rule. The roman empire was responsible for the draining of an enormous quantity of water of the Albufera Park. That hugely transformed the local ecosystem at the time. This example is examined in more detail in chapter 3. However, as the population started to grow exponentially, it began to represent a real threat to the integrity of the planet and human subsistence. Scientists in the XVIII century started pondering on those ideas. Some of them noticed that humanity might reach a point in which it is impossible to provide enough food and water to a continuously increasing population. In the year 1798, Thomas Robert Malthus published "An Essay on the Principle of Population". In that essay, Malthus tried to predict the limits of population growth by using differential calculus(Broten, 2017). Because of the development of modern agricultural techniques, his predictions ended up not being accurate. However, it raised questions that are still unanswered today: What is the maximum amount of people Earth can sustain? And, how can we push that limit to avoid undesirable outcomes?

It was also during those years when some scientists started to grasp the influence humans have over the global climate. From the 18$^{th}$ century, naturalists such as Buffon and James Hutton (Georges-Louis Leclerc, 1780) (James Hutton, 1788) developed theories about changes in the global climate throughout the ages. It was not until the year 1824 when Joseph Fourier theorized that it is the atmosphere that keeps the planet warm. He also pointed out the possibility of humans having an influence on those changes in the global climate: *"The establishment and progress of human societies, the action of natural forces, can notably change, and in vast regions, the state of the surface, the distribution of water and the great movements of the air. Such effects are able to make to vary, in the course of many centuries, the average degree of heat; because the analytic expressions contain coefficients relating to the state of the surface and which greatly influence the temperature."* (Fourier, 1827). In the year 1872, John Tyndall demonstrated that gasses such as Methane ($CH_4$) and carbon dioxide ($CO_2$) block infrared radiation, which gave a plausible explanation to Fourier's theory. Many scientists started developing theories connecting natural phenomena to the alteration of the global climate. Piotr Alekseevich Kropotkin could probably be considered the first that saw a relation  between the industrial revolution and the melting of the Siberian glaciers (Ivanova and Markin, 2008).

Svant Arrhenius, in 1896, introduced the idea that burning fossil fuels would add more $CO_2$ to the atmosphere, thus raising the average temperature of the globe (Arrhenius, 2013). However, Arrhenius thought this could have beneficial effects. The overall scientific community dismissed the theory and practically ignored it (Arrhenius, 2013).  In 1938, Guy Stewart Callendar, an amateur scientist, believed in it and tried to estimate the rise in global temperature (Charlson, 2007). Despite the early skepticism, several scientists started to pay attention to Callendar's and Arrhenius's claims in the following decades. Many tried to model and improve them, but it was not until 1967 when Syukuro Manabe and Richard Wetherald were able for the first time to calculate in detail the greenhouse effect considering convection(Manabe and Wetherald, 1967).

However, the main catalyst for change in the energy industry was the oil crisis of 1973 (Jeffs, 2008). After the oil embargo led by Saudi Arabia, oil prices increased by 300%. This situation generated a huge economic crisis. After that, politicians all over the world realized that the dependency for oil came with great danger. For that reason, nations all over the world started to strive to be self sufficient energy-wise. At the same time, this situation gave notoriety to many environmentalists that were alerting about the climate change generated by carbon emissions. Because of the combination of the crisis generated by the oil embargo and the inoperability of the US government due to the Watergate scandal, the environmental movement gained significant momentum in the United States. This crisis forced western societies to examine energy use and efficiency. Scientists and environmentalists proposed the use of technologies that capture the energy of the wind, the sun, and the geothermal hot water. Although none of those technologies were new, they were only used in a limited way. That was the turning point for experimenting with new technologies such as alternative fuel cars, With hindsight, we can see that that was the start of the global renewable industry we see today (Staff, 2019).

After the overwhelming amount of studies warning about the change in the earth climate, in 1987, the United Nations published Our Common Future (also known as the Brundtland report) in which the UN showed its intentions of tying development and the environment together as one single issue (World Commission on Environment, 1987). A year later, the International Council of Scientific Unions, the United Nations Environment Programme (UNEP), and the World Meteorological Organization (WNO) founded the Intergovernmental Panel on Climate Change (IPCC)("IPCC - Intergovernmental Panel on Climate Change," n.d.). Also backed by the United States Environmental Protection Agency (EPA), this organization provides scientific information through the publication of annual reports, comprehensive assessments, and methodologies. These publications are commonly used as a reference when it comes to obtaining reliable information on the topic of climate change.

From that point on, governmental institutions started to develop plans with climate change and sustainability as one of the main objectives. The first of those plans was the United Nations Framework Convention on Climate change (UNFCCC) in 1992. Commonly known as the Earth Summit, it took place in Rio de Janeiro in 1992. A total of 154 states signed the treaty, which meant promoting research on the topic, attending regular meetings, negotiations, and future policy arrangements. The Kyoto Protocol, which is probably the most famous example of those plans, extended the agreement reached in the UNFCCC and implied the commitment to reduce the emissions of six different greenhouse gasses: carbon dioxide ($CO_2$), Methane ($CH_4$), nitrous oxide ($N_2O$), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride ($SF_6$) (United nations, 1998). In the year 2016, 191 members of the UNFCCC signed the Paris agreement. This agreement has as its objective to keep the rise in global average temperature to 1.5 ºC.

There were also other plans, that despite not being only related to climate change and the environment, intended, among other things, to foster specific measures related to sustainability. In the year 2000, the United Nations established the Millennium Development Goals (MDGs). The United Nations member states committed to achieving eight specific goals with the idea of shaping the 21$^{st}$ century. Goal 7 was the one that specifically focused on ensuring environmental sustainability. Although the targets lacked specificity, this proved that it is possible to reach international agreements on sustainable development (Lomazzi et al., 2014). The MDGs were replaced in 2015 by the Sustainable Development Goals (SDGs) (Gigliotti et al., 2018). There are 17 SDGs. The common objective of all of them is to be a "blueprint to achieve a better and more sustainable future for all". Although all of them deal with sustainability in one way or another, some of them aim specifically at sustainability and the environment. That is the case of objective 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities), and 13 (climate action).

The European Union has been pursuing to develop its own strategy regarding climate change and sustainability in general ("Carbon Neutrality by 2050: theWorld's Most Urgent Mission | United Nations Secretary-General," n.d.). In the year 2019, the EU approved its environmental policy, the European Green Deal. The European Green Deal consists of a set of initiatives with the overarching aim of making Europe climate neutral by 2050. This plan is supported by specific deadlines oriented to achieve the ultimate goal progressively. The environmental strategy of the European Commission also includes funding research projects with programs such as LIFE and Horizon Europe ("LIFE," n.d.)("Horizon Europe | European Commission," n.d.). The combination of those plans makes the European Union a global referent when talking about sustainable development. The main initiatives on climate change by the European Union and the United Nations are depicted in Figure 0.1.

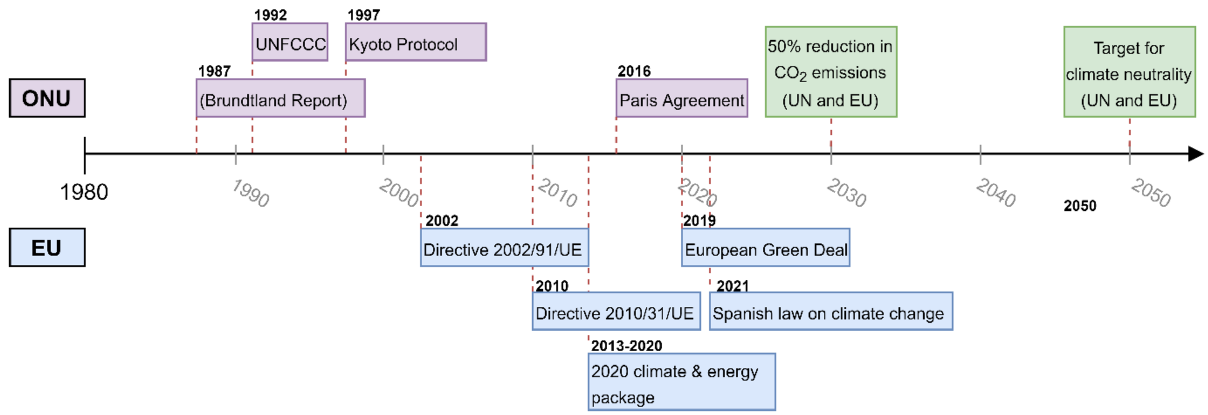


**Figure 0.1.** Main initiatives by the UN and the EU on climate change

However, the European Union is not the only governmental institution that is pursuing climate neutrality. Many nations such as the United Kingdom, South Korea, and China have committed to reaching that goal in the next 30 to 40 years. Many governments have released, or plan to release, measures oriented to avoid negatively affecting the environment. Those negative effects are commonly referred as environmental impacts. The consequences of those impacts are the biggest threats humanity will face in the following decades. The emission of carbon dioxide and other Greenhouse Gases (GHG) is probably the most recognizable of those impacts. As mentioned in previous paragraphs, GHGs are responsible for the greenhouse effect or global warming. Despite the enormous relevance carbon emissions have, many other environmental impacts are also worth noting. Land transformation, water use, eutrophication ionizing radiation are only a few of those impacts. Every human activity has an impact on the environment. The solution is to avoid those activities that have a higher impact and replacing them with sustainable alternatives. That is not that easy, though. How do we know the actual impact of any given human activity? We need to know the exact environmental effect it might have to make conscious decisions. Otherwise, we are only guessing. The solution to that problem is systematically analyzing the environmental effect of each process embedded in a particular activity. That methodology, which is currently widely spread and standardized is known as Life Cycle Assessment (LCA), took decades for the experts to develop.

## Life Cycle Assessment and Environmental impacts in the built environment

The early beginnings of Life Cycle Assessment (LCA) date back to the 60s (Hauschild et al., 2017). Several environmental studies that resembled what today we call LCA were released in those years. Although the answer to which one of those was the first LCA study is debatable, perhaps the Harold Smith study on the cumulative energy requirements of chemical products presented in 1963 at the World Energy Conference can be considered the first life cycle-oriented study (Džidić, 2017). Later in the decade, the Coca-Cola company commissioned a study on the environmental impacts of beverage cans (Darnay and Nuss, 1971). It wasn't until 1974 when the first public and peer-reviewed LCA study was published (Hunt et al., 1974). This study also analyzed the environmental impacts of beverage cans. The late 80s and the 90s were crucial to the development of the methodology. The year 1989, the company Thinkstep released, GaBi the first commercial software for LCA calculations. One year later, PRé Sustainability released Simapro, another hugely popular LCA software. That same year, the term LCA was officially coined by the Society of Environmental Toxicology and Chemistry (Fava, 1990). In 1997, a new milestone was reached when the ISO 14040 standard on LCA principles and framework was released. It was followed by the ISO 14041 and the 14042 and 14043 in the early 2000s (ISO 14040, 2006). However, despite the standardization, there was still a lack of comprehensible databases. That situation improved after the release of the first Ecoinvent database in 2003 (ISO 14040, 2006). After that series of events, the LCA methodology was on track to becoming the staple environmental assessment methodology we know today.

As introduced in an earlier paragraph, the building sector has a dramatic influence on the environment. Buildings not only need a huge amount of resources for their construction, but also host most human activities. Therefore, buildings not designed adequately can be hugely detrimental to the environment. Many architects and industry professionals have been aware of the determinant relation between buildings and their environment. A great example of that is Solar architecture, which started as a trend in the 30s in the United States. Solar architecture involved taking advantage of orientation and glass surfaces to provide sufficient light and heat to interior rooms. The anxiety about the possible lack of sufficient energy supply after the Second World War gave a boost to solar architecture. Some remarkable examples are the Sloan House (1939) and the Duncan House (1941) both by Fred Keck, the MIT solar house (1939) and the Dover House by Maria Telkes and Eleanor Raymond (1948). However, the increase in the use of oil and natural gas, as well as the fascination for the possibilities of nuclear power, undercut these innovative solar designs in the fifties (Barber, 2016). Along those years, other pioneers in bioclimatic architecture started making their mark. Victor Olgyay was published his book *Design With Climate*, published in 1963 (Victor Olgyay, 1963). Baruch Givoni was also a pioneer in the field. He became well known for his book *Man, Climate and Architecture,* where he presented his famous bioclimatic diagram (Givoni, 1969). As it was explained in previous paragraphs, due to the oil embargo, during the 70s, energy optimization was in the limelight again. Counter-cultural movements led to another wave of interest in designing with the sun (Denzer and Gardzelewski, 2019). They felt attracted not only to the positive effect those houses had over the environment but also to the revolutionary shapes and designs they had. The work of those early adopters was instrumental to the development of our current standards on efficient and sustainable construction such as Passivhaus (Santy et al., 2017).

As discussed in every chapter of this thesis, especially the fourth one, the life cycle of a building is divided into several phases (Figure 0.2). The impacts of each phase vary depending on several decisions taken during the project phase: the building materials, the location, the design, and the processing of the materials after the end of life. As it happens with every industry, the building sector needs to reinvent itself to meet the new sustainability standards. Terms such as Nearly Zero Emissions Buildings are more popular than ever before (Hermelink et al., 2013). These kinds of concepts are tied to conventional sustainability. Conventional sustainability is based on the idea of creating an equilibrium between taking and giving back to the environment. However, today we need to go one step forward and contribute to the regeneration of ecosystems. Once the ecosystems are in a healthy state again, the best option is to take a Regenerative approach. Regenerative sustainability consists of developing a co-creative partnership with nature, Figure 0.3 (du Plessis, 2012). This topic is also discussed in detail in chapter four. This thesis deals extensively with building materials. Although the manufacturing process of the materials is not the most impacting phase in the life cycle of a building, the building materials will configure and determine all the building life cycle phases. Some examples can be given to illustrate this concept. Local materials would significantly reduce the impacts related to transportation. Light materials would require smaller vehicles to transport them to the building site. Long-lasting materials would not need to be replaced as often. Building envelopes composed of high thermal insulating materials would reduce the amount of energy needed for heating and cooling.

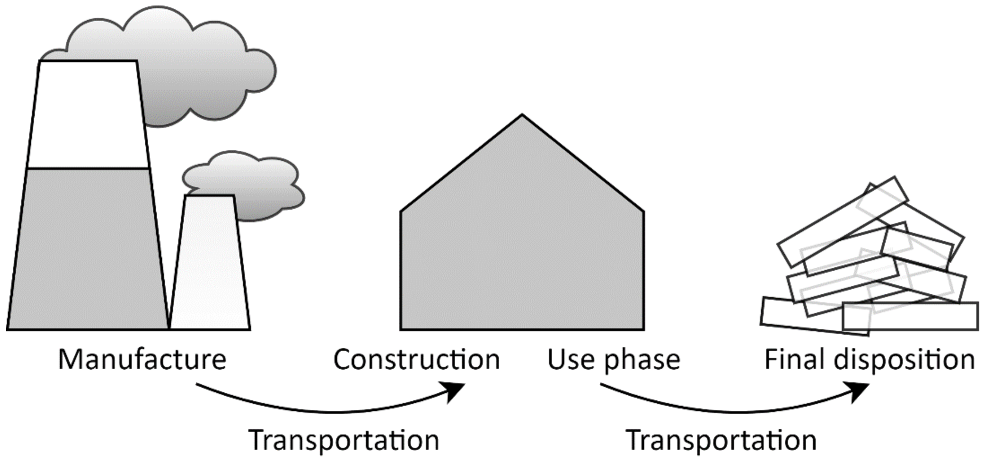


**Figure 0.2.** Phases in the life cycle of buildings

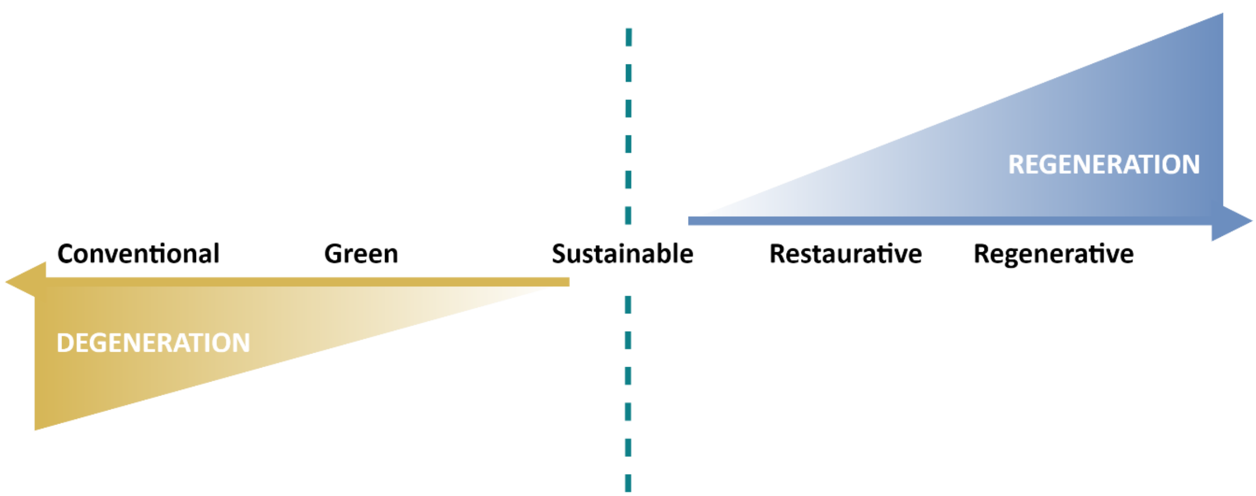


**Figure 0.3.** Regenerative and conventional sustainability

The use of masonry blocks, bricks, and other kinds of materials made from minerals has been common practice in many parts of the world for thousands of years. Those materials come from quarries which, besides having a limited amount of resources, alter and damage the landscape. Those kinds of materials also require an enormous amount of energy to extract. As the world population grows, the demand for building materials also grows. The most indicative example of the potential impact of those materials is the production of cement, which is well known for its enormous GHGs emissions. Although this is not the case for other materials, it is crucial to understand that minerals are associated with high environmental impacts. Moreover, there is a tendency of homogenizing building techniques. Globalization and the industrialization of the building sector tend to promote using the same materials and construction typologies in every country. Not so long ago, buildings needed to be built using proximity materials. With the development of new transportation systems, nowadays, it is easy to import any material from anywhere on earth. This kind of mindset comes with a huge environmental load due to transportation. It also detaches architects and dwellers from their surroundings. However, this must not be understood as a justification for using local materials no matter their impact on the environment. There should be a push for using local materials while accounting for their environmental impacts on a global scale. This concept could be named Glocal. Multi natural companies such as McDonald's and Coca-Cola use this term to define their strategy of adapting to the local markets while maintaining their global branding and image. This concept has been used before in architecture, but with a slightly different goal (Nagashima, 1999).Replacing conventional materials with new sustainable ones is a challenge. Building materials are required to perform in a specific way for a long time. For example, replacing reinforced concrete with a new biopolymer would require extensive research to prove that the new material can withstand the building loads for, at least, as long as reinforced concrete. That in itself is, as I said, challenging. But after being able to prove that, it is also necessary to convince all the stakeholders involved in a particular project of the advantages a particular innovative material might bring. As said in a previous paragraph, we would also need to be sure that the new material is better for the environment than reinforced concrete. There are economic concerns, performance concerns, and sustainability concerns. It is an overall delicate matter. The three first chapters of this thesis compare the performance and the environmental impacts of sustainable materials with conventional ones. Specifically, those chapters analyze two crucial performance indicators that are often forgotten: acoustic insulation and thermal insulation. Those aspects are decisive when considering the replacement of materials for the building envelope. The thermal insulation of a façade not only determines the comfort of the building users but also influences the energy use for heating and cooling (Yang and Moon, 2019). In the case of both building partitions and façades the acoustic insulation plays a notable role in the health and comfort of the dwellers, as it has been proven that being exposed to significant noise levels can lead to a wide range of diseases (European Environment Agency, 2020). For that reason, this document combines the life cycle approach with the evaluation of the acoustic and thermal performance of the studied materials.

As explained in the first section of this introduction, the overarching idea of this thesis is to explore ways of reducing the environmental impacts of buildings in three levels: the materials, the construction typologies, in this case, façades and partitions, and the building. This is done through four case studies corresponding to a chapter of this document. The first one deals with individual materials. It consists of the study of several bio-composites and their environmental impacts in comparison to the impacts of gypsum plasterboard. The second and the third are conceived at the level of constructions as the conjunction of several building materials. The second consists of the LCA and the simulation of the airborne acoustic insulation of building partitions. The study deals with the airborne acoustic simulation and the LCA of six different partition configurations mixing conventional materials and new bio-based materials. The third one seeks to analyze the possibilities of using façade panels made of rice straw waste generated in Valencia instead of the conventional brick façade typology used in the area. The study compares the airborne acoustic performance, the thermal transmittance, and the environmental impacts of the two constructions. Additionally, the study contains an assessment of the hygrothermal behavior of the rice straw façade. The fourth one analyzes the environmental impacts at the building level. It seeks to assess the difference between the environmental impacts of the same building set in five different locations in Europe.

The thesis can also be understood as a transition from the analysis of materials that can be considered conventional sustainability materials to exploring solutions that lean on the idea of glocality and regenerative sustainability. The two first articles analyze highly engineered sustainable alternatives to conventional solutions. However, as the third chapter indicates, it is possible to use proximity materials, such as rice straw in the case of Valencia, which can lead many times to more satisfactory results in terms of their environmental impact. These kinds of materials can be considered glocal as long as they combine the ideas of being used locally and contributing to the mitigation of climate change. Going that extra step that separates conventional sustainability from being beneficial to the environment and the local communities can be understood as regenerative sustainability. This concept of regenerative sustainability is explored in chapter four. This chapter highlights the fact that it is not possible to reach a point of building regenerative houses by only thermally insulating the building and using wood for its frame.

## Objectives

The main objective of this thesis is to identify ways to reduce the environmental impact of buildings, from the materials and the construction industry to the whole life cycle of the buildings. This objective is carried out through the following sub-objectives:

- Exploring the possibilities of the Life Cycle Assessment methodology being not only used for research but as an actual project decision-making tool in the building industry. Using

LCA during the project phase would enable the stakeholders to make informed decisions regarding sustainability in buildings.

- Determining if composites made with bio-based epoxy resin and natural fibers can be a viable sustainable alternative to conventional drywall partitions. The overuse of non-renewable materials such as gypsum significant it's a significant source of environmental impacts. Finding bio-based alternatives to such materials could contribute to reducing construction waste, land transformation, and other impacts on the environment.
- Studying the environmental and acoustic effects of combining different acoustic absorbents in drywall partitions with the bio-composites. The motivation for this is to check if it is possible to substitute conventional acoustic absorbents with more sustainable alternatives without compromising the acoustic insulation of the partition.
- Analyzing the environmental effect of using rice straw from the Albufera park to build building façades. Using the rice straw as a building material would reduce the damages produced by the conventional waste management practices produced. The idea is to explore the concept of glocality.
- Determining the acoustic, thermal and hygrothermal performance of rice straw façades. These parameters are crucial for any building façade typology. Rice straw façades would need to meet the requirements of the building regulations to be considered an alternative to the conventional façade solutions.
- Studying how the environmental impacts of the different life cycle phases of wood houses change depending on the location in Europe. Understanding how climate and energy sources interlink with the environmental impacts produced over the life cycle of a building is crucial for finding ways to build more sustainably.

## Methodology

The methodology of this thesis is carried out through comparative case studies, all of them centered around Life Cycle Assessment. Each chapter contains a detailed methodology section as they can be read as individual studies. However, as a summary, the overarching methodology consists of the following items:

- Comparative Life Cycle Assessment (LCA): the comparative LCA in each article has been carried out following the guidelines of the ISO 14040 (ISO 14040, 2006). The Life Cycle Inventories were developed using the software Simapro. The data was obtained from the Ecoinvent database, from literature, and the companies involved in each study.

- Airborne acoustic simulation: the airborne acoustic simulation was performed using the software Aisla 3 (Fernández et al., n.d.). This software uses the mathematical model proposed by Ookura & Saito (Ookura and Saito, 1978) and Chen & Jan (Jensen and Raspet, 2010), which uses the mechanical data of the materials to determine the coupling impedance ($Z_{ij}$) between layers.
- Experimental measurements of the airborne acoustic insulation: the experimental measurements were conducted in an acoustic transmission chamber following the guidelines established by the International Organization for Standardization (ISO) 717-1 standard (ISO 717-1, 2013).
- Experimental measurements of the thermal transmittance: this process is performed according to the ISO 9869-1:2014 standard (ISO 9869-1, 2014). The process consisted of generating a temperature difference between the two rooms and evaluating the transfer rate of temperature through the element.
- Hygrothermal analysis: this process is conducted following the guidelines of the ISO 13788:2012 (ISO 13788, 2012).
- Energy simulation: a steady-state energy simulation is computed using EnergyPlus and DesignBuilder 6.1 (United States Department of Energy, 2019) (Design Builder, 2019). The weather data was obtained from The American Society of Heating, Refrigerating and Air-Conditioning Engineers ("ASHRAE," 2017),

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# Chapter 1

## Comparative Life Cycle Assessment of gypsum plasterboard and a new kind of bio-based epoxy composite containing different natural fibers

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Alberto Quintana-Gallardo, Jesús Alba, Romina del Rey and Ignacio Guillén-Guillamón

# Abstract

A comparative LCA from cradle to grave between traditional plasterboard, for drywall applications, and different composite boards, made by natural fiber and a bio-based epoxy resin (Supersap CLR), was carried out. The goal of the study was to determine whether the composites based on such a resin combined with natural fibers could be an eco-friendly alternative to plasterboard in the building sector. Moreover, the impacts related to each of the fibers used are also assessed separately from cradle to gate in order to get a better understanding of its influence. Both the results obtained through the IPC.GWP 100a method and the recipe endpoint show a remarkable difference between the plasterboard and all the different composites, the composites offering a 50% reduction in the $CO_2$ emissions. The calculations performed regarding the impacts related to the different fibers showed only small differences between them.

# 1. Introduction

Nowadays, there is evidence that supports the existence of global warming (Cox et al., 2000)(Le Quéré et al., 2015)(Parmesan and Yohe, 2003). This situation is making society become increasingly aware of the imminent danger that global warming may cause (Thomas et al., 2004). This change in attitude can not only be observed in the general population but also in new international and even regional laws, norms and regulations. All of them reflect this change in mentality with a common main objective: to avoid the occurrence of global warming or if not possible, to reduce drastically its effects.

Every industry field is undergoing deep change in their production process in order to succeed in making the least damaging products they can. We can consider the construction industry to be especially sensitive in this matter due to the enormous amounts of raw materials required to perform any activity in such a field (González-Vallejo et al., 2015). The search for ecological materials becomes crucial in meeting this necessity (Cabeza et al., 2014). Natural fibers are on the spotlight of many companies and scientific studies (Alves et al., 2010)(John and Thomas, 2008), with the common idea that its use as a raw material results in low environmental impacting products. But are the natural fiber made materials really less detrimental to the environment? In order to answer this question, it is necessary to analyze all the processes involved in the life cycle of each particular material from the moment the manufacturing is started until the end of life of the resulting product. This methodology is known as the Life Cycle Assessment (LCA) defined in the international ISO 14040, 2006 norm (International Organization for Standardization, 2006).

Until now, several studies have been carried out demonstrating that the use of natural fibers in relation with traditional materials, implies a reduction in the impacts associated with the automobile industry (Pegoretti et al., 2014)(La Rosa et al., 2013)(Cicala et al., 2016), the electronics industry (Deng et al., 2016) and in other areas as well. However, only a few studies have been performed concerning a product or a material with direct application to the building sector (Asdrubali et al., 2012).

## 1.1 Context of the case study

The case study presented in this paper was conducted within a larger project, based on the research of new materials and products applicable to the building industry with a low environmental impact and the study of its acoustic and thermal properties as well. The project is developed in Spain by the Polytechnic University of Valencia (UPV), so all the estimated consumption of energy related to transportation and electricity mix were made considering the necessary steps to manufacture the materials in such a country. Despite this fact, the study is easily applicable anywhere else as seen in the subsequent sections.

The building sector in Spain is based on materials extracted from quarries such as clay for bricks or tiles, plaster for drywalls, concrete for the structure or even stone for products like mineral wool. The vast majority of construction projects use these kinds of materials whose extraction from the land implies a huge environmental impact on the ecosystems (Rodríguez et al., 2015). The quest for alternatives to brick and plaster is key to assure a sustainable development and evolution in such a market anchored to the traditional products which sees any use of new materials with skepticism.

In order to counter this skepticism, it is necessary to prove to companies, without any doubt, that the alternatives offered guarantee not only equivalent mechanical, acoustic and thermal properties, but also that they bring noticeable improvement for the environment, therefore adding value to their products. The use of these alternatives opens a whole new market of eco-friendly consumers for the company. Currently the most highly trusted certificates for green construction such as BREAM and LEED reward the use of those kinds of materials.

# 2. Methodology

## 2.1 Goal and scope definition of the study

The main goal of this study is to perform a comparative Life Cycle Assessment between two construction-oriented materials. One of them is the traditional gypsum plasterboard, widely used all over the world as a drywall component, and a new kind of epoxy composite, produced in the UPV laboratory , thought to be an alternative to the previous one.

The epoxy composites produced have an epoxy-made matrix with ecological content known commercially as Supersap ("Entropy Resins delivers sustainable composites," 2011) and natural fibers of different kinds (flax, hemp, coir, jute and shredded cotton fibers) as the solid filling. The objective pursued is to determine, with a quantitative analysis, if the use of these composites may suppose an ecological alternative to traditional plasterboard.

The motivation for this study comes from a recent industrial production innovation made a few years ago by the company Entropy Resins in creating the epoxy resin Supersap, which is partially made out of ecological materials. The company claims to reduce $CO_2$ emissions to around a 50% with respect to regular epoxy resins ("Entropy Resins delivers sustainable composites," 2011). An LCA of the environmental impacts generated by composites made using Supersap and natural fibers compared to those generated by epoxy with glass fiber has already been performed (Angela Daniela La Rosa et al., 2014). The study included a comparison between the impacts generated by Supersap epoxy resin and Petroleum based epoxy resin (depicted in Table 1.1). That comparison shows that the impacts generated by Supersap are significantly lower in most categories. In addition, a comparative LCA using Supersap in building envelope solutions was carried out with special attention to thermal conductivity(A. D. La Rosa et al., 2014). However, composites made using Supersap have not been compared to gypsum plasterboard, yet.

This comparative LCA is performed from cradle to grave, meaning that the processes considered are the ones from the beginning of the production of every material used, going through each process of manufacturing until the end of life of the final product, in this case its landfilling. As it is explained in the following sections, the use phase in the studied materials won't produce any impact over the environment.

**Table 1.1**
Potential environmental impacts associated to 1 tonne of petroleum-based epoxy resin and 1 tonne of plant-derived Supersap Entropy resin

| Impact category | Units | Petroleum-based epoxy resin[a] | SuperSap Entropy[b] |
|---|---|---|---|
| Abiotic depletion (ADP) | kg Sb eq | 59,4 | 0,01 |
| Acidification Potential (AP) | kg SO2 eq | 40,3 | 25,44 |
| Eutrophication Potential (EP) | kg PO4--- eq | 6,6 | 6,9 |
| Global warming (GWP100a) | kg CO2 eq | 6663 | 4079 |
| Ozone layer depletion Potential (ODP) | kg CFC-11 eq | 1,26E-06 | 0 |
| Human toxicity Potential (HTP) | kg 1,4-DB eq | 490,44 | 545,17 |
| Fresh water aquatic ecotoxicity Potential (FAETP) | kg 1,4-DB eq | 246,5 | 66,39 |
| Terrestrial ecotoxicity Potential(TETP) | kg 1,4-DB eq | 29,1 | 228,63 |
| Cumulative Energy Demand (CED) | MJ eq | 2,16 | 1,9 |

[a,b] Values published by (Angela Daniela La Rosa et al., 2014)

## 2.2 Functional unit

The functional unit considered in this study is 1 $m^2$ of material, each material having a slightly different thickness. This difference in volume between them is not considered to be relevant because they accomplish the same task as a part of a drywall system regardless of their thickness.

## 2.3 Inventory analysis

An Inventory analysis based on the model described in the subsequent sections has been performed following the framework provided by the ISO 14040 (International Organization for Standardization, 2006). The objective of an inventory analysis is to account for every activity, raw material and process that can impact the environment. For that purpose, reliable data has been collected to describe the mentioned model. The tool used to model the Life Cycle Inventory is the software Simapro 8.3.0.0, the last version of one of the most popular software programs used for LCA calculations.

In relation to the geographical representativeness, the energy and production data used is adapted to the European market. All the transportation impacts are considered in the scope of the study, as shown in table 1.2.

**Table 1.2**

| Raw material | Means of transportation | Distance (Km) |
|---|---|---|
| Flax fiber | Lorry 16 metric tons | 250 |
| Jute Fiber | Transoceanic ship | 6711 |
| | Lorry 16 metric tons | 100 |
| Coir | Transoceanic ship | 3584 |
| | Lorry 16 metric tons | 350 |
| Hemp Fiber | Lorry 16 metric tons | 450 |
| Recycled shredded cotton fiber | Lorry 16 metric tons | 50 |
| Epoxy resin | Transoceanic ship | 6000 |
| | Lorry 16 metric tons | 250 |

### 2.3.1 Data quality

The production data of Supersap Manufacturing was extracted from the technical documentation offered by the company. The data related to the proportions of fibers and epoxy was obtained during the manufacturing process of the epoxy boards. The rest of the data used comes from the Ecoinvent V3 database (Ecoinvent, 2016). The Ecoinvent database, a not-for-profit association founded by institutes of the ETH Domain and the Swiss Federal Offices, is one of the most comprehensive international Life Cycle Inventory (LCI) databases. The available data in it covers processes from a wide range of industries classified by country such as chemical, building sector, agriculture, transport, energy and so on. Moreover, its data is highly reliable due to its peer review process, in which any data is revised by an LCA expert before being approved to be in the database(Pascual-González et al., 2016). Ecoinvent is used in many LCAs all over the world and with the release of the V3 and recently V3.1 it expands the already extensive capabilities it had in previous versions and its transparency (Wernet et al., 2016).

### 2.3.2 Production phase model

*Production process of gypsum plasterboard*

Gypsum plasterboard is made out of a plaster core covered on its two sides by a cellulose layer. The production process goes as follows: The gypsum rocks are extracted from the quarry having approximately a maximum diameter of 5 cm, then the gypsum rocks are transported to a production factory where they are grinded into powder and heated up to 160 ºC. During this process, the gypsum loses about a 70% of its moisture which turns into stucco. Then, it becomes slurry when mixed with water and some chemical substances. Afterwards it is poured over a big cellulose layer which is unrolled onto a long board machine. Another layer of paper is unrolled on top of the slurry and then it goes through a system of different rolls compacting the core to the proper thickness. A few minutes later the slurry begins to harden and is prepared to be cut to the desired size. The last step consists in putting the board into an oven to remove the remaining moisture. The production process is summarized in Figure 1.1. A comparison between the impacts produced by 1kg of plasterboard and 1kg of petroleum-based epoxy resin is depicted in Table 1.3. The main impacting steps during the manufacturing process are specified in table 1.4.

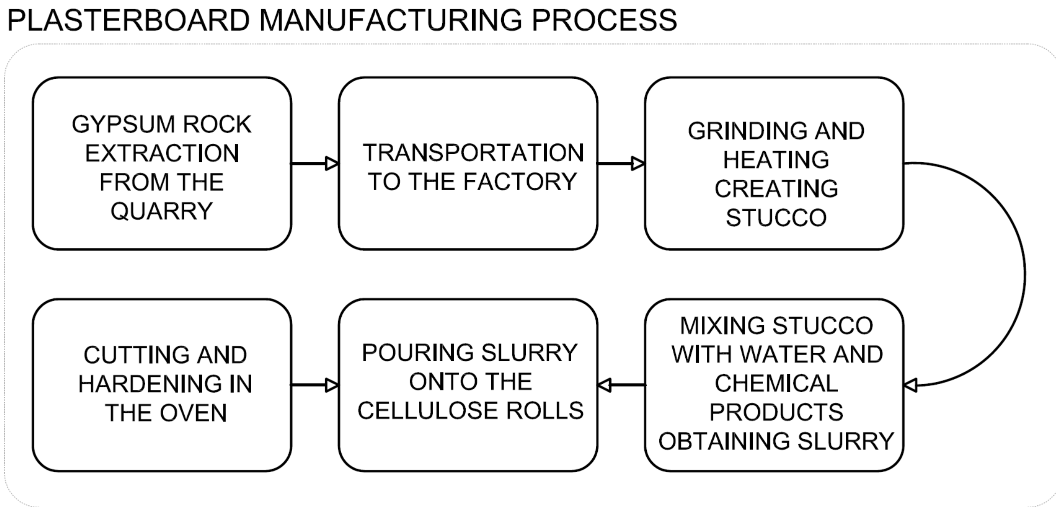



**Figure 1.1.** Plasterboard manufacturing process

**Table 1.3**

Comparison between 1kg of Plasterboard and 1 kg of Petroleum based epoxy resin

| Impact category | Units | Gypsum plasterboard | Petroleum based epoxy resin |
|---|---|---|---|
| Abiotic depletion | kg Sb eq | 2,52E-07 | 1,19E-06 |
| Abiotic depletion (fossil fuels) | MJ | 29,996372 | 122,42557 |
| Global warming (GWP100a) | kg CO2 eq | 2,1386249 | 6,9448216 |
| Ozone layer depletion (ODP) | kg CFC-11 eq | 1,63E-07 | 1,41E-08 |
| Human toxicity | kg 1,4-DB eq | 0,048522658 | 0,68101491 |
| Fresh water aquatic ecotox. | kg 1,4-DB eq | 0,003153629 | 0,89204571 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 53,231855 | 4848,7284 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 0,00281531 | 0,029100246 |
| Photochemical oxidation | kg C2H4 eq | 0,000335308 | 0,001196045 |
| Acidification | kg SO2 eq | 0,005004837 | 0,041101898 |
| Eutrophication | kg PO4--- eq | 0,000804968 | 0,006681138 |

**Table 1.4**
Inventory of the main impacting steps for 1k of gypsum plasterboard

| | Quantity | Unit | kg CO2 eq |
|---|---|---|---|
| Transport, freight lorry | 0,117 | tkm | 0,0155 |
| Stucco | 0,811 | kg | 0,066 |
| Folding boxboard/chipboard | 0,0484 | kg | 0.103 |
| Organic bonded boards | 1,67E-11 | p | 0,00186 |
| Electricity, medium voltage | 0,5991 | MJ | 0,124 |
| Industrial heat | 2,521 | MJ | 0,2463 |

*Production process of the epoxy composite boards*

All the composite boards analyzed have the usage of Supersap Epoxy resin in common, each one of them containing a different kind of natural fiber. The materials used and its cultivation process are summarized as follows (Figures 2, 3):

Flax: After harvesting, the first step is retting; a method used to dissolve much of the cellular tissues and pectin surrounding the fiber. Afterwards, the stems have to be submitted to a process called scutching, in which the stems are crushed by a pair of fluted rollers and beaten by a rotating blade to make the shive (the inner body tissue) fall off. A big variety of products can be obtained by scutching, such as long and short fibers, shive, flakes and seeds. The scutched fibers are then hackled to remove the remaining impurities and wood particles, getting as a result slivers and hackled tows. Once this process has finished, the slivers can be twisted into yarn using one of two different methods: wet spinning or dry spinning. Wet spinning involves further processes such as roving or bleaching and is generally used to produce fine textiles whereas the dry spinning is a much more simple process carried out by applying the spinning directly to the long fibers. As a result, using the dry spinning we get coarse and less expensive fibers and the use of chemical products is reduced. Considering that the fibers used in a composite material do not need to be particularly pleasant to the eye, the most suitable method for this particular application is the dry spinning process, therefore excluding the bleaching and roving (Le Duigou et al., 2011).

Hemp: the hemp fiber is produced from Cannabis Sativa varieties with lower cannabinoid content and with higher fiber proportion than other members of the species. After the sowing and cultivation period, the plants are harvested as soon as the male plants begin to exude pollen. Afterwards the dew retting process begins; the stems are placed on the floor for several weeks where due to the effect of the sun and the wind the pectin rots baring the bast fibers. There are further sophisticated processes using chemical products if needed, but they are not considered for this case study. The final separation of the fiber is accomplished in a way similar to the flax process, starting by the breaking operation in which the wood portion of the straw is broken mechanically or manually, followed by the scutching process removing the wood particles called shive and finally hackling for further elimination of the shive and short fibers. Nowadays this whole process is easily made using modern machinery. Once the fibers are separated and bundled together the spinning operation begins.

Jute: The jute cultivation and processing to obtain fiber is very similar to the ones used for flax and hemp, all of them depicted in Figure 1.2. The manufacturing steps needed in order to obtain the fiber are roughly the same: Harvesting, retting, breaking, scutching, hackling and spinning.

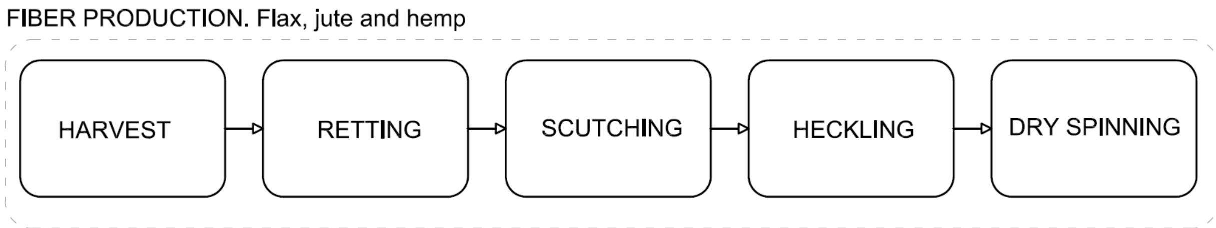



**Figure 1.2.** Flax, jute, and hemp manufacturing process

Coir: as opposed to the previously mentioned fibers, which are obtained from medium to small size plants, coir is obtained from the exterior husk of the coconut tree fruit. The coconut tree can reach 30 meters tall, making the harvesting process more complex than in smaller plants or trees. The gathering of the coconuts can be done by climbers, from the ground using bamboo reeds or even with trained monkeys. Once the coconut is harvested, it is dehusked impaling it with a steel-tipped spike. After carrying out this processes the next steps are the same as seen previously. It starts with retting, followed by breaking, scutching, hackling and finally spinning. The processes followed are depicted in Figure 1.3.

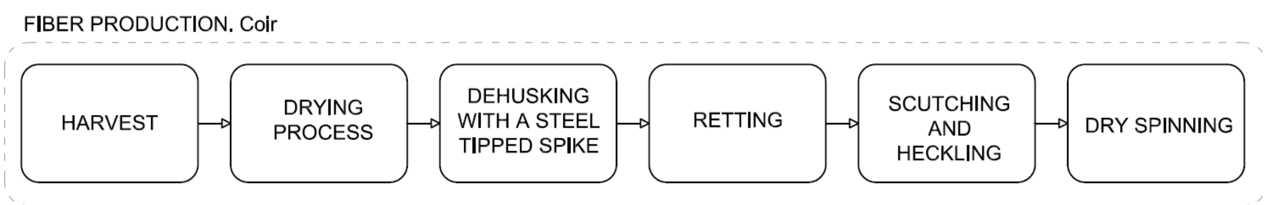



**Figure 1.3.** Coir manufacturing process

Recycled shredded cotton: this material is completely different from the rest, being the only one in this study which comes from recycled material obtained from textile residue. The residues are collected and transported to big processing plants where they are classified depending on the content and its destination. Once classified, the waste is transported to a second plant where, in this case, the residue is shredded and compacted obtaining shredded cotton fiber. The processes are represented in Figure 1.4. The inventory of each fiber used is depicted in table 1.5.

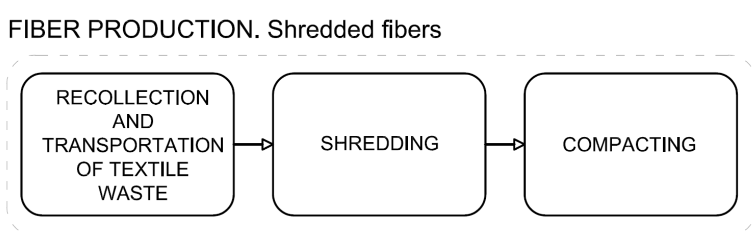



**Figure 1.4.** Shredded cotton fiber manufacturing process

**Table 1.5**

Inventory of main impacting steps for 1 kg of fiber

| | Quantity | Unit | kg CO2 eq |
|---|---|---|---|
| **Jute** | | | |
| Phosphate fertilizer, as P2O5 | 0,0124 | kg | 0,0132 |
| Urea as N | 0,0311 | kg | 0,0982 |
| Irrigation | 0,5806 | m3 | 0,20692 |
| Stalk | 1,7 | kg | 0,252 |
| **Hemp** | | | |
| Fertilizing by broadcaster | 38,1 | m2 | 0,107 |
| Urea as N | 0,0189 | kg | 0,0598 |
| Irrigation | 0,4095 | m3 | 0,1449 |
| Stalk | 1,7 | kg | 0,252 |
| **Cotton** | | | |
| Transport by lorry | 0,229 | tkm | 0,03188 |
| Transport by train | 0,000684 | tkm | 0,000118 |
| Irrigation | 0,2539 | m3 | 0,1121 |
| Electricity, low voltage | 0,807 | MJ | 0,2302 |
| Ammonium nitrate as N | 0,00734 | kg | 0,0598 |
| **Coconut** | | | |
| Poultry manure, dried | 0,0624 | kg | 0,0311 |
| Urea as N | 0,00606 | kg | 0,0191 |
| Potassium fertilizer as K2O | 0,00935 | kg | 0,00337 |
| Packaging for pesticides | 0,059 | kg | 0,0147 |
| Trellis system | 1,68 | m2 | 0,107 |
| Irrigation | 0,341 | m3 | 0,1533 |
| **Flax** | | | |
| Phosphate fertilizer, as P2O5 | 0,02 | kg | 0,0335 |
| Ammonia liquid | 0,012 | kg | 0,0226 |
| Potassium fertilizer as K2O | 0,0161 | kg | 0,00835 |
| Tillage, ploughing | 2,75 | m2 | 0,036 |
| Tillage, rotary cultivator | 1,37 | m2 | 0,0119 |
| Tillage, harrowing | 1,37 | m2 | 0,00979 |
| Fertilizing by broadcaster | 4,12 | m2 | 0,0116 |
| Plant protection product | 7,55 | m2 | 0,00977 |
| Electricity, low voltage | 2,5 | MJ | 0,294 |

Supersap Epoxy Resin: The term “epoxy resin” describes a wide variety of thermosetting polymers which share the common characteristic of the primary cross linking caused by the reaction of an epoxide group. Its chemical structure can be thought of as an epoxy, which is a molecule containing a three membered ring consisting of one oxygen atom and two carbon atoms. However, this structure varies depending on the purpose of the final product. This diversity is one of the reasons for the success of epoxy resins in such a wide range of applications (Boyle et al., 2001).

The epoxy class analyzed for this article is Phenolic glycidyl ether. This class of epoxy is produced by the reaction of epichlorohydrin (ECH), which is the key component of the vast majority of commercial epoxy resins, and a phenol group, being the bisphenol-A (BPA) the most widely used today(Dusek, 1985). However, it must be taken into consideration that the Supersap resin manufacturing process has some key differences with respect to the conventional epoxy resins, all of them subject to a confidentiality agreement.

Composite assembly: The composite boards are built using the resin infusion process. This process consists in introducing the resin into a mold using vacuum suction. The resin is introduced through tubes or pipes. Inside this mold the amount of fiber needed for the specific type of board chosen is previously placed. This procedure is one of the most modern methods to manufacture composite materials, presenting several improvements in economic and technical aspects (Hammami and Gebart, 2000). The process described above was conducted in UPV facilities. The mass of every material used in each typology is indicated in table 1.6. The physical and mechanical characteristics, measured in the UPV laboratory, are specified in table 1.7.

**Table 1.6**

Mass per $m^2$

| Product | Mass(Kg) | Fiber % | Fiber mass(Kg) | Epoxy % | Epoxy mass (Kg) |
|---|---|---|---|---|---|
| Flax board | 5,08 | 49 | 2,4892 | 51 | 2,5908 |
| Jute board | 5,08 | 44 | 2,2352 | 56 | 2,8448 |
| Coir board | 7,61 | 22 | 1,6742 | 78 | 5,9358 |
| Hemp board | 4,31 | 32 | 1,3792 | 68 | 2,9308 |
| Shredded cotton board | 4,89 | 27 | 1,3203 | 73 | 3,5697 |

**Table 1.7**

Physical and Mechanical Characteristics

| Board | Thickness (mm) | Density (g/cm3) | Mass/m2 | Shore C Hardness[1] | Impact resistance[2] |
|---|---|---|---|---|---|
| Plasterboard | 12,5 | 0,776 | 9,7 | 47,72 | 14,9 |
| Flax board | 4,62 | 1,183 | 5,08 | 76,2 | 76,72 |
| Jute board | 5,1 | 1,084 | 5,08 | 70,2 | 14,09 |
| Coir board | 8,14 | 1,027 | 7,61 | 64,7 | 5,23 |
| Hemp board | 4,24 | 1,146 | 4,32 | 70,07 | 5,71 |
| Shredded cotton board | 5,1 | 1,071 | 4,89 | 70,3 | 8 |

[1] Shore Durometer model Instruments J.Bot 673D (ISO 868:2003). Scale Shore D 30º

[2] Charpy impact test. Pendulum by Metrotec (ISO 179:1993). Scale used: 1J

### 2.3.3 Use phase model

Considering that there is no difference, during the building construction, between any of the typologies under this study, the only processes that need to be taken into account are those related to transportation. Furthermore, the material once used in the construction does not generate any impact to the environment, being the use phase the less relevant for the analysis of the impacts of building materials.

### 2.3.4 End of life model

Despite the differences between the gypsum plasterboard and each one of the composite boards, every typology analyzed should reach the end of its life cycle together with the building. For this reason we consider them to have the same durability. As the end of life scenario, all the materials analyzed are considered for landfilling. This option has been chosen because it is the most common scenario in the current situation of the Spanish construction market. Neither the reuse nor the recycling represent an important percentage in the final disposal of building materials for the moment. The life cycle of the composite boards is summarized in Figure 1.5. Considering that this situation may change in the near future, a complete analysis concerning the possibilities of recovering some of the materials at their end of life is advisable for future studies, yet beyond the scope of this one.

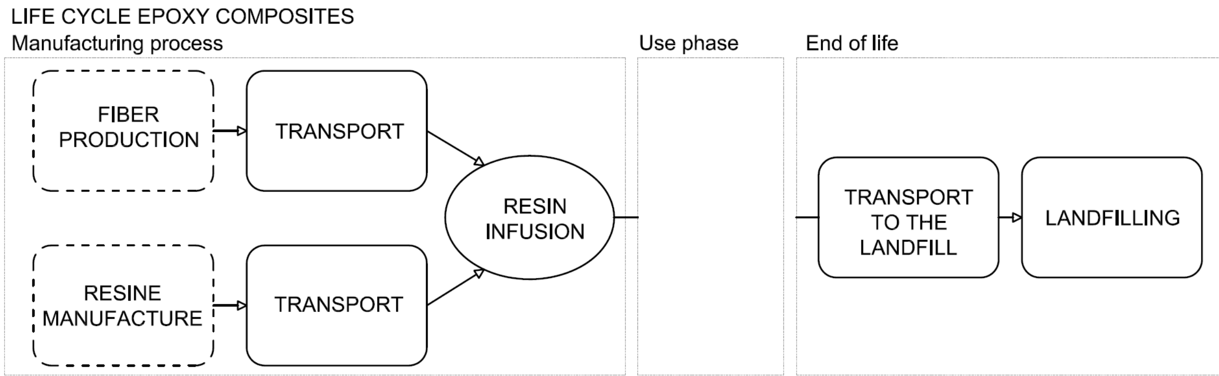



**Figure 1.5.** Life cycle of the composite plasterboards

## 2.4 Life Impact Assessment

### 2.4.1 Allocation principle

Due to the multifunction processes involved in cultivating and manufacturing the fibers, the use of an allocation principle becomes a necessity (Ekvall, 2001). The issue is easily identified for instance in the case of coconut. The environmental burdens of coconut cultivation have to be divided among the different products obtained, such as the coconut water, the pulp and the coir produced with the husk.

Overcoming the difficulties of assigning the proper burdens to each product is not a straight forward issue and has many possible solutions. Each of them has its own benefits and drawbacks. Through the use of the Ecoinvent Database V3.1 it is possible to choose between two main approaches: Consequential and Allocation at the Point of Substitution. The consequential approach is chosen due to its simplicity and reliability. This approach is also considered to be one of the most theoretically correct.(Tommie Ponsioen, 2015). The Consequential System Model is one of the major innovations that were introduced when the Ecoinvent Database V3 was released. This model uses substitution (system expansion) to convert multi-product datasets into single-product datasets. Therefore all the Ecoinvent Database processes chosen are Consequential.

### 2.4.2 Evaluation method

Among all the available methods for performing the life cycle assessment, two of them are selected: The IPCC.GWP 100a used for calculating the greenhouse gas emissions (equivalent $CO_2$ Kg) emitted by each material separately and the Recipe Endpoint method. The latter is intended to replace the two most important methods up to this point, the Eco-Indicator99 and the CML 2002 combining the mid-point approach and the end-point approach in a harmonic way (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

# 3. Impact assessment results and discussion

The flowcharts depicted in Figures 1.6, 1.7, 1.8, 1.9, 1.10 and 1.11 show the steps modeled using Simapro with the corresponding carbon dioxide impacts.

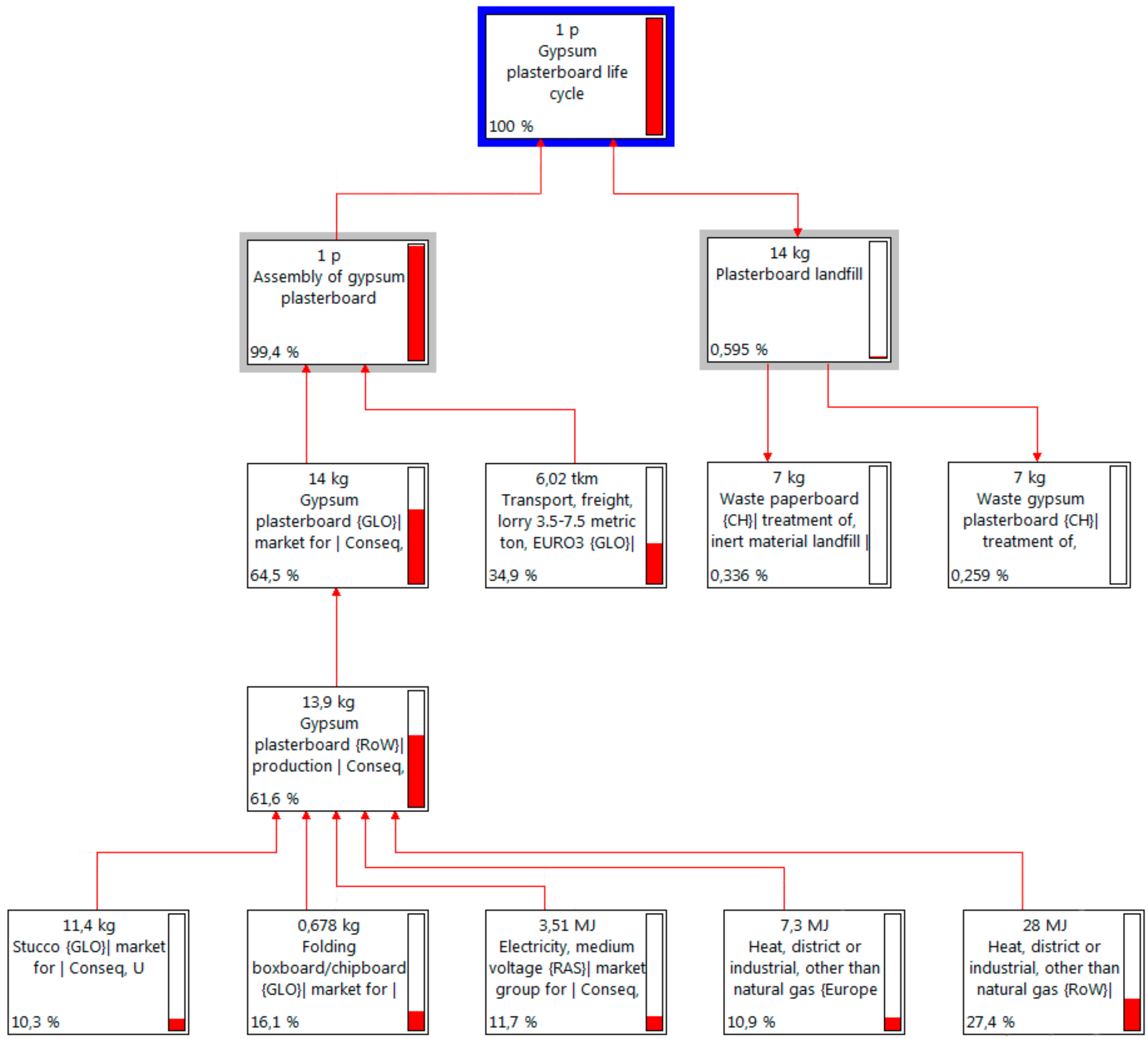



**Figure 1.6.** Network of the life cycle of gypsum plasterboard

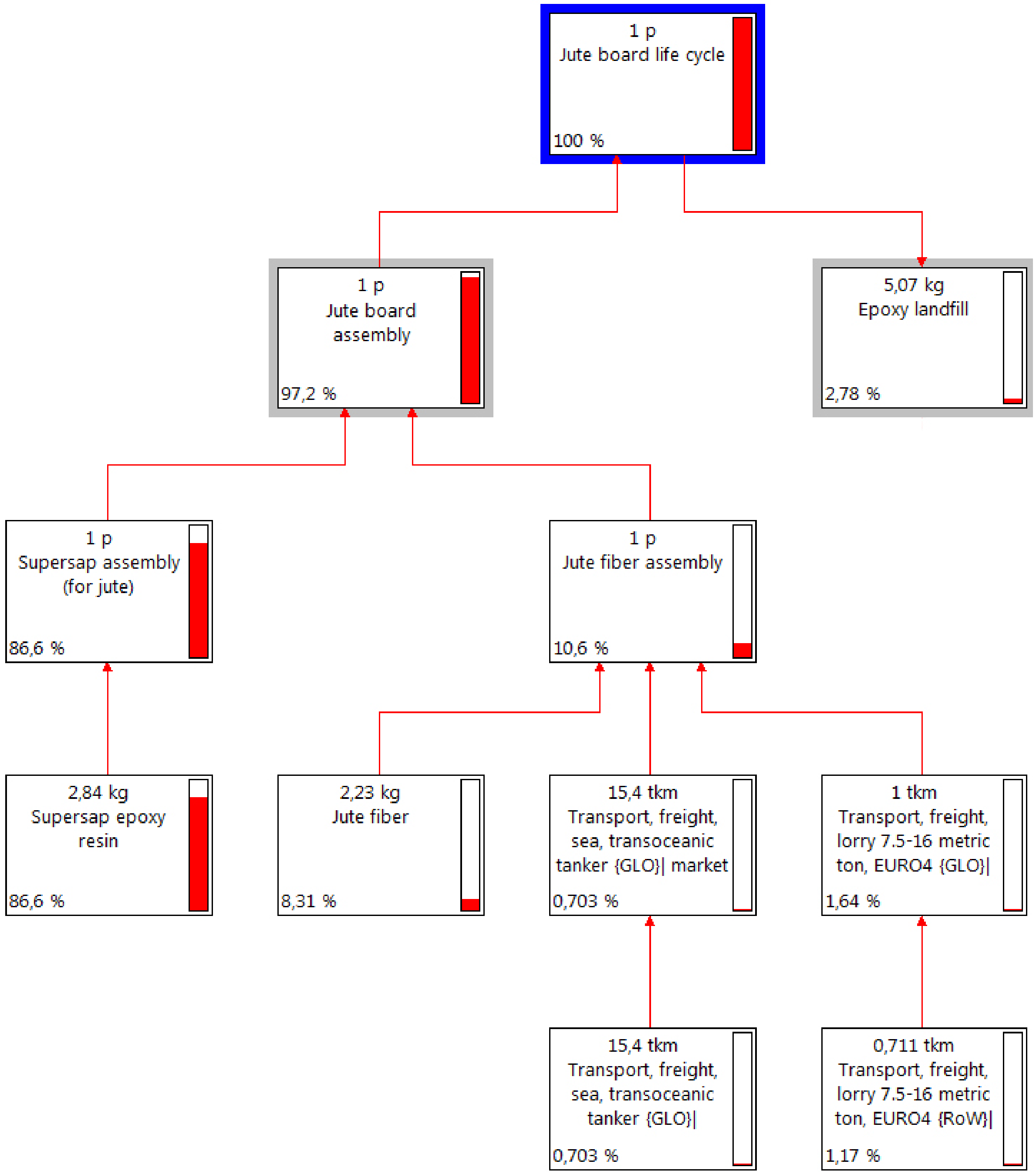



**Figure 1.7.** Network of the life cycle of the jute composite board

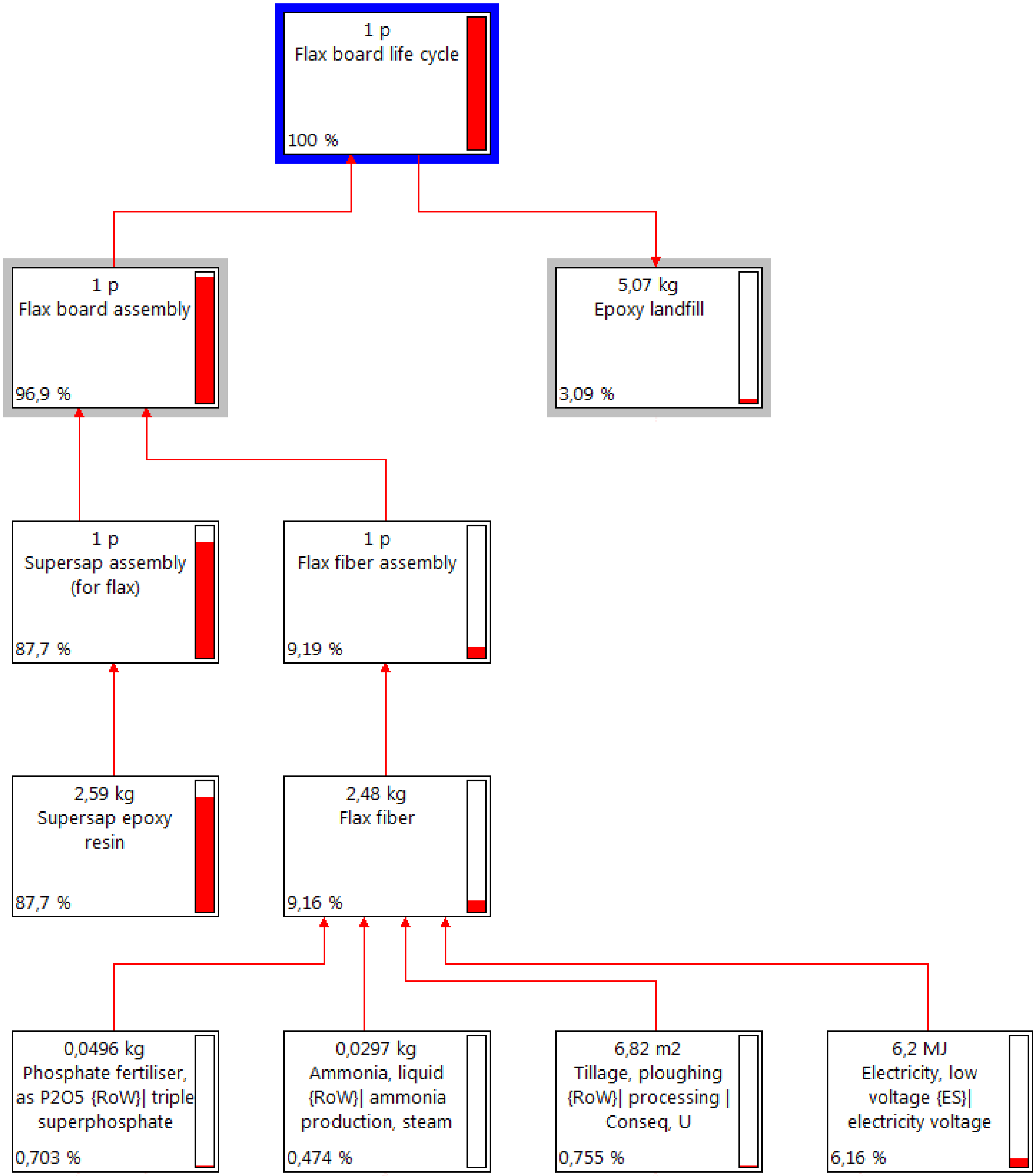



**Figure 1.8.** Network of the life cycle of the flax composite board

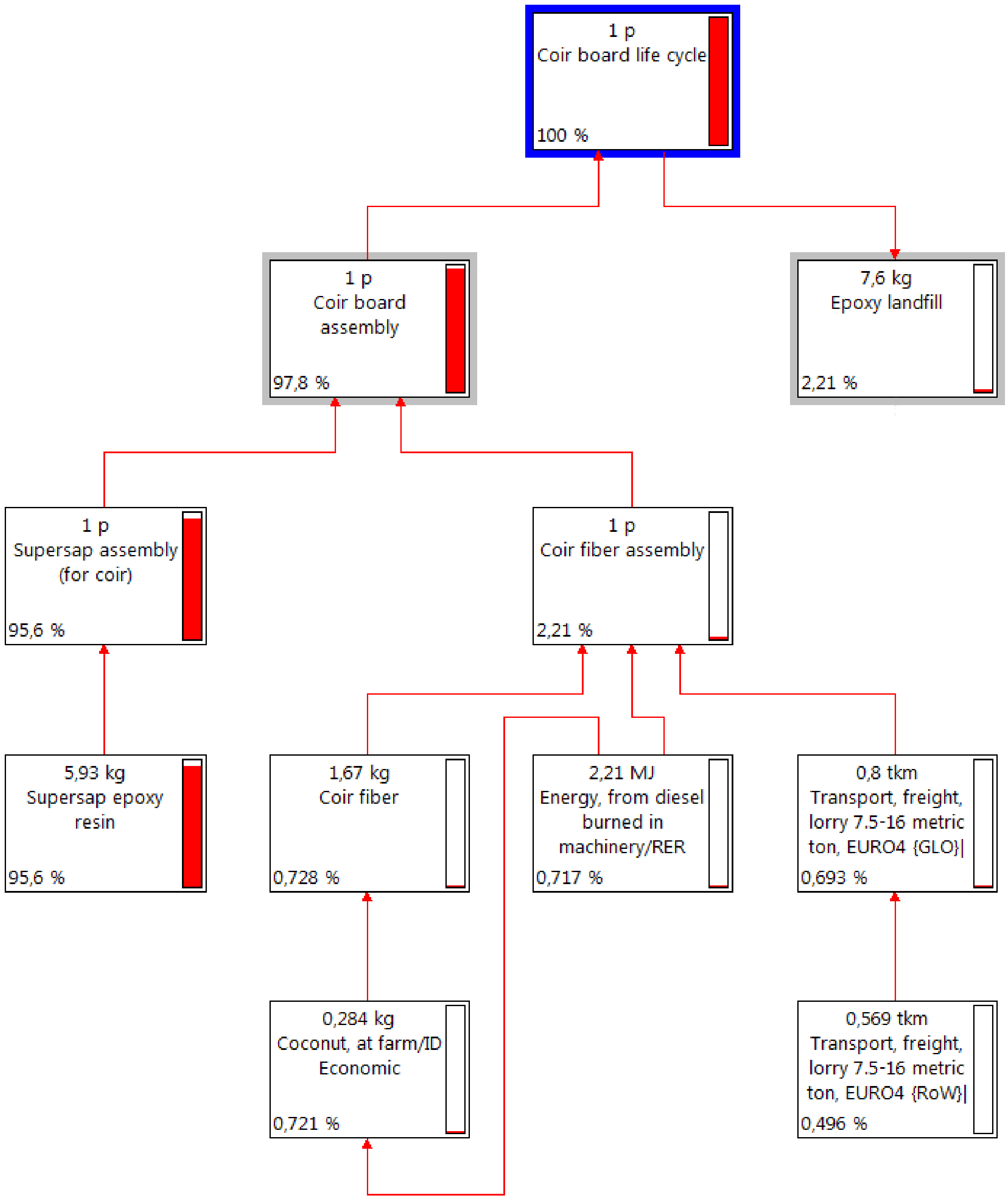



**Figure 1.9.** Network of the life cycle of the coir composite board

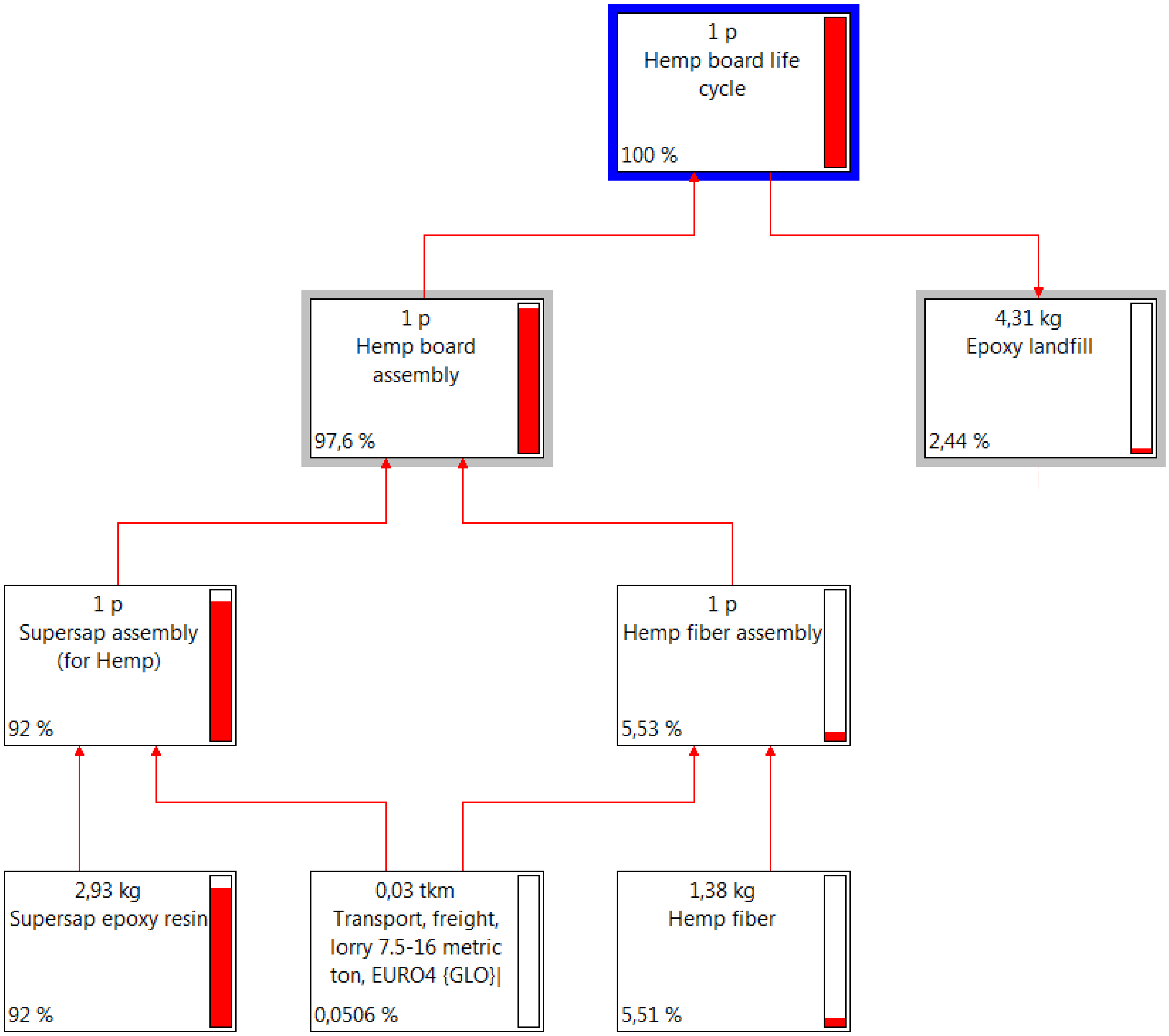



**Figure 1.10.** Network of the life cycle of the hemp composite board

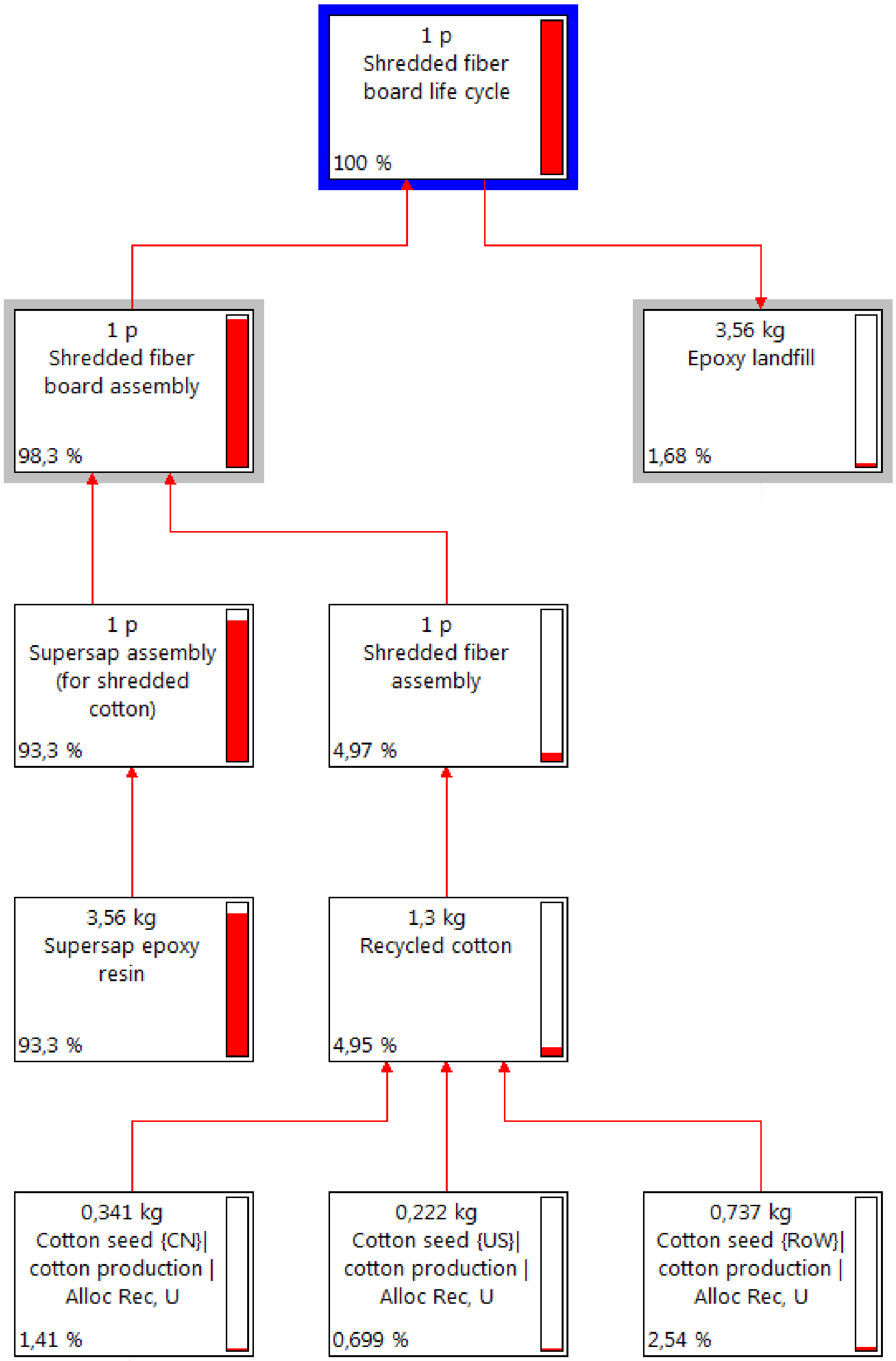



**Figure 1.11.** Network of the life cycle of the shredded cotton composite board

## 3.1 IPCC.GWP 100a method comparative results. Carbon Dioxide emissions

As shown in Figure 1.12, all the composites except the coir board have considerably lower carbon emissions than the gypsum plasterboard. The results show more than a 50% reduction in the Kg $CO_2$ equivalent in the case of flax. The results obtained with the coir board are almost as high as the gypsum plasterboard. The reason why the impacts are superior in the case of coir is because the quantity of Supersap per square meter is much higher (Table 6). Comparing the rest of the composites, the results are quite similar with small differences such as the flax composite emissions being slightly lower. That lower $CO_2$ emission is due to a higher proportion of fiber in its composition.

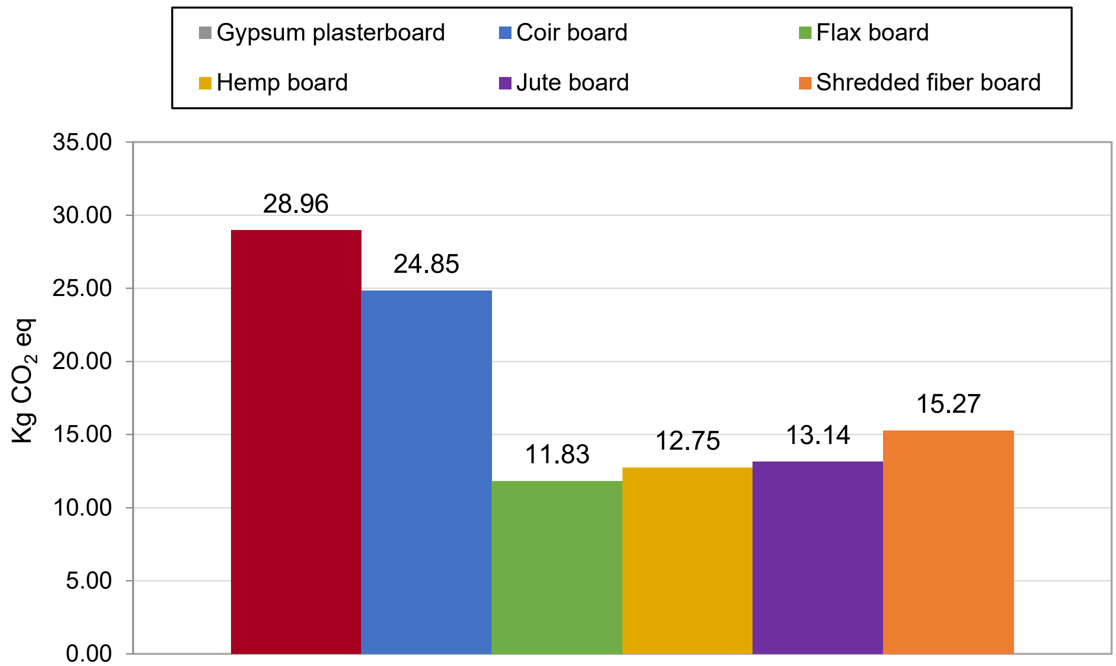
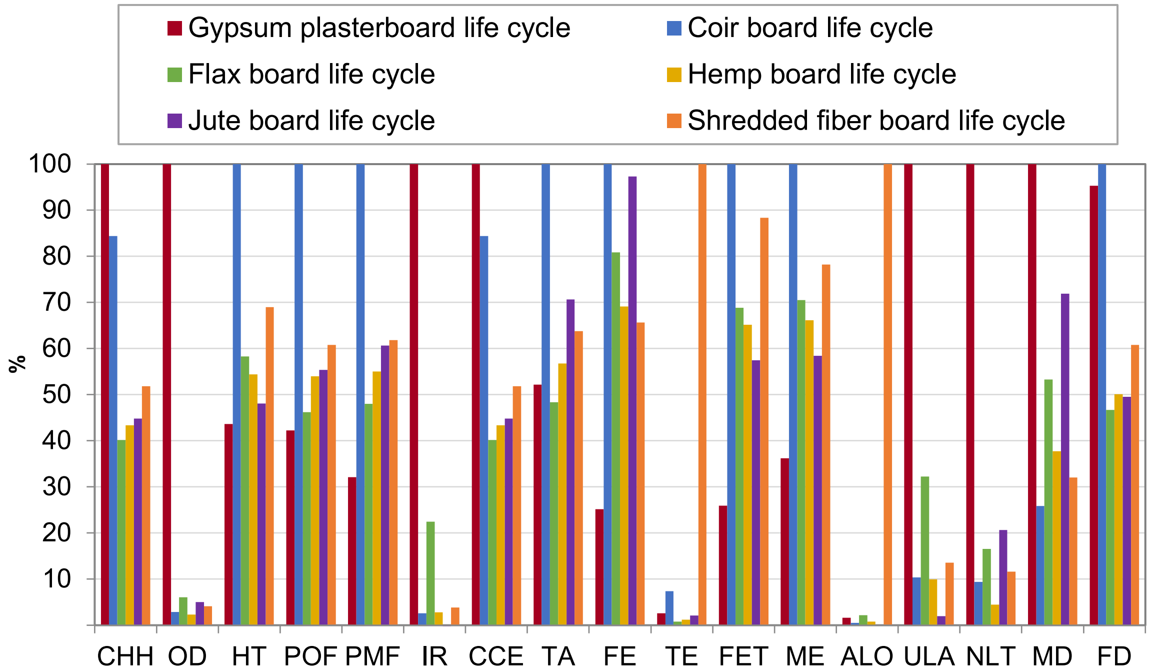



**Figure 1.12.** Comparative assessment of the carbon dioxide emissions by 1m$^2$ of material

## 3.2 Recipe Endpoint method comparative results

Using the Recipe Endpoint method, the results of seventeen different impact categories are obtained separately. As shown in Figure 1.13, the gypsum plasterboard and the coir board have the higher impact result in fifteen of the seventeen categories studied. The only categories were the score is not superior are Terrestrial Acidification and Agricultural Land Occupation. In those two categories the Jute board stands out as the most impacting material.




| | | | | | |
|---|---|---|---|---|---|
| **•CHH:** | Climate change Human Health | **•CCE:** | Climate change Ecosystems | **•ALO:** | Agricultural land occupation |
| **•OD:** | Ozone depletion | **•TA:** | Terrestrial acidification | **•ULO:** | Urban land occupation |
| **•HT:** | Human toxicity | **•FE:** | Freshwater eutrophication | **•NLT:** | Natural land transformation |
| **•POF:** | Photochemical oxidant formation | **•TE:** | Terrestrial ecotoxicity | **•MD:** | Metal depletion |
| **•PMF:** | Particulate matter formation | **•FET:** | Freshwater ecotoxicity | **•FD:** | Fossil depletion |
| **•IR:** | Ionizing radiation | **•ME:** | Marine ecotoxicity | | |

**Figure 1.13.** Characterization using the Recipe Endpoint (H) method. Comparative analysis of the environmental impacts produced by a 1m$^2$ board.

With the purpose of offering a global impact score for each material, the categories are summarized into three main aspects: Ecosystems, Human Health and Resources. In order to add up together all these different categories, all of them had to be submitted to three processes performed using Simapro: impact evaluation, normalization and weighting. Once these processes are completed, these three categories, obtained by the addition of the others, can also be added together obtaining a global result of the impact of each material. As shown in Figure 1.14 the results are significantly lower in the composites than in the gypsum plasterboard, with a difference of around 40 to 50 per cent depending on the natural fiber used. The only exception is the coir board, which has the highest impact among all the materials studied. Those high impacts coincide with the coir composite being the one with the higher Supersap content.

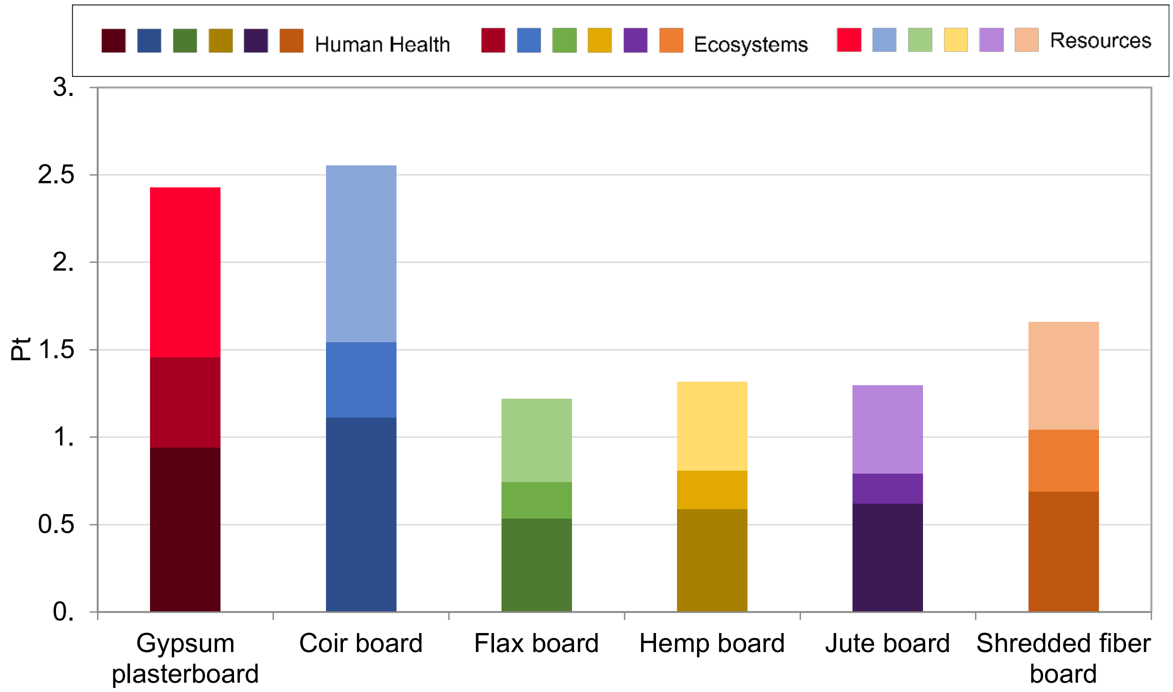



**Figure 1.14.** Single score result using the Recipe Endpoint (H) method. Comparative analysis of the environmental impacts produced by a 1m$^2$ board

## 3.3 Fiber impact comparison

Once the results have shown that the Supersap epoxy composites are an all-around less environmentally impacting alternative to the gypsum plasterboard, a comparison between the fibers used in the composites is advisable. In order to perform the calculations, only the fiber cultivation and manufacturing process have been taken into account. Therefore considering the scope of the calculations from the cradle to the gate.

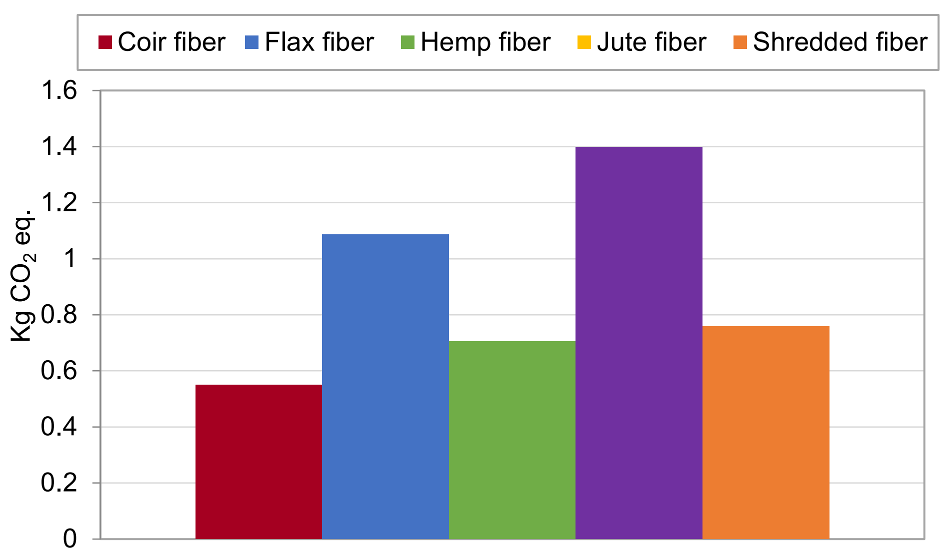



**Figure 1.15** Comparative assessment of the carbon dioxide emitted by each fiber

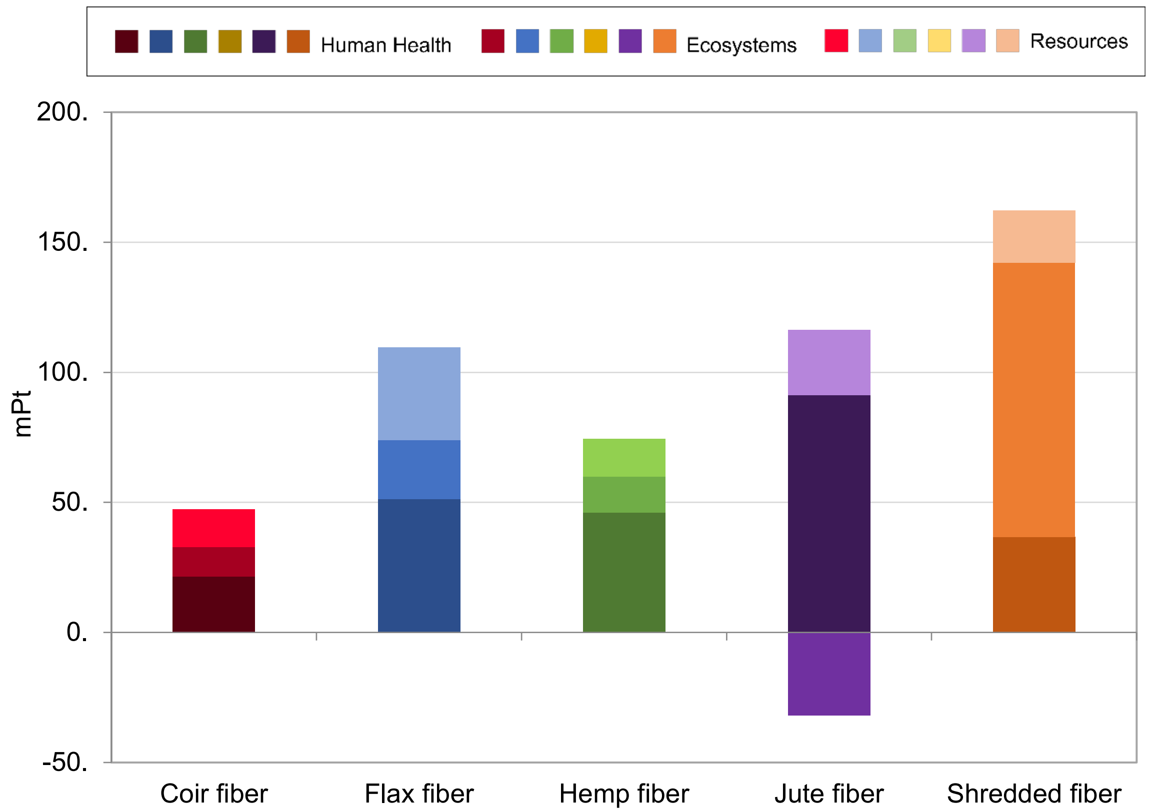



**Figure 1.16** Single score result of each fiber. IPCC.GWP 100a. method. Comparative analysis of the environmental impacts produced by each fiber

As seen in Figure 1.15, there is a distinguishable difference between the $CO_2$ generated by flax fiber and jute fiber the other ones. Figure 1.16 shows a similar pattern in all the fibers except the Shredded cotton, which turns out to be the all-around most impacting fiber. Despite that fact, it is important to state that those impacts results are small compared to those generated by the Supersap Epoxy resin. Moreover the coir fiber is the one with the lowest impacts in both methods while the whole coir composite ends up being the most impacting one.

# 4. Conclusions

This LCA study analyzed and compared the environmental impacts generated by different types of boards with application in the construction market from cradle to grave. The main objective was to determine whether the impacts generated by new natural fiber epoxy based composites are lower or higher than the ones emitted by the gypsum plasterboard.

The LCA is performed using two different highly trusted methods, the IPCC. GWP 100a and the Recipe Endpoint methods. Throughout analysis of the result obtained by the two methods, it is concluded that the use of natural fiber epoxy-based composites with Supersap Resin reduce the environmental impact in every category analyzed. In the case of carbon emissions calculated through the IPCC. GWP 100a the emissions are reduced from 40% in the case of the shredded cotton board up to 60% in the case of the flax board. When the calculations are performed using the Recipe Endpoint method, the difference between the gypsum plasterboard and the composites vary from 31 per cent to 50 per cent, depending on the natural fiber used, with respect to the gypsum plasterboard. The composites obtained lower impact results in resources, ecosystems and human health separately. The only exception is the coir board which has an impact over the environment very similar to the one generated by the gypsum plasterboard.

Besides, a comparison between the different fibers used in the composite is also carried out, coming to the conclusion that the fiber used does not represent a significant difference because of the low environmental impact of them all with respect to the other materials.This paper shows the necessity of further research into new construction materials with low environmental impact that could replace traditional ones with guarantees. Although this case study was performed for the Spanish market, the results could be applicable to any other region, considering that the impacts associated to the transport and electricity emissions don't represent a big percentage in the total.

## 4.1 Further research opportunities

The study of those factors outside the scope of this article need to be assessed in the near future. The recycling capabilities of the Supersap Epoxy resin are yet to be considered and could be a cornerstone of the market opportunities in the building market for this material. Further research may also include a detailed analysis of the disposal scenarios, considering different possibilities such as landfilling with energy recovery and incineration of the composites as a fuel. Additionally, the possibility of incineration with energy recovery could be an eco-friendly solution due to the high organic content of the composite. The reuse of the assembled composites is something to bear in mind as well. The acoustic performance of the material will be evaluated as a part of this project in the short-term.

# 5. Acknowledgements

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# Chapter 2

# Life-Cycle Assessment and Acoustic Simulation of Drywall Building Partitions with Bio-Based Materials*

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## Abstract

The ecological transition is a process the building industry is bound to undertake. This study aimed to develop new bio-based building partition typologies and to determine if they are suitable ecological alternatives to the conventional non-renewable ones used today. This work started with the development of a bio-based epoxy composite board and a waste-based sheep wool acoustic absorbent. Six different partition typologies combining conventional and bio-based materials were analyzed. A drywall partition composed of gypsum plasterboard and mineral wool was used as the baseline. First, a cradle-to-gate life cycle assessment was performed to compare their environmental impacts. Secondly, a mathematical simulation was performed to evaluate their airborne acoustic insulation. The LCA results show a 50% decrease in the amount of CO2 equivalent emitted when replacing plasterboard with bio-composite boards. The bio-composites lower the overall environmental impact by 40%. In the case of the acoustic absorbents, replacing the mineral wool with cellulose or sheep wool decreases the carbon emissions and the overall environmental impact of the partition from 4% and 6%, respectively. However, while the bio-based acoustic absorbents used offer good acoustic results, the bio-composites have a lower airborne acoustic insulation than conventional gypsum plasterboard.

# 1. Introduction

The building industry is responsible for one-third of the total carbon emissions in the world. Building materials, which usually come from non-renewable sources, are responsible for a big part of those emissions (Nußholz et al., 2019). Transitioning towards sustainable constructions requires finding materials with a lower impact over the environment, and using bio-based materials is possibly the best route (Ingrao et al., 2016). However, this transition is an especially complex process for the building industry (Lines et al., 2015). Construction materials need to have a specific set of characteristics to ensure proper habitability for the dwellers. Potential customers need the assurance that the materials used will perform adequately for decades before investing in a new home. This situation makes stakeholders lean towards safer choices, which tend to have higher impacts on the environment. There is only one solution to counteract this tendency, to prove that the new bio-based construction materials are not only better for the environment but can also perform to the required standards. The life cycle assessment (LCA) methodology has a proven record of success in the evaluation of the environmental performance of both building and building materials (Bahramian and Yetilmezsoy, 2020). Over the last decade, the number of studies dealing with the LCA of sustainable building materials has grown substantially (Asdrubali et al., 2015). Through this methodology, it is possible to assess the environmental footprint of any material and to establish a comparison with other materials in a reliable way. Having reliable information about the effect that a particular material has over the environment is crucial to foster the use of new sustainable alternatives.

Besides the environmental performance, building requirements greatly vary depending on the building element. Whereas the building envelope must provide sufficient thermal and acoustic insulation, partition systems only need to be able to perform acoustically. Despite being sometimes forgotten, acoustic insulation is one of the key aspects to consider in terms of habitability. Having properly insulated walls has a major impact on comfort (Al horr et al., 2016). One of the most widely spread partition typologies is drywall. Drywall is typically formed by a frame, two plasterboards on each side of the frame, and an inner acoustic absorber. Plasterboard is manufactured from gypsum rocks, which are non-renewable minerals extracted from quarries. The manufacturing process, as it is discussed in subsequent sections, involves using a high amount of energy. The inner layer, which provides acoustic absorption, can be composed of many different materials, the most common being mineral wool. The primary raw material to produce mineral wool is basalt. Besides the impacts related to the extraction of minerals, basalt is heated to its melting point during the production process of mineral wool, which requires a large amount of energy. The main goal of this article is to explore the possibilities of using bio-based alternatives to plasterboard in the building market.

## 2. Materials and Methods

The environmental impacts and the airborne acoustic insulation of several building partitions combining conventional and new bio-based materials are studied. Conventional drywall containing plasterboard and mineral wool is used as the baseline. A bio-epoxy composite board with flax fiber as its solid filling is proposed as an alternative to plasterboard. The name of this bio-epoxy resin is Supersap, produced by the company Entropy Resins. The company claims to reduce $CO_2$ emissions by 50% compared to regular epoxy resins ("Entropy Resins delivers sustainable composites," 2011). Flax was chosen as the solid filling because of its regional availability and its mechanical properties (La Rosa et al., 2014). A comparison between gypsum plasterboard and Supersap composites has been previously performed (Quintana et al., 2018). However, neither the influence those bio-composites have over the total environmental impacts of the partition nor their acoustic performance have been assessed. Two different bio-based materials are considered to replace mineral wool as the acoustic absorbent. The first one is recycled cellulose, which is gaining popularity as a sustainable acoustic absorbent and thermal insulator (Asdrubali et al., 2012). The acoustic properties of cellulose have been previously studied (Arenas et al., 2014). However, the relation between its acoustic properties and its environmental impacts has not been assessed yet. The second alternative is produced using the wool waste generated during the manufacturing process of sheep wool and adding PET in its formulation to increase its rigidity. This material was developed by researchers at the Polytechnic University of Valencia in conjunction with a sheep wool manufacturing plant. The acoustic absorption of this material has been previously studied, but an assessment of its environmental impacts has not been performed yet (del Rey et al., 2017). When it comes to the frame of drywall partitions, it can be built using many kinds of materials, wood being the most widely spread in many parts of the world. However, in countries such as Spain, drywall frames are usually made of galvanized steel, probably due to resource availability. For that reason, galvanized steel is used as the material for the frame in this work. The using wood as the frame of drywall partitions is outside the scope of this study. The different configurations analyzed in this study are represented in Figure 2.1. The main components of each typology are described in Table 2.1. The proportions of Supersap bio-epoxy resin and flax fiber are specified in Table 2.2. The physical characteristics of the bio-composite board were tested in the university facilities, Table 2.3.

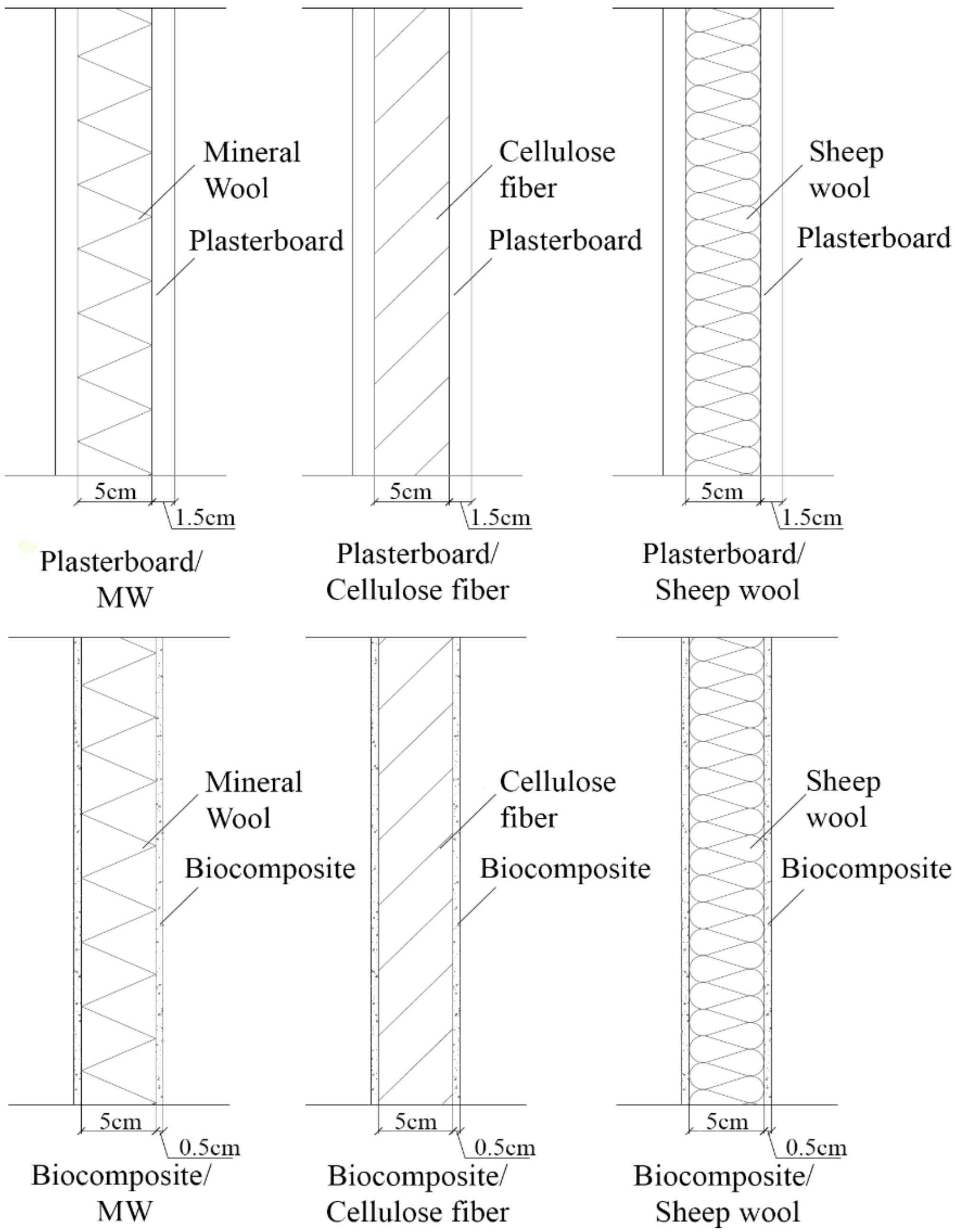


**Figure 2.1.** Partition typologies under study.

**Table 2.1**
Materials in 1m$^2$ of typology

| Typology | Components | Mass (kg) | Total Mass (kg) |
|---|---|---|---|
| | Plasterboard | 12.0 | |
| Plasterboard/MW | Mineral wool | 3.5 | 16.9 |
| | Steel | 1.40 | |
| | Plasterboard | 12.0 | |
| Plasterboard/Cellulose | Cellulose | 2.4 | 15.8 |
| | Steel | 1.40 | |
| | Plasterboard | 12.0 | |
| Plasterboard/Sheep wool | Sheep wool | 1.5 | 14.9 |
| | Steel | 1.4 | |
| | Bio-composite | 5.1 | |
| Bio-composite/MW | Mineral wool | 3.5 | 9.9 |
| | Steel | 1.4 | |
| | Bio-composite | 5.1 | |
| Bio-composite/Cellulose | Cellulose | 2.4 | 8.9 |
| | Steel | 1.4 | |
| | Bio-composite | 5.1 | |
| Bio-composite/Sheep wool | Sheep wool | 1.5 | 7.9 |
| | Steel | 1.4 | |

**Table 2.2**
Composite content proportions and mass per m$^2$

| | Flax Board |
|---|---|
| Mass (kg) | 5.08 |
| Fiber % | 49 |
| Fiber mass (kg) | 2.49 |
| Bio-epoxy % | 51 |
| Bio-epoxy mass (kg) | 2.59 |

**Table 2.3**
Physical and Mechanical Characteristics

| Board | Thickness (mm) | Density (g/cm³) | Mass/m² | Shore C Hardness [1] | Impact Resistance [2] |
|---|---|---|---|---|---|
| Plasterboard | 12.5 | 0.776 | 9.7 | 47.7 | 14.9 |
| Flax board | 4.6 | 1.183 | 5.1 | 76.2 | 76.7 |

[1] Shore Durometer model Instruments J.Bot 673D (ISO 868:2003). Scale Shore D 30°, [2] Charpy impact test. Pendulum by Metrotec (ISO 179:1993). Scale used: 1J.

## 2.1. Acoustic Simulation Methodology

The airborne sound insulation of each solution has been computed using the simulation software Aisla 3 (Fernández et al., n.d.). This software applies the mathematical model proposed by Ookura & Saito (Ookura and Saito, 1978) and Chen & Jan (Jensen and Raspet, 2010), which uses the mechanical data of the materials to determine the coupling impedance ($Z_{ij}$) between layers. The simulation process is summarized in Figure 2.2.

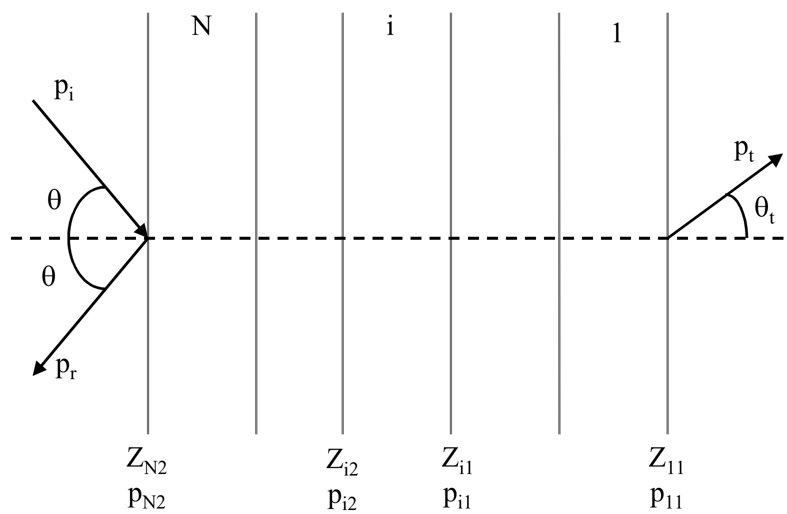


**Figure 2.2.** Ookura & Saito simulation process. $p_t$: transmitted pressure, $p_i$: incident pressure, $p_r$: reflected pressure, $\theta$: angle of incidence of the acoustic wave, Z: complex characteristic impedance. N references the number of elements. The physical parameters are numbered with the subscript i = 1, 2, …, n to indicate the element and a second subscript to indicate the right or the left face of the element.

The critical frequency ($f_c$) is obtained using the expression Equation (1) where $D$ (N·m) is the flexion stiffness of the board, $c$ the speed of sound, η the loss factor of the material, and m the mass per surface unit of the material.

$$f_c = \frac{c^2}{2\pi}\sqrt{\frac{m}{D}} \tag{1}$$

The cellulose fiber absorbent formulas are obtained from (Arenas et al., 2014). The formulas to assess sheep wool behavior can be found in (del Rey et al., 2017). The data used for the calculations, which were obtained by testing the materials in the university facilities, can be seen in Table 2.4. The margin of error due to the material values was assessed (Jesús et al., 2008), concluding that there is a possible deviation of 2 to 3 decibels. This margin of error is accepted by the Spanish technical building code (Gobierno de España, 2007). The transmission coefficient is assessed from the simulation results according to the ISO standard 717-1 (ISO 717-1, 2013).

**Table 2.4**
Data for the acoustic simulation

| | | | |
|---|---|---|---|
| **Air** [1] | | | |
| t, temperature (°C) | | | 20 |
| c, sound velocity (m/s) | | | 343 |
| ρ, density (kg/m$^3$) | | | 1.21 |
| **Boards** [2] | | | |
| | Bio-composite | | Plasterboard |
| m, mass (kg/m$^2$) | 5.51 | | 13.5 |
| $f_c$, frequency (kHz) | 18.2 | | 2.8 |
| η, loss factor | 0.32 | | 0.035 |
| **Acoustic Absorbents** [3] | | | |
| | Mineral wool | Cellulose | Sheep wool |
| σ, flux resistivity (rayls/m) | 30000 | 43000 | 8300 |

[1] Parameters found in (Talbot-Smith, 1993). [2] Measured following the methodology described in (ASTM International, 2017). [3] Tested using an impedance tube following the methodology proposed in (Rey Tormos et al., 2013).

## 2.2. Life Cycle Assessment Methodology

A cradle-to-gate life cycle assessment (LCA) of the different partition configurations has been carried out. The LCA follows the framework of the ISO 14040 (ISO 14040, 2006).

### 2.2.1. Functional Unit

The functional unit considered for the study is 1 $m^2$. This is the most adequate functional unit for evaluating the environmental impacts of interior partitions. Due to the different thicknesses of each configuration and the fact that they are multi-layered elements, using mass or volume reference units would not be suitable for this study.

### 2.2.2. Inventory Analysis

An inventory analysis has been performed according to the ISO 14044 (The International Standards Organisation, 2006). The inventory analysis, which accounts for any activity susceptible to having an impact over the environment, has been carried out using Simapro 9.0.0.35, the last version of one of the most popular software programs used for LCA calculations. All the information used for this study combines data provided by the industry, data collected from the laboratory, and data extracted from databases. The production company of the sheep wool acoustic absorber supplied the necessary data related to their product. The information about the bio-composite assembly was obtained during the testing and manufacturing of the boards in the laboratory. In the case of the production of the Supersap bio-epoxy resin, the information came directly from the manufacturer. The rest of the data comes from the Ecoinvent V3.5 database (Ecoinvent, 2018). Ecoinvent is a not-for-profit organization founded by institutes of the ETH Domain and the Swiss Federal Offices. This database collects highly reliable information due to its peer review process (Pascual-González et al., 2016). The production processes of each material used in this study are summarized as follows:

Production process of gypsum plasterboard: Gypsum plasterboards are composed of a plaster core with one protective cellulose layer on each side. The manufacturing process begins by extracting the gypsum rocks from the quarry. Those rocks, which have a maximum diameter of 5 cm, are taken to a factory. Once the rocks get there, they are ground into a fine powder and put into an oven at 160°C. This process turns the original material into stucco. The stucco is then mixed with water creating slurry. This slurry is poured onto a cellulose layer, and then another cellulose layer is unrolled on top of it. After a compacting process in which the core reaches the desired thickness, it hardens and is prepared to be cut at the intended size. As a final step, the boards are put in an oven to remove any remaining moisture.

Production process of the bio-epoxy composite boards: As mentioned in previous sections, the bio-composite boards are made of a bio-epoxy matrix and a flax fiber solid filling. The obtention of flax fibers begins with the harvest. The harvested fibers are submitted to a retting process intended to dissolve most of the cellular tissues and pectin that surround the fiber. Subsequently, the flax fibers go through scutching, which involves crushing the stems with a pair of fluted rollers and beating them with a rotating blade, therefore making the inner body tissue fall off. The scutched fibers are then hackled to remove the remaining impurities and wood particles, obtaining slivers and hackled tows. The last step is spinning. Although there are several kinds of spinning processes, the one used for these kinds of applications is usually dry spinning. Dry spinning produces coarser fibers than wet spinning but uses fewer chemical products. The bio-epoxy resin used is manufactured by the company Entropy Resins. The feature that makes this epoxy resin different from others is the biological content in its formulation. The epoxy class analyzed in this study is phenolic glycidyl ether. This kind of epoxy resin is obtained by the reaction of epichlorohydrin (ECH), a key component of the vast majority of commercial epoxy resins, and a phenol group, in this case bisphenol-A (BPA) which is the most widely used today (Dusek, 1985). However, the manufacturing process of Supersap has some key differences compared to the conventional epoxy resins. The specifics about those differences are subject to a confidentiality agreement. The last step of the bio-composite manufacturing is the assembly of the matrix and the filler. In this case, the method used was resin infusion. The quantity of flax fiber required is placed inside a mold. Then, the resin is introduced through tubes by vacuum suction. This method is one of the most modern methods of composite manufacturing (Hammami and Gebart, 2000). The process described was conducted in the laboratory of the Polytechnic University of Valencia.

Production process of mineral wool: The production process of mineral wool starts with the extraction of basalt from the quarry and its transportation to a manufacturing plant. Once the raw material is in the plant, it is loaded into a cupola in alternating layers with coke. The commonly used proportions are five parts of mineral and one part of coke. Then, the coke is burnt, which heats the basalt to a temperature from 1300°C to 1650°C. Once the basalt melts, it exits the cupola and is taken through pipes to a fiberization machine. This machine has a rotor system that revolves at high speed to take advantage of the centrifugal force to distribute the material over its round surface. At the end of this process, the material is discharged from the machine and poured onto a conveyor belt that takes it to a blowchamber. In this chamber, air is blown to the material to create a wool blanket. The wool blanket is then compressed to reach the appropriate density while air is passed through the blanket until the binder is baked. The manufacturing ends after cooling and cutting the material to the desired size (United States Environmental Protection Agency, 2005).

Production process of sheep wool: As explained in previous sections, the development of the sheep wool absorbent has been made in conjunction with sheep wool industry partners as a part of this research project. The sheep wool insulating panels are primarily made from the waste generated in the wool industry. The production process begins by washing, cutting, and drying the wool fibers. After that, the material undergoes a carding process. Then, the wool is mixed with PET fibers in a thermobonding process. The inventory of the material can be seen in Table 2.5.

**Table 2.5**
Inventory of 1 kg of the sheep wool acoustic absorbent

| | Quantity | Unit |
|---|---|---|
| Sheep wool waste | 0.85 | kg |
| Polyethylene terephthalate (PET) | 0.15 | kg |
| Electricity medium voltage (ES) | 1.588 | MJ |

Production process of cellulose fiber: The insulating cellulose fiber panels are commonly made out of wastepaper. The process begins with taking the collected paper waste to the factory. Once there, the waste is loaded onto a conveyor belt which takes it to a primary mixer. The primary mixer prepares the waste for shredding by removing any metals and other non-desired elements in the mix and washing it using anhydrous borax. Once that process is completed, the waste is loaded into the shredder where it is reduced to small particles and mixed with boric acid. Once the particles reach the desired size, they are taken to a fiberizer where the particle size is reduced up to 4 mm and mixed with more boric acid (*High-performance and specialty fibers: Concepts, technology and modern applications of man-made fibers for the future*, 2016). The inventory of the material can be seen in Table 2.6.

**Table 2.6**
Inventory of 1 kg of cellulose fiber acoustic absorbent

| | Quantity | Unit |
|---|---|---|
| Wastepaper | 1 | kg |
| Boric acid, anhydrous, powder | 0.111 | kg |
| Borax, anhydrous, powder | 0.136 | kg |
| Electricity medium voltage | 0.52 | MJ |
| Heat, district, or industrial, natural gas | 2.22 | MJ |

### 2.2.3. Allocation Principle

As recommended by the ISO standard 14040, allocation has been avoided when it has been possible. However, in some cases, due to the multifunctional nature of some processes and materials, allocation is required. The consequential approach was chosen to overcome the difficulties associated with multifunction processes. This approach uses substitution to resolve multifunctionality in datasets instead of allocation (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010).

### 2.2.4. Evaluation Methods

The evaluation methods chosen for this comparative LCA are the IPCC.GWP 100a and the ReCiPe method. Developed by the intergovernmental panel on climate change ("IPCC - Intergovernmental Panel on Climate Change," n.d.), the IPCC.GWP method is used to calculate the greenhouse emissions of each typology separately. In the case of the ReCiPe method, created by the Dutch public administration (National Institute for Public Health and the Environment. Ministry of Health, 2011), it is used to calculate the environmental impacts divided into several categories. The ReCiPe method uses two different approaches: the midpoint and the endpoint approach. While the midpoint approach keeps each category separate, the endpoint normalizes and weighs them to add them up and offer a single figure representing the environmental impact. Both the midpoint and the endpoint approach were used in this study.

# 3. Results

## 3.1. Airborne Noise Insulation Results

The airborne noise insulation results are depicted in Figure 2.3. As can be seen, the partitions using the bio-composite boards have lower insulation values in most frequencies than the ones using plasterboard. Therefore, as it is reflected in Table 2.7, the sound reduction index reached by the partitions using plasterboard is higher than the one obtained by the partitions with bio-composite boards. As it is discussed in subsequent sections, the main reason behind the lower acoustic insulation is likely to be the lower mass of the bio-epoxy composite compared to plasterboard.

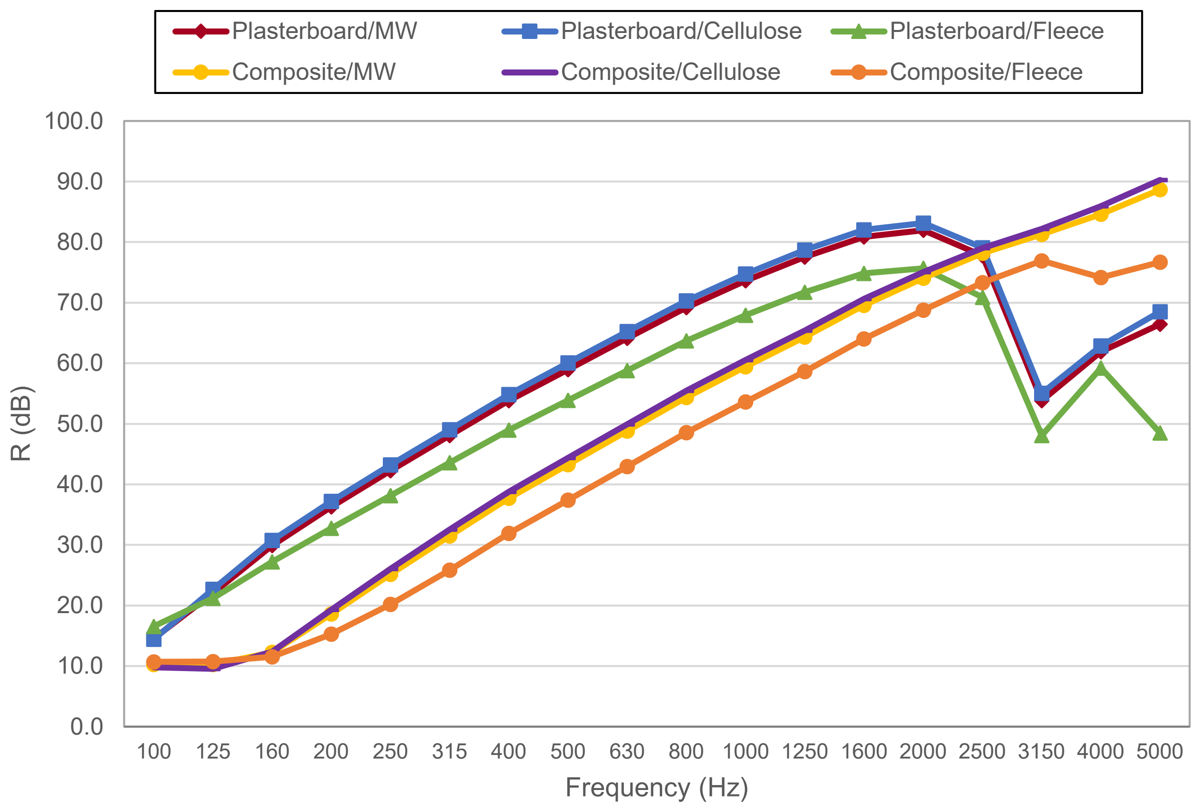


**Figure 2.3.** Airborne noise insulation simulation results of each typology under study.

**Table 2.7**
Sound reduction index of each typology

| | R (dB) |
|---|---|
| Plasterboard/MW | 42.7 |
| Plasterboard/Cellulose | 42.9 |
| Plasterboard/Sheep wool | 42.8 |
| Composite/MW | 32.0 |
| Composite/Cellulose | 31.9 |
| Composite/Sheep wool | 30.6 |

## 3.2. Life Cycle Assessment Results

In this section, the environmental impacts obtained by performing an LCA are assessed using the IPCC GWP 100a method and the ReCiPe method.

### 3.2.1. IPCC GWP 100a Method Comparative Results: Carbon Dioxide Emissions

The IPCC GWP 100 results, depicted in Figure 2.4, show a clear gap between the partitions with plasterboard and the ones with bio-composite boards. The $CO_2$ emissions over the production of the partitions using bio-composite boards are 50% lower than the ones of the typologies with plasterboard. In the case of the acoustic absorbents, the influence they have over the total carbon emissions is not as substantial. When compared to mineral wool, cellulose fiber reduces carbon emissions by around 3.5% and the sheep wool absorbent by slightly more than 4%. The carbon emissions of each material used are represented in Table 2.8 to illustrate their contribution to the total carbon emissions of every respective partition typology. As can be seen, plasterboard is the material with the higher $CO_2$ emissions. Its contribution to the total carbon emissions of each partition ranges from 82.2% to 87.3%. When it comes to the acoustic absorbents, mineral wool accounts for almost 7% of the total carbon emissions. This percentage is lower in the case of cellulose fiber, 2.17%, and even lower using sheep wool, 1.12%. The percentual impact the bio-composites have is smaller than the one obtained with plasterboard, ranging from 63.3% to 72%. In this case, the percentual impact the acoustic absorbent has is higher. It accounts for 14.3% using mineral wool, 4.73% with cellulose fiber, and 2.48% with sheep wool. The galvanized steel used for the frame is responsible for around 10% of the total carbon emissions, in the case of the partitions using plasterboard, and up to 25% in the partitions with bio-composite boards.

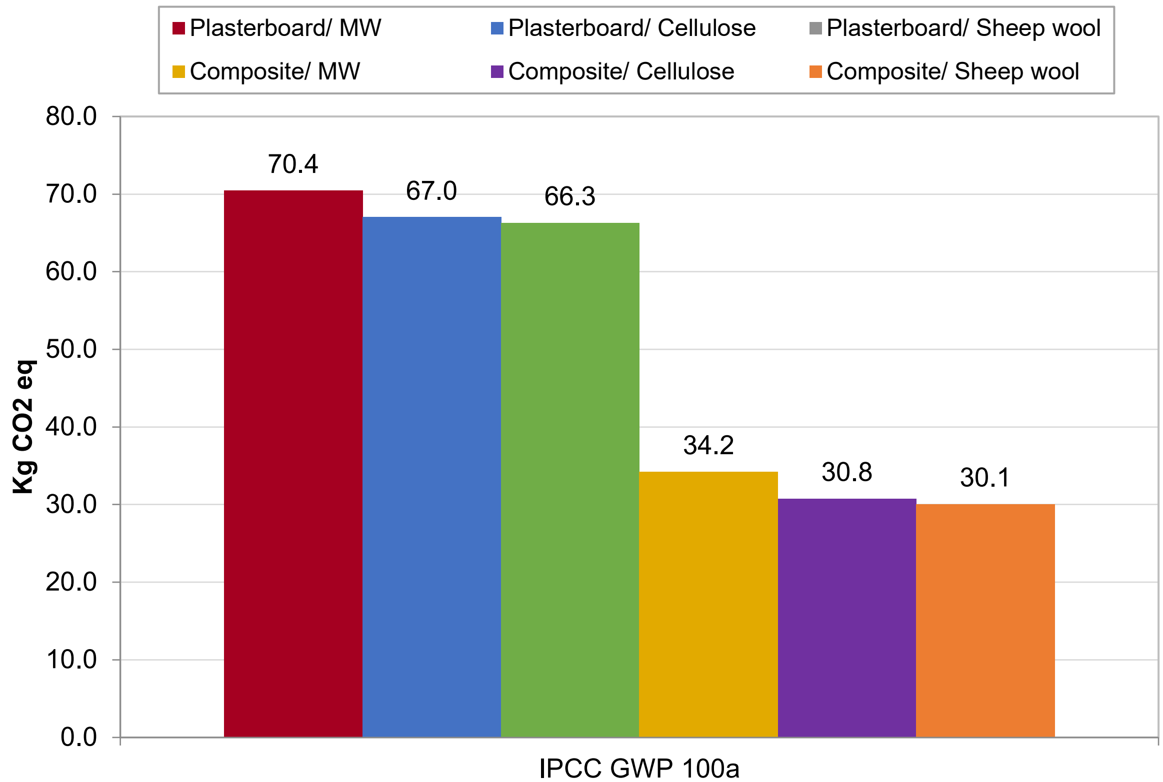


**Figure 2.4.** Carbon dioxide equivalent emitted by each typology. IPCC GWP 100a.

**Table 2.8**
Carbon dioxide emitted by each material in the partitions

| | **Amount** | **Kg of $CO_2$ Eq.** |
|---|---|---|
| Plasterboard 1.5 cm | 2 $m^2$ | 57.87 |
| Bio-composite 0.5 cm | 2 $m^2$ | 21.65 |
| Galvanized steel frame | 1.4 kg | 7.64 |
| Mineral wool | 3.5 kg | 4.89 |
| Cellulose fiber | 2.4 kg | 1.45 |
| Sheep wool | 1.5 kg | 0.74 |

### 3.2.2. ReCiPe Method Comparative Results

ReCiPe midpoint: The ReCiPe midpoint method classifies the environmental impacts in eighteen different categories. As can be seen in Table 2.9, the impact results of the three partitions with plasterboard are higher in almost every category. Only the results in marine ecotoxicity and water depletion are higher in the partitions containing the bio-composites. However, looking at the raw figures can be misleading due to the lack of comparative perspective that they offer. That is the reason why the ReCiPe midpoint offers the possibility to normalize them. The results are displayed in Figure 2.5. Despite the normalization process, it is still complex to identify which solutions have an overall less impacting production process. While the freshwater and marine ecotoxicity results have smaller impacts on the solutions using gypsum plasterboard, other categories such as climate change, natural land transformation, and fossil depletion show higher impact results. The next step is to use the ReCiPe endpoint method to group the categories.

**Table 2.9**

ReCiPe midpoint characterization

| **Impact Category** | **Unit** | **Plast./MW** | **Plast./Cell.** | **Plast./Sheep Wool** | **Comp./MW** | **Comp./Cell.** | **Comp./Sheep Wool** |
|---|---|---|---|---|---|---|---|
| Climate change | kg $CO_2$ eq. | 69.7412 | 66.3669 | 65.6729 | 33.4817 | 30.1074 | 29.4135 |
| Ozone depletion | kg CFC-11 eq. | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Terrestrial acidification | kg SO2 eq. | 0.2236 | 0.2013 | 0.1947 | 0.2026 | 0.1804 | 0.1737 |
| Freshwater eutrophication | kg P eq. | 0.0095 | 0.0084 | 0.0081 | 0.0098 | 0.0087 | 0.0083 |
| Marine eutrophication | kg N eq. | 0.0115 | 0.0110 | 0.0105 | 0.0082 | 0.0077 | 0.0073 |
| Human toxicity | kg 1,4-DB eq. | 18.6697 | 17.6842 | 17.0793 | 19.2523 | 18.2669 | 17.6619 |
| Photochemical oxidant formation | kg NMVOC | 0.1841 | 0.1662 | 0.1619 | 0.1916 | 0.1736 | 0.1694 |
| Particulate matter formation | kg PM10 eq. | 0.0867 | 0.0799 | 0.0752 | 0.1060 | 0.0991 | 0.0945 |
| Terrestrial ecotoxicity | kg 1,4-DB eq. | 0.0064 | 0.0065 | 0.0061 | 0.0049 | 0.0050 | 0.0046 |
| Freshwater ecotoxicity | kg 1,4-DB eq. | 0.3562 | 0.3491 | 0.3313 | 0.4474 | 0.4402 | 0.4225 |
| Marine ecotoxicity | kg 1,4-DB eq. | 0.3972 | 0.3906 | 0.3735 | 0.4649 | 0.4583 | 0.4412 |
| Ionizing radiation | kBq U235 eq. | 4.1787 | 4.2771 | 4.1624 | 0.5287 | 0.6270 | 0.5123 |
| Agricultural land occupation | $m^2a$ | 0.9723 | 1.8088 | 0.7931 | 1.6142 | 2.4506 | 1.4349 |
| Urban land occupation | $m^2a$ | 0.3818 | 0.3616 | 0.3162 | 0.2466 | 0.2263 | 0.1809 |
| Natural land transformation | $m^2$ | 0.0053 | 0.0038 | 0.0034 | 0.0033 | 0.0018 | 0.0014 |
| Water depletion | $m^3$ | 0.4771 | 0.4696 | 0.4622 | 0.5845 | 0.5770 | 0.5696 |
| Metal depletion | kg Fe eq | 6.5388 | 6.3924 | 6.2534 | 6.4010 | 6.2546 | 6.1156 |
| Fossil depletion | kg oil eq | 21.2216 | 20.1604 | 20.1179 | 11.6111 | 10.5500 | 10.5074 |

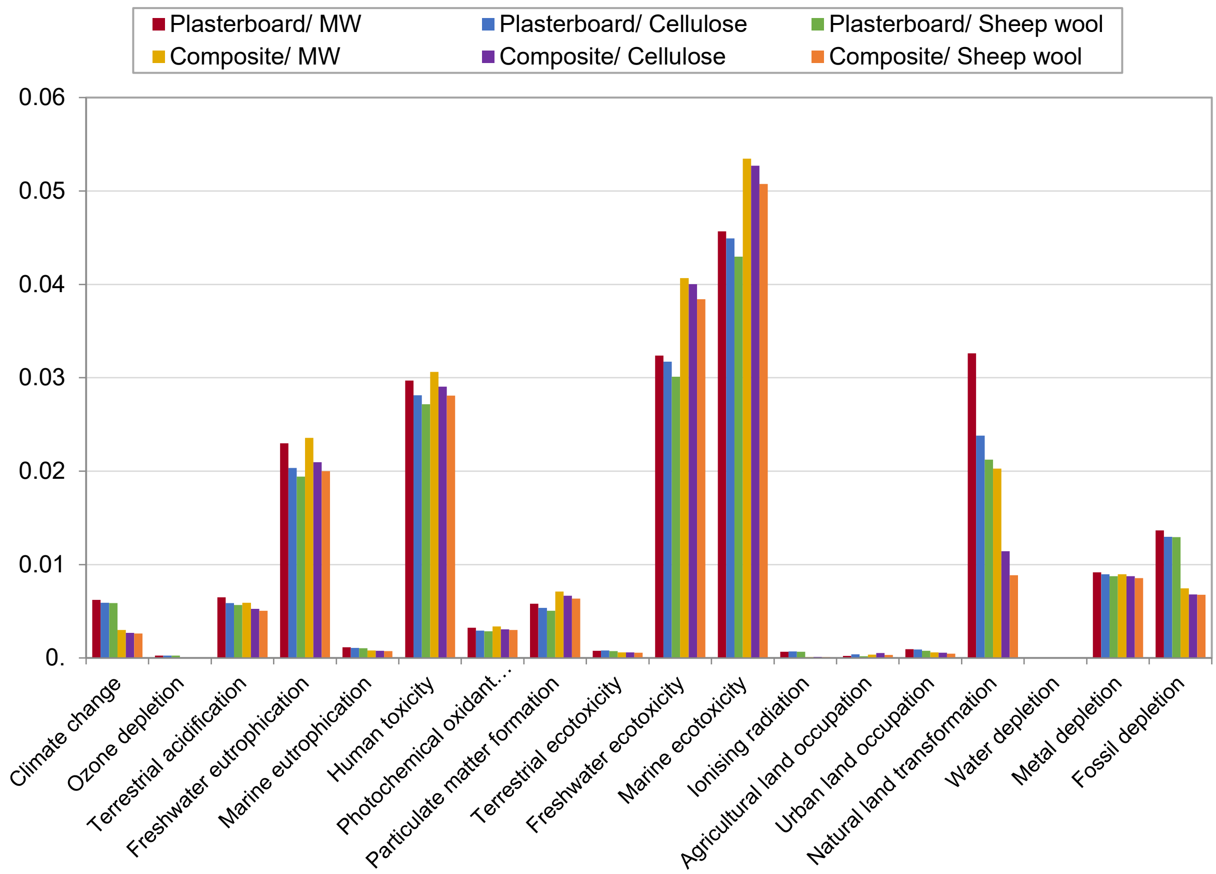


**Figure 2.5.** ReCiPe midpoint normalization results.

ReCiPe endpoint: The ReCiPe endpoint methodology is used to simplify the results displayed in the ReCiPe midpoint. After a normalization process, the ReCiPe endpoint groups the results in three different categories, human health, ecosystems, and resources, Figure 2.6. These categories are the result of normalizing and adding up the categories of the Recipe midpoint method. The results in the three categories show a clear difference between the solutions using plasterboard and the ones using the bio-composite boards. The use of the bio-epoxy composite lowers the environmental impact in all of them, especially in Resources. As for the influence of the inner filling, there is a relatively small reduction in the impacts when mineral wool is replaced by either cellulose fiber or sheep wool. As the final step, the results are weighted and grouped in a single score result, Figure 2.7. Following the same trend identified in previous results, the substitution of the plasterboard for the bio-epoxy composite reduces the overall environmental impact. The results oscillate from a 30% reduction in case of the one filled with sheep wool to a 40% reduction in the case of the one filled with mineral wool.

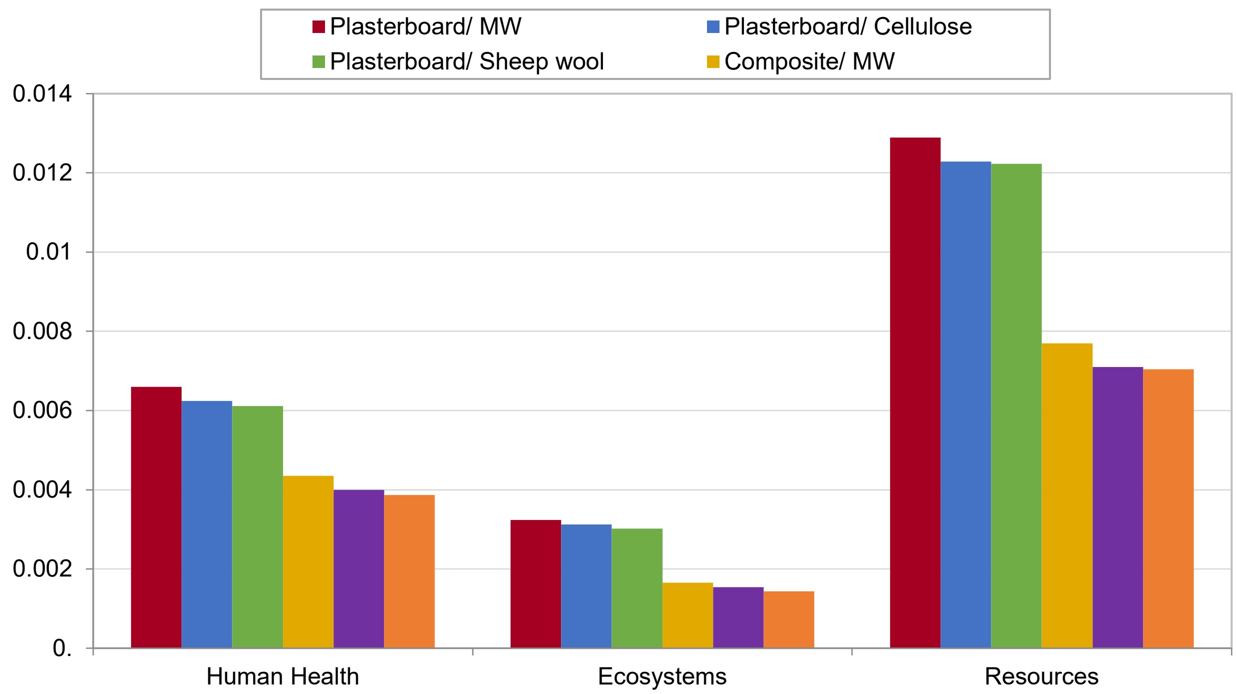


**Figure 2.6.** ReCiPe endpoint normalization results.

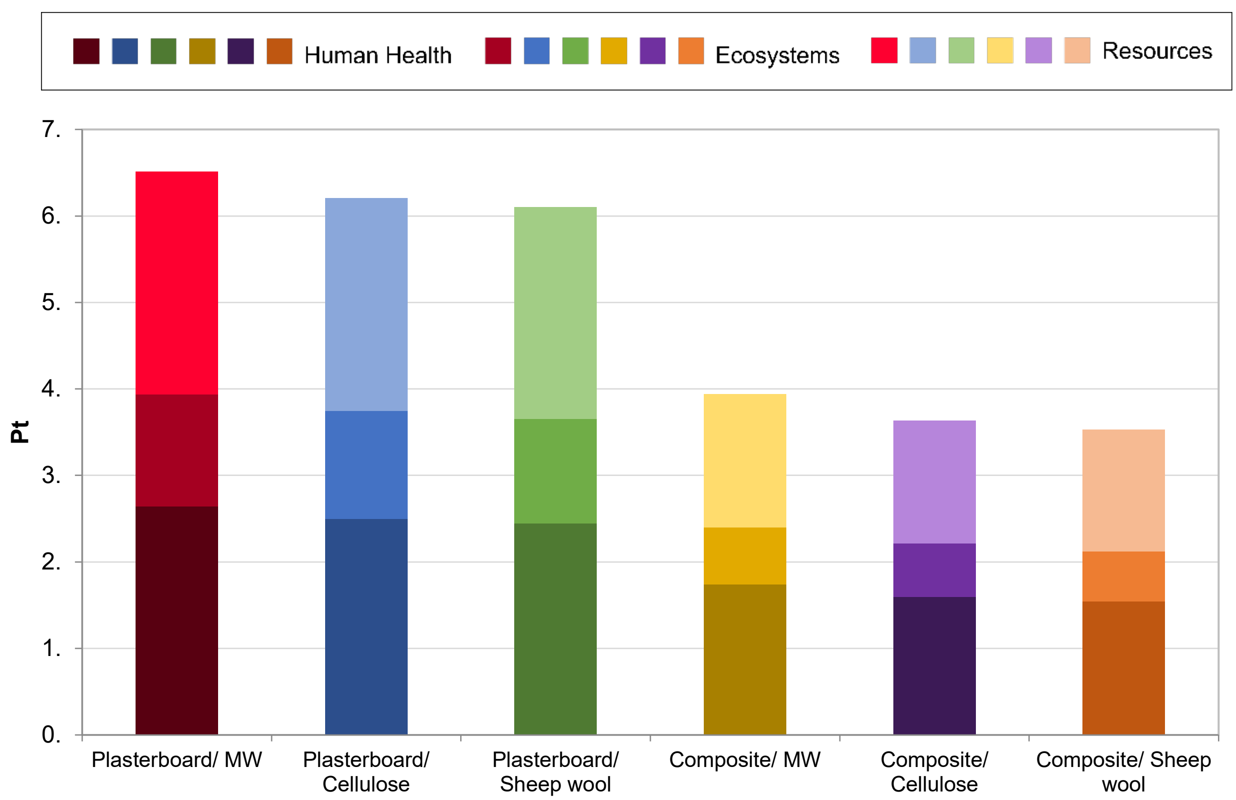


**Figure 2.7.** ReCiPe endpoint single-score results.

## 4. Discussion

The results obtained in this study highlight the potential reduction in the environmental impacts that can be attained by using bio-based materials in building partitions. The life cycle assessment results indicate that plasterboard is the main contributor to the environmental impacts in drywall partitions. The results also show a significant reduction in the environmental impacts generated when plasterboard is replaced with the bio-composite boards. In the case of the carbon emissions, those assessed using the IPCC GWP method show that plasterboard is responsible for more than 80% of the carbon emissions of the partition. This indicates the need to find ecological alternatives to that building material. Results also show that using the proposed bio-epoxy boards reduces carbon emissions by more than 50%. Besides carbon emissions, the categories analyzed using the ReCiPe endpoint method show that the use of the bio-composite boards decreases human health-related impacts by 35%, impacts related to ecosystems by around 50%, and the ones related to resource depletion by approximately 40%. Therefore, it can be stated that the LCA results reflect the environmental benefits of using the bio-composite boards instead of conventional plasterboard. When it comes to the absorbent materials, the results indicate that the influence they have over the total environmental impact of the partition is smaller compared to the boards. Replacing mineral wool by cellulose fiber reduces the carbon dioxide equivalent by 4.7%, and 6.35% in the case of sheep wool. As it was the case with the results obtained in the IPCC GWP 100a method, the ReCiPe endpoint method shows that replacing mineral wool with cellulose reduces the impacts by 4.7% and 6.35% with the sheep wool absorbent. Although those percentages are small when comparing the impacts of the partitions as a whole, the results show that the carbon emissions of the sheep wool absorbent are around 85% lower than the ones generated by mineral wool, and 70% lower in the case of cellulose fiber. Due to the enormous volume of materials that it is used in the building industry, that reduction in the carbon emissions over hundreds of buildings would have a significant effect in combating climate change. One aspect worth mentioning is the impact on the environment of the steel frame of the partitions. The steel frame, the only element that has not been replaced with a bio-based alternative in this study, is responsible for 7.6 kg of $CO_2$ equivalent per square meter, which accounts for 10% to 25% of the total carbon emissions of the partition depending on the board used. Drywall frames in countries such as Spain are commonly made of galvanized steel, despite wood being probably the most common material worldwide in this kind of application. The use of steel is possibly due to material availability and the several blast furnaces in Spain during the twentieth century. Depending on the tree species, it would probably be possible to significantly reduce the environmental impacts of the partitions by using wood to build the frame.

In contrast with the good LCA results, the acoustic simulation showed that the use of the bio-composites significantly decreases the airborne acoustic insulation. The sound reduction index drops from more than 42 decibels to around 31. This is probably due to the small thickness and lightweight of the boards since weight is one of the key elements of airborne sound isolation. Since the boards were designed with a sustainability goal in mind, their thickness was reduced to the maximum to decrease the amount of material while maintaining adequate mechanical properties. Decreasing the material amount used not only lowers the environmental impacts during production but also lowers the amount of waste generated at the end of life of the building. Despite the noticeable difference between the results, the airborne insulation is over 30 dBA in every bio-epoxy typology. This value has been accepted in most international legislations for many years if the wall divides rooms of the same housing unit. However, building acoustics legislations are getting more and more restrictive nowadays. It would be necessary to increase the thickness of the boards to provide enough airborne noise insulation, especially in countries with restrictive noise regulations. On the other hand, the influence that changing the acoustic absorbent has on the acoustic insulation of the studied partitions is almost negligible. This could be considered a good result because the inner acoustic absorbent could be replaced with one of the two alternatives presented, reducing the environmental impact, and not compromising the acoustic insulation.

# 5. Conclusions

The idea behind this project was to develop sustainable alternatives to conventional drywall partitions with mineral wool. As an alternative to plasterboard, a bio-composite board using Supersap resin and flax fiber was developed and manufactured in the university facilities. As for the inner layer, two materials were analyzed as alternatives to mineral wool. The first one is manufactured using recycled cellulose fiber, and the second one is produced with waste generated in the sheep wool industry. Six different partition configurations were studied combining the conventional and the bio-based materials mentioned. The environmental impacts of the partitions are compared by performing a life cycle assessment. A mathematical simulation was used to evaluate their airborne acoustic insulation. The main objective of the study was to determine the influence each element has over the environmental impacts and the acoustic insulation of the whole system. Therefore, it can be determined how much it is possible to lower the environmental impact while maintaining adequate acoustic insulation.

After finishing this study, several conclusions can be drawn. First, it can be stated that the bio-composite panels reduce the $CO_2$ emissions of the whole partition by 50%. According to the results obtained using the ReCiPe endpoint method, the panels reduce the overall environmental impacts around 35%. Therefore, it can be said that the bio-composite panels analyzed significantly reduce the environmental impact when compared to plasterboard. In the case of the acoustic absorbers studied, using cellulose fiber reduces the total carbon emissions of the typology by 4.7% and 6.35% using sheep wool. The same results are obtained using the ReCiPe endpoint method, a reduction of 4.7% with cellulose fiber, and 6.35% with sheep wool. Although this difference is small, it would translate into a big reduction in the emissions considering the significant amount of materials required. The panels, however, have proved to lower the acoustic insulation while the acoustic absorbers offer a very similar result. The typology using the bio-composite panels and the sheep wool is the one that reduces the environmental impacts the most but also has the worst acoustic performance. Therefore, it can be concluded that using the bio-composite panels either with cellulose or sheep wool absorbent can be a sustainable option in cases where there is not a need for high airborne insulation. Consequently, it is necessary to improve the acoustic insulation of the partitions that use the bio-composite boards to comply with most acoustic legislations worldwide. Augmenting the amount of bio-epoxy resin to increase the weight would compromise the sustainability of the partition wall. Finding the optimum balance between both sustainability and acoustic insulation could be an interesting middle ground. It would be worth exploring other possibilities, such as using layers of different bio-based materials combined with the composite boards.

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# Chapter 3

## Waste valorization of rice straw as a building material in Valencia and its implications for local and global ecosystems

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## Abstract

The environmental implications of rice straw cultivation in the Spanish city of Valencia have generated controversy in recent decades. The paddy fields surround a natural park called Albufera, and the need to protect the local environment requires the cultivation to be as sustainable as possible. Every year over 75000 tons of rice straw generated after the harvest are burned or mixed with the soil. Both practices emit greenhouse gases and have huge effects on the surrounding areas' population and environment. One way to avoid those emissions is to use rice straw as a raw material for building products. A building façade panel using rice straw as its main component is presented as an alternative to the conventional double-layered brick façades widely used in this area. This article describes the life cycle assessment (LCA) and the acoustic and thermal insulation of the rice straw façade compared to those of a conventional brick façade. Additionally, the surface and interstitial condensation have also been studied through a simulation. The LCA, conducted using the Environmental Footprint methodology, indicates that the rice straw façade has a lower impact on the environment in every studied category. The rice straw façade emits 78% less $CO_2$e than the benchmark typology. If the emissions of either burning the straw or mixing the straw with the soil are subtracted, each square meter of rice straw façade prevents the emission of 18.85 kg of $CO_2$e and 52.64 kg of $CO_2$e, respectively. The measured acoustic insulation is similar in both studied façades. The sound reduction index of the brick façade is 49dB and the obtained with the rice straw façade is 47±1.93 dB. Both results comply with the local building regulations. The thermal insulation of the rice straw façade (as measured by thermal transmittance) is 0.29±0.08 $W/m^{2o}C$, which doubles that of the benchmark typology (0.629 $W/m^{2o}C$). The hygrothermal behavior also complies with the local building regulations. The straw façade shows no signs of Surface condensation since the interior surface temperature factor of the façade is 0.927, higher than the required by the conditions of the most restrictive month (0.430). Also, there is no risk of interstitial condensations in any month. These results indicate that the rice straw panels can be both a suitable sustainable alternative for the building industry in Spain and a viable solution to the environmental problems caused by rice straw mismanagement.

| **Nomenclature** | | | |
|---|---|---|---|
| *Norms, regulations and institutions* | | Hygrothermal simulation | |
| CTE | Spanish Technical Building Code | $\theta_e$ | Exterior temperature (ºC) |
| CTE DA-HE/2 | Chapter on interior and surface condensation assessment | $\theta_{si,min}$ | Minimum acceptable surface interior temperature (ºC) |
| CAP | Common Agricultural Policy of the European Union | $f_{Rsi,min}$ | Minimum interior surface temperature factor |
| NBE-AT-79 | Basic Building Regulation | $f_{Rsi}$ | Interior surface temperature factor |
| CEC-CTE | Spanish Catalog of Building Elements | $\varphi_e$ | Exterior relative humidity (%) |
| IPCC | Intergovernmental Panel on Climate Change | $\varphi_i$ | Interior relative humidity (%) |
| LCA | Life Cycle Assessment | $\theta_n$ | Temperature in layer n (ºC) |
| LCI | Life Cycle Inventory | $\theta_{n-1}$ | Temperature in layer n-1 (ºC) |
| GHG | Green House Gasses | $R_n$ | Thermal resistance in layer n (m2·K/W) |
| EF | Environmental Footprint methodology | $R_T$ | Total thermal resistance (m2·K/W) |
| *Airborne acoustic measurement* | | $\theta_i$ | Interior temperature (ºC) |
| $R_{,w}$ | Sound reduction index (dB) | $P_{sat}$ | Saturation pressure (Pa) |
| L1 | Emitted sound pressure level in room 1 (dB) | $P_n$ | Saturation pressure in layer n (Pa) |
| L2 | Sound pressure level in room 2 (dB) | $P_{n-1}$ | Saturation pressure in layer n-1 (Pa) |
| B | Background noise (dB) | $S_{dn}$ | Equivalent thickness in layer n (m) |
| *Thermal transmittance measurement* | | $\sum S_{dn}$ | Total equivalent thickness (m) |
| U | Thermal transmittance | $P_i$ | Presión de vapor del aire interior (Pa) |
| N | Number of samples | $P_e$ | Presión de vapor del aire exterior (Pa) |
| u(U,rep) | Uncertainty due to the measurement repeatability. Standard deviation. | $g_c$ | Condensation flux density (g/m2·month) |
| u(U,devices) | Uncertainty connected to the measurement instruments | $M_a$ | Accumulated moisture per surface unit (g/m2) |
| $u_c(U)$ | Combined standard uncertainty of the thermal transmittance | $S_d$ | Diffusion equivalent air layer thickness |
| | | $\lambda$ | Thermal conductivity (W/(m·K)) |
| | | $\mu$ | Water vapor diffusion resistance factor |

# 1. Introduction

Rice cultivation in the Spanish region of Valencia is a substantial contributor to economic activity and one of the most recognizable elements of local culture. However, some processes involved in rice cultivation have generated tension between farmers, local policymakers, and European regulators. The rice fields in Valencia are connected to a coastal lagoon called Albufera (Figure 3.1). This lagoon and its surroundings form a natural park that hosts enormous biodiversity and is protected by national legislation. Since the rice fields and the Albufera are connected, cultivation practices can have a severe adverse effect on the park if not carefully planned. In the past, some fertilizers and chemical products used in rice cultivation have damaged the park's ecosystem. It was not until recent decades that this issue has been resolved (Marí and Peydró, 2010), (García and Giménez, 2004).

The current conflict originates from the management of rice straw that remains in the fields after the harvest. Every year, between 75000 and 90000 tons of rice straw are generated over only a few weeks (Ribó et al., 2017). To avoid the high costs of managing such a large quantity of straw, farmers have traditionally burned it in the fields. This practice generates $CO_2$ emissions and represents a toxicological risk for the surrounding population due to the emission of $NO_x$, $SO_x$, hydrocarbons, dioxins, and other particles. For this reason, burning the straw has been banned by the common agricultural policy (CAP) of the European Union (Ribó et al., 2017). As a result, the most viable remaining waste management technique for farmers was to mix the straw with the soil and use it as a fertilizer. Although this practice might appear harmless, there is evidence that mixing the straw with soil may be as damaging as burning it. The anaerobic oxidation of the straw inside the paddy field generates a huge amount of $CH_4$, which has a global warming potential 28 times higher than $CO_2$ (Sanchis Jiménez et al., 2014). Moreover, the resulting excess of nutrients in the water generates eutrophication, significantly damaging the local flora and fauna (Oliver, 2017).

In light of the aforementioned factors, the most viable option for reducing the environmental impact of rice straw is to enhance its value by creating products that use it as a raw material. Many studies published in recent years analyze different ways of utilizing rice straw (Singh and Arya, 2020)(Singh et al., 2020).The valorization of rice straw would allow the rice industry in Valencia to take part in a circular economy model that would have massive implications for the local society. It would also serve to mitigate the environmental impact caused by the most common rice management practices. Due to the enormous amount of straw generated each year, several products that use rice straw are needed in order to generate steady demand.

A façade panel in which the straw is compressed and housed inside a wooden frame was designed by a local company called Okambuva (Okambuva, 2020). These kinds of constructions are designed to constitute the core element of a wall. Unlike strawbale constructions, these panels could even be used in mid-rise buildings by adapting the wooden frame to the structural requirements. Other European companies use similar panels with straw generated from other crops such as wheat (“EcoCocon | EcoCocon,” 2020). This study analyzes the environmental impact these types of panels could have on the local and global ecosystems and the local building industry.

Strawbale constructions have proven to be a viable sustainable alternative to conventional materials (Koh and Kraniotis, 2020), (Platt et al., 2020). An extensive literature review covering some of the main performance indicators of strawbale constructions was done in chapter 9 of the book Nonconventional and Vernacular Construction Materials: Characterization, Properties and Applications (Walker et al., 2019). This book chapter covered many aspects such as fire resistance, durability, and mechanical properties. Constructions using bio-based materials such as straw are currently gaining popularity (Liuzzi and Stefanizzi, 2016)(Jones and Brischke, 2017). Some institutions are even actively fostering the ecological transition through new regulations and policy initiatives. This is the case of the new European Green Deal, released by the European Commission in 2019, which has the overarching aim of making the European Union climate neutral by 2050 ("The European Green Deal," 2019). For example, concrete is responsible for 8% of the total carbon emissions in the world (Andrew, 2017). Using bio-based construction materials such as straw bale plays a key role in achieving carbon neutrality, thanks not only to the low environmental impact of the materials themselves, but also to their low thermal transmittance (Cornaro et al., 2020). Over the last decade, many researchers have focused on finding ways of utilizing agricultural waste for building applications (Madurwar et al., 2013)(Liuzzi et al., 2017).

Several recent studies deal with the development of novel applications of rice straw waste that could help in mitigating the impact generated by its management practices (Shang et al., 2020)(Doliente and Samsatli, 2021). However, there is a lack of studies on the use of rice straw as a building material in the Spanish context. Accounting for the possible environmental benefits of using rice straw waste to build prefabricated panels might foster their incorporation into the Spanish building market. To our knowledge, the acoustic insulation of rice straw prefabricated panels has not been measured in an acoustic chamber yet. Also, analyzing how these kinds of materials interlink with the local regulations is a must to push for an ecological transition in the building sector.

The first building regulation in Spain, NBE-AT-79 (Basic Building regulation), was passed in 1979. This regulation defined for the first time the amount of thermal insulation required in buildings. However, it was not a comprehensive code that regulated every significant aspect of buildings in Spain. After almost 30 years, in 2007, the Spanish Ministry of Development passed the Spanish technical building code (CTE) (Ministerio de Fomento. Gobierno de España, 2007). The Energy Efficiency Document of the CTE divides the country into different zones to account for the significant climatic variation in the country. According to the Köppen climate classification, while the southern and eastern areas have a Mediterranean climate, mild winters, and hot summers, the northern and western parts have temperate oceanic climates. Other factors such as altitude also play a significant role in the climate conditions of the Spanish territory. Valencia is on the western side of the Mediterranean basin. Its meteorological conditions can be described as mild and humid., Valencia has a hot-summer Mediterranean climate (Csa) (Beck et al., 2018). The temperatures are stable, ranging from 6 to 16 degrees Celsius in winter and 22 to 30 degrees

Celsius in summer. The reason for this stability is its east orientation, opposite to the Atlantic current. The average monthly temperatures are depicted in Figure 3.2. According to the CTE, Valencia is characterized as a B3 zone. The letter refers to the severity of winters, on a scale from A to E, and the number to the severity of summers, on a scale from 1 to 4. Until 2020, buildings in Valencia needed to have a building envelop with a maximum thermal transmittance of 0.82 $W/m^2K$. There has been a recent modification of the law, which currently enforces a thermal transmittance of 0.38 $W/m^2K$ (Ministerio de Fomento. Gobierno de España, 2020). However, most buildings in Valencia were built before 2007, which means that there is a need for either retrofitting thousands of buildings around the country or constructing new ones to meet the current standards.


**Figure 3.1.** Plan of the Albufera natural park and the surrounding areas

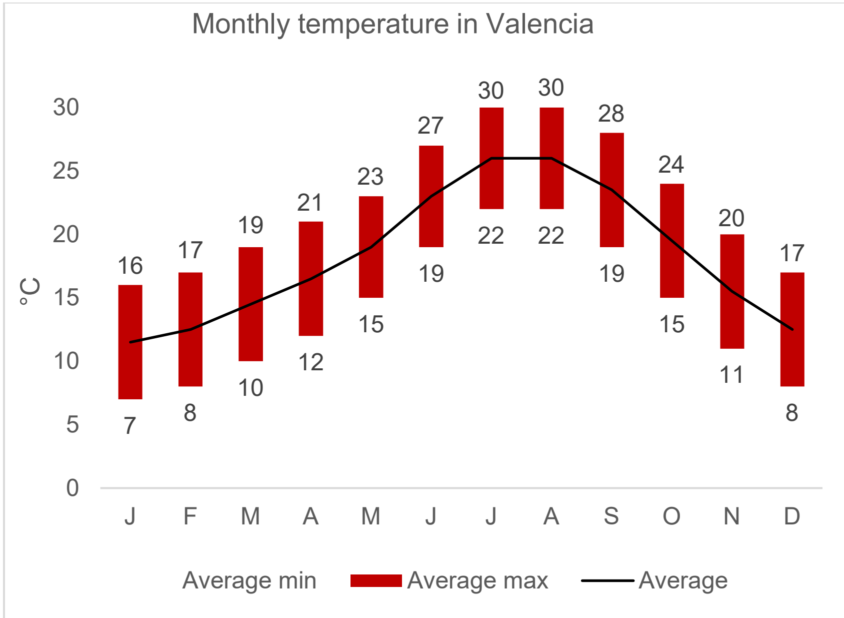


**Figure 3.2.** Monthly temperature in Valencia (State Meteorological Agency AEMET, 2019)

# 2. Materials and methods

This study was developed through the comparison of a conventional façade construction in Spain and a new kind of construction material that uses rice straw waste from the Valencian paddy fields. Through this comparison, it was possible to assess the suitability of rice straw construction for the local market and the effect that it could have on the environment. First, the acoustic and thermal properties of the façade typologies were evaluated. Second, a comparative Life Cycle Assessment (LCA) was performed to assess their environmental impact.

As previously mentioned, the rice straw panel consists of a rice straw core compressed into a wooden frame to a density of 130kg/m$^3$. The wood used to build the panel frame is pine (Pinus halepensis), a common species in the Valencian Community. Although the shape and form of the panels could vary, the design and dimensions of the standard straw panel are depicted in Figure 3.3. One of the panels used to conduct the experimental part of this study can be seen in Figure 3.4. The straw panel is covered by a 1.5 cm layer of lime mortar in the outer side and a 3cm layer of clay mortar in both the inner and the outer side. The lime layer protects the straw against molds and parasites and in combination with the clay mortar waterproofs the construction.

The benchmark typology used for the comparative study is a conventional double brick wall with 4 centimeters of mineral wool (Figure 3.5). This wall type is described in the Spanish Technical Building Code in its Catalog of Building Elements (Ministerio de Fomento, 2011). These types of double-layer brick walls are the most common façade typology in the Spanish Mediterranean area (Valencian Institute of Building, 2011).

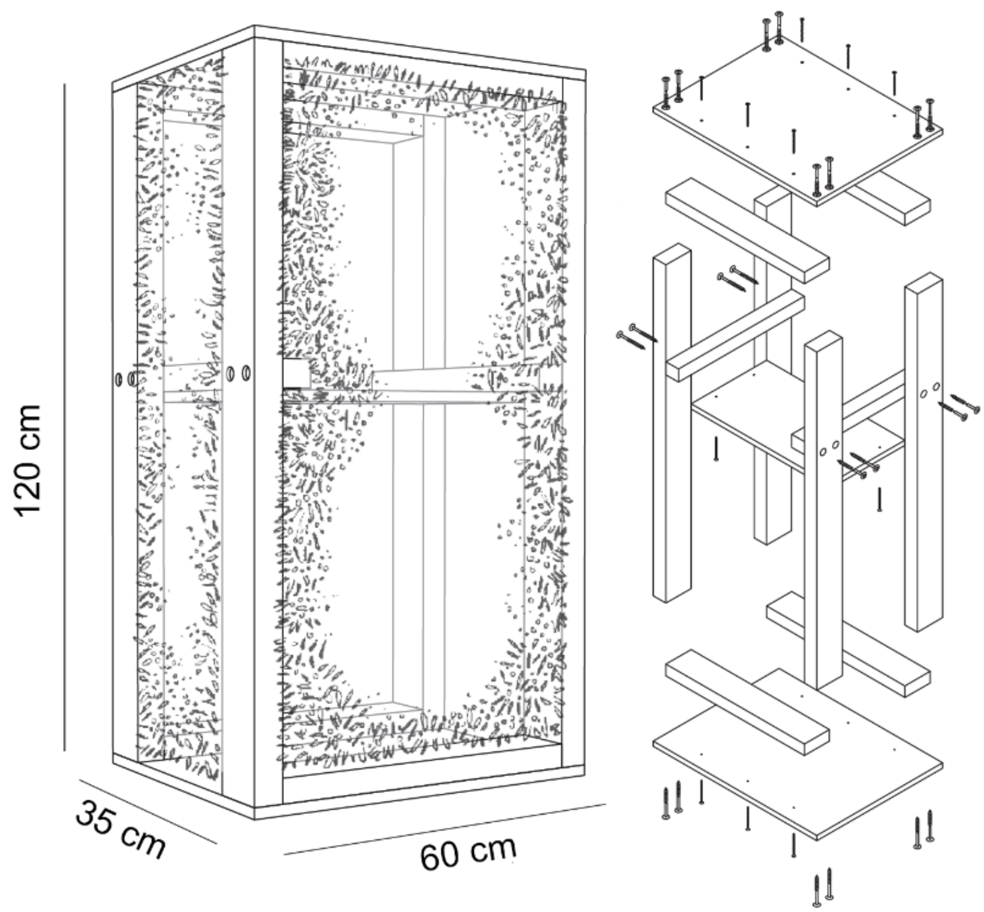


**Figure 3.3.** Straw panel dimensions and frame design

**Figure 3.4.** Straw panel in the transmission chamber

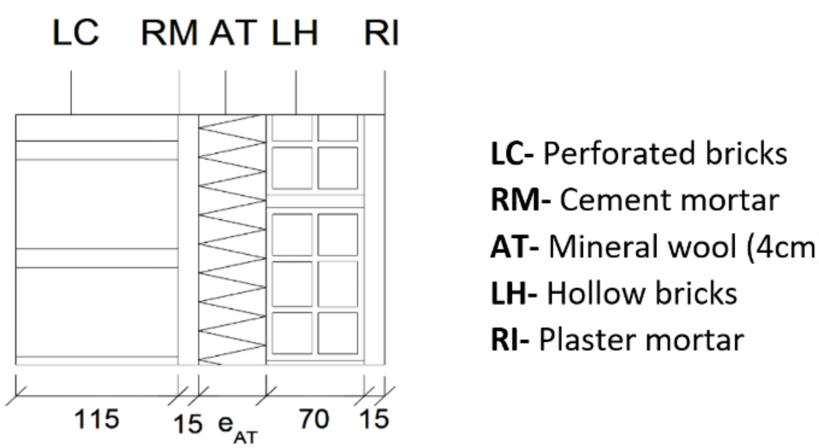


**Figure 3.5.** Double layer brick façade.

## 2.1 Airborne acoustic insulation

The airborne sound insulation of each wall was evaluated in an acoustic transmission chamber, (Figure 3.6). The measurement process followed the guidelines established by the International Organization for Standardization (ISO) 717-1 standard (ISO 717-1, 2013). The process consisted of building a 12m$^2$ sample wall dividing two rooms and measuring how much the wall attenuated the airborne sound transmission between them. A sound source emitting pink noise was placed in one of the rooms. One microphone with a rotating device was placed in each room to measure the difference in sound pressure. This difference corresponds to the amount of noise the wall is capable of attenuating. The equipment used is specified in Table 3.1. Pictures of the building process and measurement process of the straw sample wall are available in Appendix A. The uncertainty was assessed following the methodology described in the ISO 12999-1 (ISO 12999-1, 2020). The sound reduction index ($R_w$) and the uncertainty ($u(R_w)$) were assessed using the following expressions:

$$R_w = L_1 - L_2 + 10\log\frac{S}{A} \qquad (1)$$

Where: $L_1$ and $L_2$ are the sound pressure level in the emitting and receiving rooms respectively in dB, S the surface area of the sample wall, A the acoustic absorption equivalent area in the receiving room.

$$u(R_w) = \frac{-10log\sum_i 10^{(L_i - R_i + u(R_i))/10} - (-10log\sum_i 10^{(L_i - R_i - u(R_i))/10})}{2} \qquad (2)$$

Where: i denotes each frequency band, $L_i$ is the emitting sound pressure level, $R_i$ is the sound reduction index and u(Ri) are the uncertainty values for airborne acoustic insulation measurement.

**Table 3.1**
Equipment used to measure the acoustic airborne insulation

| Device | Company | Model number |
|---|---|---|
| Building acoustics analyzer | Brüel & Kjäer | 4418 |
| Spectrum analyzer | Brüel & Kjäer | 2148<br>7667 |
| 2 Microphones | Brüel & Kjäer | 4416 |
| 2 rotating microphone stands | Brüel & Kjäer | 3923 |
| Sound source | Brüel & Kjäer | 4224 |

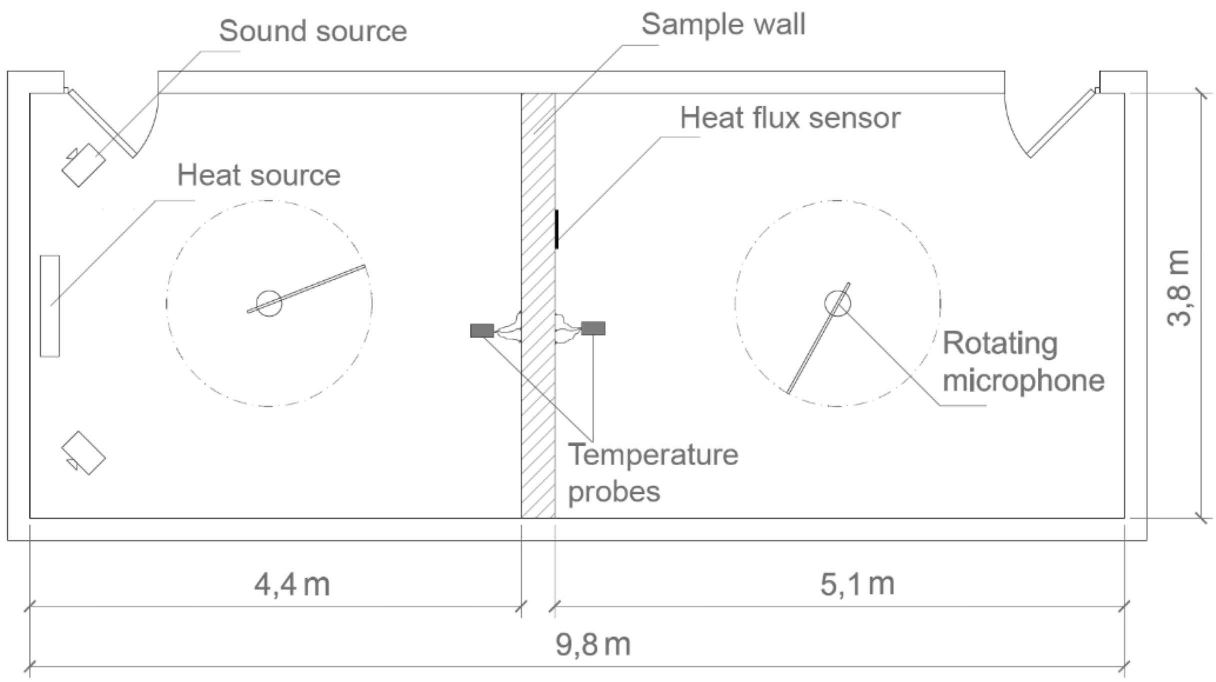


**Figure 3.6.** Transmission chamber

## 2.2 Thermal insulation

The rice straw wall's thermal insulation was assessed by measuring the thermal transmittance according to the ISO 9869-1:2014 standard (ISO 9869-1, 2014). The measurement process was conducted in the same transmission chamber used for the acoustic measurements. The transmission chamber and the placement of the equipment are specified in Figure 6. The process consisted of generating a temperature difference between the two rooms by heating what would be considered the inner side. Although the standard does not establish a minimum temperature difference, several studies suggest that it should reach at least 10 ºC to reduce uncertainty (Rasooli and Itard, 2018), (Gaspar et al., 2018). Measurements were conducted using two different measurement devices to increase to the reliability of the results. The first measurement was taken using the Testo 435-2 multi-function measuring instrument, which assesses the thermal transmittance by measuring the temperature in both rooms and the surface temperature of the wall's inner face. According to the manufacturer, the uncertainty connected to this device is ± (0.1ºC+0.2% the measured value). The second measurement was conducted using the Ahlborn ALMEMO 2590A, which measures interior and exterior surface temperature and heat flux using a thermocouple and a heat flux sensor. In the case of this device, the uncertainty is 5% of the measured value. According to the mentioned ISO standard, the contact area between the surface of the building element and the sensors can be a source of errors. Contact paste was applied between the named elements to minimize those factors. The combined uncertainty was obtained following the guidelines of the ISO/IEC Guide 98-8 (ISO/IEC, 2008).

## 2.3 Hygrothermal performance

A hygrothermal simulation of the rice straw wall has been conducted following the guidelines of the ISO 13788:2012 (ISO 13788, 2012). The local legislation CTE DA-HE/2 (Ministerio de Fomento. Gobierno de España, 2007), which is the chapter of the Spanish Technical Building code that deals specifically with hygrothermal performance, has also been employed to account for the local conditions of the region. The simulation has been performed using the software CypeTherm HE Plus (CYPE Ingenieros, 2018). The two parameters evaluated were the interstitial and the surface condensation. The characteristics of each layer are described in Table 3.2.

**Table 3.2**

Description of the layers (Ministerio de Fomento, 2011)

| Rice straw façade | e(cm) | λ(W/m·K) | R(m²·K/W) | μ | Sd(m) |
|---|---|---|---|---|---|
| $R_{se}$ | | | 0.04 | | |
| Lime mortar | 1.5 | 1.8 | 0.00833 | 10 | 0.15 |
| Clay mortar | 3 | 0.8 | 0.0375 | 6 | 0.18 |
| Rice straw | 35 | -* | -* | 9** | 3.15** |
| Clay mortar | 3 | 0.8 | 0.0375 | 6 | 0.18 |
| $R_{si}$ | | | 0.13 | | |

* Values indicated in the results section

** Data obtained from (Marques et al., 2020)

### 2.3.1 Surface condensation

Assessing the surface condensation of a building element consists of comparing the temperature factor of the inner surface $f_{Rsi}$ with the minimum required monthly temperature factor of the inner surface $f_{Rsi,min}$. $f_{Rsi,min}$, and $f_{Rsi}$ are assessed using Equation (3) and (4), respectively:

$$f_{Rsi,min} = \frac{\theta_{si,min} - \theta_e}{20 - \theta_e}; \quad (3)$$

$$f_{Rsi} = 1 - U \cdot 0.25; \quad (4)$$

where: $\theta_e$ (ºC) is the exterior temperature; $\theta_{si,min}$ (ºC) is the minimum acceptable interior temperature according to the vapor saturation pressure $P_{sat}$, obtained from the hygrothermal conditions of the inner surface; U is the thermal transmittance of the building element [W/m$^2$K].

The Spanish legislation CTE DA-DB-HE/2 was used as a reference to perform the calculations. As mentioned in previous sections, the climate of Valencia is classified as a B3 climate. The exterior relative humidity and minimum temperature have been obtained from the Spanish State Meteorological Agency (State Meteorological Agency AEMET, 2019). The interior temperature was assessed following the methodology of the ISO 7730:2006. That methodology takes into account the optimum comfort temperature variation, which depends on the clothing insulation index. The calculation process described in section 4.3.2 of the ISO 13788:2012 was used to obtain the interior relative humidity. Based on the comfort recommendations of the ISO 7730:2006, the maximum interior humidity was set to 60%. The hygrothermal conditions described in the norm are specified in table 3.3.

**Table 3.3**

Monthly hygrothermal local conditions

| | Exterior conditions | | Interior conditions | |
|---|---|---|---|---|
| | Temperature, $\theta_e$ (°C) | Relative humidity, $\varphi_e$ (%) | Temperature, $\theta_i$ (°C) | Relative humidity, $\varphi_i$ (%) |
| Jan | 7.1 | 64.0 | 21.0 | 48.4 |
| Feb | 7.8 | 64.0 | 21.0 | 48.7 |
| Mar | 9.6 | 63.0 | 21.0 | 49.2 |
| Apr | 11.5 | 62.0 | 21.0 | 50.0 |
| May | 14.6 | 65.0 | 21.0 | 55.2 |
| Jun | 18.6 | 66.0 | 23.0 | 55.7 |
| Jul | 21.5 | 67.0 | 23.0 | 60.0 |
| Ago | 21.9 | 68.0 | 23.0 | 60.0 |
| Sep | 19.1 | 67.0 | 23.0 | 57.4 |
| Oct | 15.2 | 67.0 | 21.0 | 57.4 |
| Nov | 10.8 | 66.0 | 21.0 | 51.5 |
| Dec | 8.1 | 65.0 | 21.0 | 49.2 |

## 2.3.2 Interstitial condensation

The calculation process of the interstitial condensation is based on the comparison between the vapor pressure and the vapor saturation pressure in the different layers of the building element in inner and outer conditions. If the vapor pressure is inferior to the vapor saturation pressure, interstitial condensation will not occur. To obtain those results, first, the temperature distribution is obtained using Equation (5), then, the vapor saturation pressure distribution for the temperature distribution using Equation (6), and the vapor pressure distribution using Equation (7):

$$\theta_n = \theta_{n-1} + \frac{R_n}{R_T} \cdot (\theta_i - \theta_e); \quad (5)$$

Where: $\theta_n$ is the temperature in layer n (ºC); $\theta_{n-1}$ is the temperature in layer n-1 (ºC); $R_n$ is the thermal resistance of layer n ($m^2 \cdot k/W$); RT is the total thermal resistance ($m^2 \cdot k/W$), $\theta_i$ is the inner temperature(ºC) and $\theta_e$ is the external temperature (ºC).

$$P_{sat} = 610.5 \cdot e^{\frac{17.269 \cdot \theta_n}{237.3 + \theta_n}}; \quad (6)$$

Where: $\theta_n$ is the temperature in layer n (ºC), and $P_{sat}$ is the saturation vapor pressure (Pa).

$$P_n = P_{n-1} + \frac{S_{d(n)}}{\sum S_{dn}} \cdot (P_i - P_e); \quad (7)$$

Where, $P_n$ is the air vapor pressure in layer n (Pa); $P_{n-1}$ is the air vapor pressure in layer n-1 (Pa); $S_{dn}$ is the equivalent thickness of layer n (m); $P_i$ is the interior air vapor pressure (Pa); $P_e$ exterior air vapor pressure (Pa).

## 2.4 Life cycle assessment

A comparative LCA of both walls was performed following the guidelines of the ISO 14040:2006 (ISO 14040, 2006) and the European Standards (EN) 15804:2013 (“EN 15804:2013 - Standards Publication Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products,” 2013). The modules considered in this study are A-1, A-2, and A-3, which cover the entire production process of the materials. Therefore, considering that the aim of this study is to assess the production stage of the façade typologies being studied, this is a cradle-to-gate LCA. The life cycle inventory (LCI) is modeled with a consequential approach, which is based on the use of system expansion as its allocation principle (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). Among the many available LCA calculation methods, the Environmental Footprint 3.0 was selected as the most suitable for this study. This calculation method was developed by the European Platform on Life Cycle Assessment of the European (European Platform on Life Cycle Assessment, 2020). This method partitions LCA results into 18 impact categories. Each of these categories has different impact indicators, which are quantifiable representations of an EF impact category. This process of classification is called characterization. After the characterization step, the values in the impact categories are multiplied by a characterization factor. This normalization process has the objective of expressing the relative impact of each impact category in terms of its contributions to the total environmental impact. The final step is the weighting, in which the normalized results are multiplied by a set of weighting factors that represent the perceived relative importance of the impact categories under consideration (Zampori L and Pant R, 2019). This process allows the results to be compared across categories and summed to obtain a single score.

Extensive documentation on the Environmental Footprint method, including the normalization and weighting process of the results, was developed by (Zampori L and Pant R, 2019).

### 2.4.1 Functional unit

The functional unit in an LCA study refers to the element used as the comparative reference. In this case, the functional unit has been chosen to be one square meter of façade wall. This functional unit is the most suitable to compare the life cycle of building envelopes.

### 2.4.2 Life cycle inventory

The LCI was modeled using the software Simapro v9.1. Simapro is one of the most recognized tools for LCA studies (Herrmann and Moltesen, 2015). The data used to model the LCI come from several reliable sources. Data were first compiled in collaboration with the Center for International Rural and Agricultural Studies (CERAI) ("Centro de Estudios Rurales y de Agricultura Internacional (CERAI)," 2018). The data on straw management practices' carbon emissions were obtained from the study conducted by Elena Sanchis Jiménez (Sanchis Jiménez et al., 2014). Data about other aspects of rice straw cultivation were extracted from other studies (Sanchis et al., 2012), (Nguyen et al., 2016). The remaining data were extracted from the Ecoinvent database V3.6, the most comprehensive database for environmental studies (Pascual-González et al., 2016). The effect of the two most common straw management practices on greenhouse gas (GHG) emissions is reflected in Table 3.4. The amount of GHG emissions per kg of straw was obtained by considering a total of 8000 kg of rice straw for each hectare of paddy field.

**Table 3.4**
Effect of straw management on GHG emissions per hectare (Sanchis Jiménez et al., 2014)

| Management practice | kg of $CH_4$ | kg of $CO_2$ |
|---|---|---|
| Straw burning | 69.3 | 3253 |
| Mixing with the soil | 307.6 | 0 |

In accordance with the different possible waste management practices that rice straw can be submitted to, three different life cycle scenarios have been modeled for the rice straw façade:

**Base case scenario:** This scenario accounts for the impacts of straw collection, transport, panel manufacturing, and the extraction of the rest of the raw materials to be used. The influence of straw management is not considered.

**Avoiding burning scenario:** This scenario considers all processes included in the base case scenario and subtracts the GHGs emitted during the burning of rice straw over the fields. Through this scenario, it is possible to assess the $CO_2$ equivalents per square meter of rice straw façade that can be avoided by preventing straw incineration.

**Avoiding mixing with the soil scenario:** As in the previous scenarios, this one comprises all the impacts accounted for in the base case scenario and deducts the GHGs generated when the straw is mixed with the soil. This scenario assesses how much emissions can be reduced by using one square meter of rice straw panel rather than mixing straw with the soil.

The quantities of material required for one square meter of rice straw wall are reflected in Table 3.5. The inventory of the façade is specified in Table 3.6. The inventory network of the two typologies is depicted in Figure 3.7 and Figure 3.8.

**Table 3.5**
Inventory for 1 $m^2$ of rice straw wall

| Material | Mass (kg) |
|---|---|
| Rice Straw | 49 |
| Clay mortar | 100 |
| Lime mortar | 31.5 |
| Pine wood | 7 |

**Table 3.6**
Inventory for 1 $m^2$ of brick façade

| Material | Mass (kg) |
|---|---|
| Perforated brick | 83.63 |
| Hollow brick | 53.33 |
| Cement mortar | 90.7 |
| Mineral wool | 5 |
| Gypsum mortar | 18 |

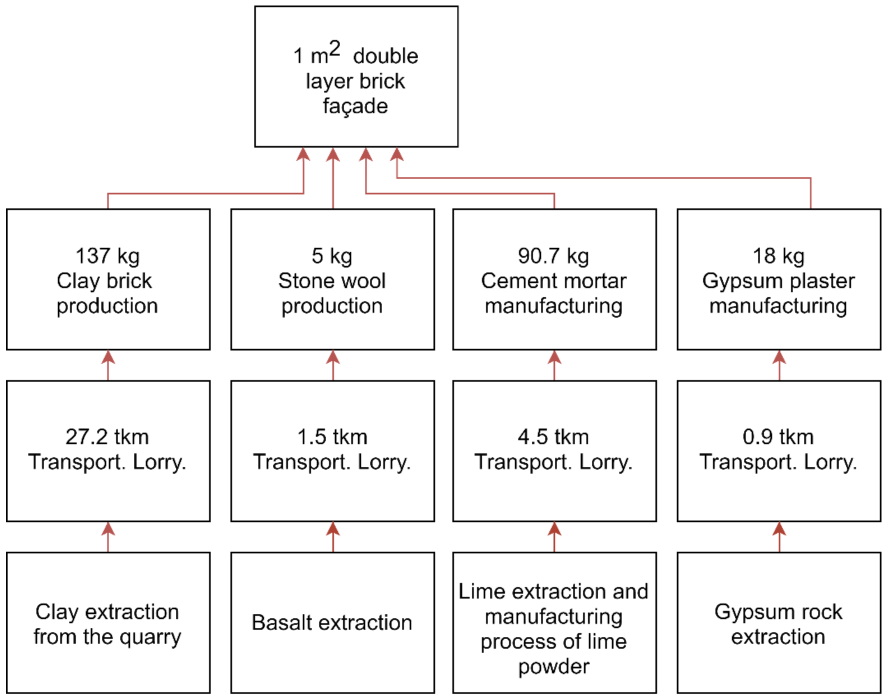


**Figure 3.7.** Brick façade inventory network

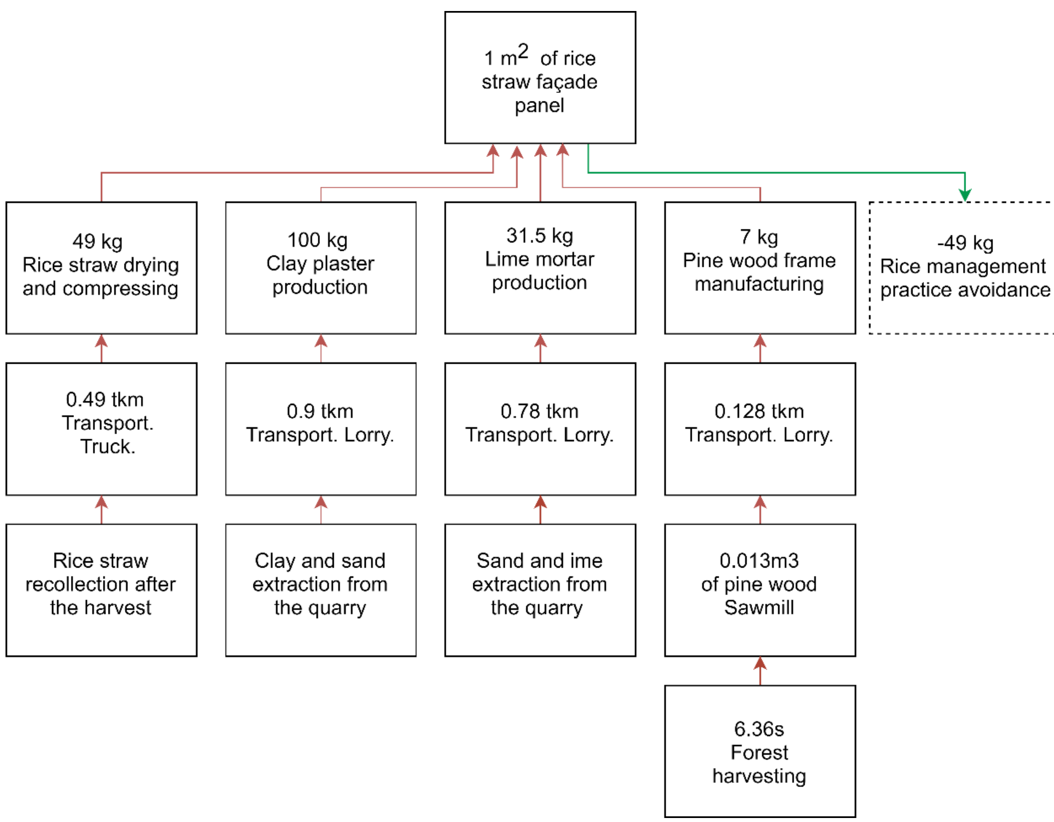


**Figure 3.8.** Straw façade inventory network

# 3. Results and discussion

## 3.1 Acoustic results

The measured airborne sound insulation of the two typologies is depicted in Figure 3.9. Although the sound reduction index is quite similar across the spectrum, there are some measurable differences. While the brick façade is observably better in low frequencies, from 100 to 250 Hz, the rice straw façade offers better results in the mid frequencies, from 500 to 2000 Hz. The weighted sound reduction index ($R_{,w}$), which can be understood as an average value for the acoustic insulation of the façade, is very similar between the two façades. The $R_{,w}$ of the brick façade is 49±2.27 dB, and the $R_{,w}$ of the rice straw façade is 47±1.93 dB. Both values meet Spanish building regulations. The raw acoustic measurements can be found in Appendix B.

Since the human auditory system can only detect differences in sound pressure level of 3 decibels or more, the airborne sound insulation of both façades can be considered equivalent. Also, due to the enormous influence that windows have on the sound insulation of the building envelope, in practice, the difference between the two typologies would be even smaller. While the brick façade has better sound insulation at low frequencies due to its higher weight, the rice straw has better results at mid to higher frequencies. One way of increasing the sound reduction index at lower frequencies would be to reduce the rigidity of the wood frame, for example, by dividing the frame into two parts and connecting them only by a spring system.

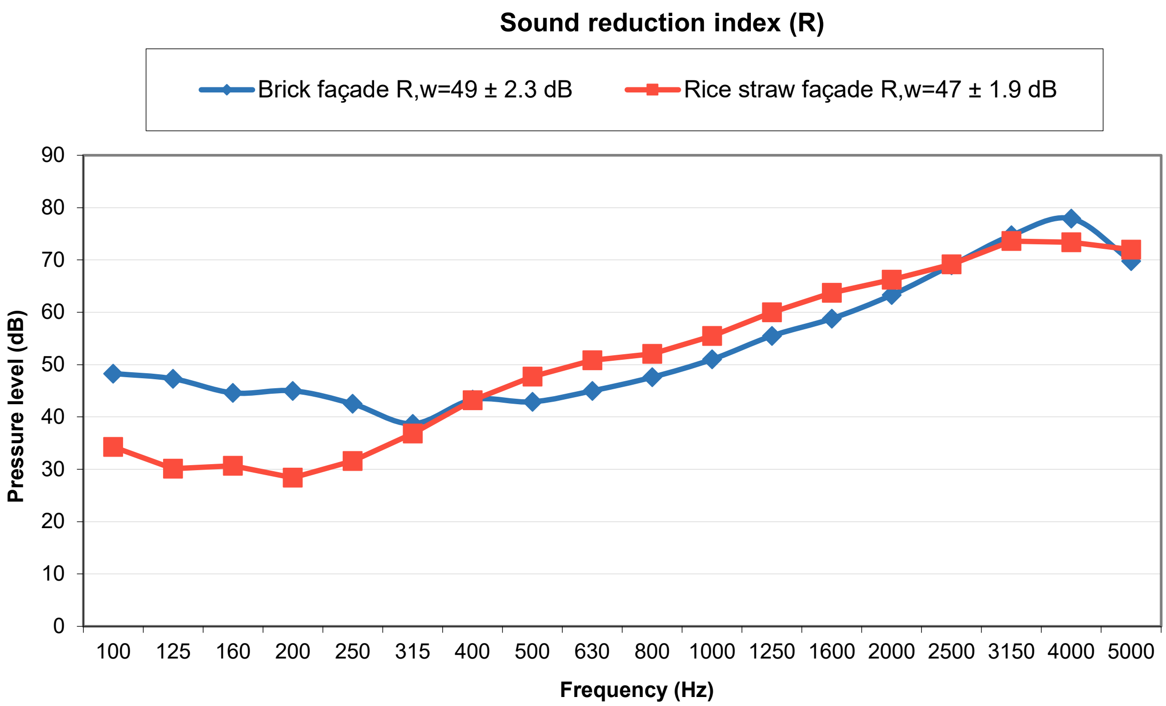


**Figure 3.9.** Sound reduction index results expressed in one-third octave bands

## 3.2 Thermal transmittance results

The rice straw façade thermal transmittance results are represented in table 3.7. The results range from 0.33±0.11 W/m$^{2}$ºC with a ten-degree temperature difference between the two rooms to 0.29±0.08 W/m$^{2}$ºC with a fourteen-degree temperature difference. Both the thermal transmittance and the standard deviation decrease as the temperature difference increases. This indicates an increase in the accuracy of the values obtained for thermal transmittance concomitant with an increase in the temperature difference between the two rooms. According to the Catalog of Building Elements of the Spanish Technical Building Code (CEC-CTE) (Ministerio de Fomento, 2011), the conventional brick façade has a thermal transmittance of 0.629 W/m$^{2}$ºC, enough to comply with the Spanish technical building code until the year 2020 ("Zebra2020. Energy efficiency trends in buildings," 2020). Assuming the 14 ºC temperature gap measurements are the most accurate, the straw wall's thermal insulation is double that of the conventional brick wall. The raw measurements can be found in Appendix C.

Considering that increasing the passive insulation of a house reduces the energy consumption needed for heating and cooling, it can be argued that this decrease in thermal transmittance would also reduce carbon emissions during the operational phase of a building. However, it is impossible to accurately assess those differences isolated from the reality of a building, as they vary depending on other aspects of the construction such as size, shape and orientation. A proper study on the operational phase would be conducted in future studies as it constitutes a whole study on its own. The operational phase is considered the most environmentally damaging phase of buildings, as it is responsible for most of the total carbon emissions of the building's life cycle (Baldassarri et al., 2017). A significant portion of those emissions could be avoided by improving thermal insulation (Hamans et al., 2008). Building regulations are becoming increasingly restrictive in most countries worldwide, and recently the section of the Spanish building code that regulates energy efficiency has been updated. Despite the new regulations, the rice straw façade would meet requirements in most climatic zones in the country (Ministerio de Fomento. Gobierno de España, 2020).

**Table 3.7**
Thermal transmittance (U) measurements of the straw wall

| Temperature difference | U ($W/m^2 {}^oC$) | N (number of samples) | Standard deviation, u(U,rep) | u(U,devices) | | $u_c(U)$ |
|---|---|---|---|---|---|---|
| | | | | Testo[a] | Ahlborn[b] | |
| 14 ºC Gap | 0.29 | 3496 | 0.08 | 0.010 | 0.015 | 0.081 |
| 13 ºC Gap | 0.31 | 5236 | 0.09 | 0.011 | 0.016 | 0.092 |
| 12 ºC Gap | 0.32 | 2063 | 0.09 | 0.012 | 0.016 | 0.092 |
| 11 ºC Gap | 0.33 | 643 | 0.11 | 0.012 | 0.017 | 0.111 |

[a] Uncertainty associated with the Testo 435-2 multi-function measuring instrument
[b] Uncertainty associated with the Ahlborn ALMEMO 2590A measuring instrument

## 3.3 Hygrothermal results

### 3.3.1 Surface condensation

The monthly minimum interior surface temperature factor ($f_{Rsi,min}$) is represented in Table 3.8. The results were obtained with Equation (1) and the components specified in Table 3.

**Table 3.8**
Monthly hygrothermal performance

| | $\theta_e$ (°C) | $\varphi_e$ (%) | $\theta_i$ (°C) | $\varphi_i$ (%) | $P_i$ (Pa) | $P_{sat}$ ($\theta_{si}$) (Pa) | $\theta_{si,min}$ (°C) | $f_{Rsi,min}$ |
|---|---|---|---|---|---|---|---|---|
| January | 7,1 | 64,0 | 21,0 | 48,4 | 1203,22 | 2485,58 | 13,1 | 0,430 |
| February | 7,8 | 64,0 | 21,0 | 48,7 | 1210,02 | 2485,58 | 13,2 | 0,406 |
| March | 9,6 | 63,0 | 21,0 | 49,2 | 1221,92 | 2485,58 | 13,3 | 0,325 |
| April | 11,5 | 62,0 | 21,0 | 50,0 | 1242,63 | 2485,58 | 13,6 | 0,217 |
| May | 14,6 | 65,0 | 21,0 | 55,2 | 1371,36 | 2485,58 | 15,1 | 0,076 |
| June | 18,6 | 66,0 | 23,0 | 55,7 | 1563,38 | 2807,81 | 17,1 | --* |
| July | 21,5 | 67,0 | 23,0 | 60,0 | 1817,17 | 2807,81 | 19,5 | --* |
| August | 21,9 | 68,0 | 23,0 | 60,0 | 1885,92 | 2807,81 | 20,1 | --* |
| September | 19,1 | 67,0 | 23,0 | 57,4 | 1612,58 | 2807,81 | 17,6 | --* |
| October | 15,2 | 67,0 | 21,0 | 57,4 | 1427,14 | 2485,58 | 15,7 | 0,088 |
| November | 10,8 | 66,0 | 21,0 | 51,5 | 1281,08 | 2485,58 | 14,0 | 0,317 |
| December | 8,1 | 65,0 | 21,0 | 49,2 | 1224,15 | 2485,58 | 13,3 | 0,406 |

* Due to $\theta_e \geq \theta_i$ there no risk of condensation

Since January has the highest minimum interior surface temperature factor ($f_{Rsi,min}$ ) it is the month with the highest risk of condensation. The $f_{Rsi}$ of the rice straw façade is obtained using equation (2) and compared to the minimum required temperature factor in January:

$f_{Rsi}$ = 0.927 > $f_{Rsi,min}$ =0.430;

The inner surface temperature factor of the straw wall is higher than the minimum required factor for January in the city of Valencia. Therefore, there is no risk of condensation in the studied location.

### 3.3.2 Interstitial condensation

A comparison between the saturation vapor pressure and the vapor pressure in each layer is performed taking into account the local hygrothermal conditions. As it was mentioned in previous sections, January is the most unfavorable month due to its higher $f_{Rsi,min}$. The calculations for the month of January are reflected in Table 9. A study of the interstitial condensation of the rest of the months has also been included in Appendix C.

As can be seen in Table 3.9 and Figure 3.10, the results show no occurrence of interstitial condensation in any of the layers of the building element. Therefore, due to the lack of moisture accumulation in any of its layers the rice Straw wall can be considered an adequate building envelope for the local climate of Valencia.

It is also worth noticing that in case of temperatures being frequently under 4 ºC there might be a risk of condensations in the external surface of the rice straw layer. For that reason, it is always best to conduct a bioclimatic study before the construction of a building. By doing that, it is possible to analyze the need, or not, of a vapor barrier. Considering as a vapor barrier any element with a diffusion resistance higher to 10 MN·s/g, equivalent to 2.7 $m^2$·h·Pa/mg.

**Table 3.9**

Hygrothermal performance by layer in January

| Rice Straw façade | θ (°C) | $P_{sat}$ (Pa) | $P_n$ (Pa) | φ (%) | $g_c$ (g/(m²·month)) | $M_a$ (g/m²) |
|---|---|---|---|---|---|---|
| Exterior air | 7,10 | 1008,23 | 645,27 | 64,0 | | |
| Exterior Surface | 7,48 | 1034,88 | 645,27 | 62,4 | -- | -- |
| Interface 1-2 | 7,56 | 1040,50 | 668,14 | 64,2 | -- | -- |
| Interface 2-3 | 7,92 | 1066,17 | 695,58 | 65,2 | -- | -- |
| interface 3-4 | 19,41 | 2252,33 | 1175,78 | 52,2 | -- | -- |
| Inner face | 19,76 | 2302,82 | 1203,22 | 52,2 | -- | -- |
| Interior air | 21,00 | 2485,58 | 1203,22 | 48,4 | | |

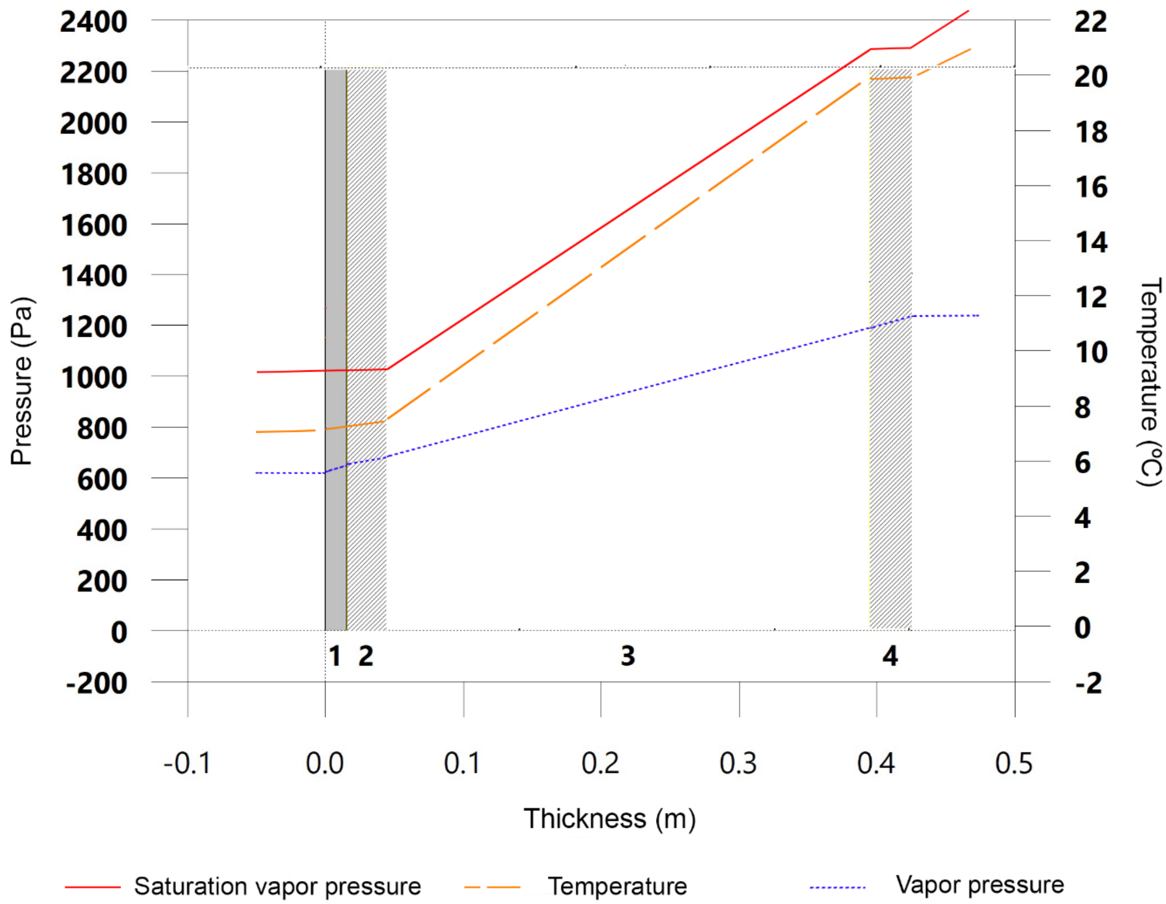


**Figure 3.10.** Saturation vapor pressure distribution

## 3.4 Life cycle assessment results

The Environmental Footprint characterization results, given in Table 3.10, show that the environmental impact of the conventional double brick façade is higher in every category except for land use and water use. This is reasonable given the amount of land that paddy fields require, and the amount of water needed to flood them. The differences between rice straw management practices can be observed in the climate change category. This category, which is assessed using the methodology of the Intergovernmental Panel on Climate Change (IPCC), expresses the contribution of each material to climate change in kilograms of $CO_2$ equivalents. If the emissions of either burning the straw or mixing the straw with the soil are subtracted, each square meter of rice straw façade prevents the emission of 18.85 kg of $CO_2$e and 52.64 kg of $CO_2$e, respectively. Even if one disregards the reduction in straw management-based emissions, the difference in carbon emissions between the two typologies studied is significant.

**Table 3.10**
Environmental Footprint characterization

| Impact category | Unit | Brick façade | Straw façade | Straw façade (avoiding burning) | Straw façade (avoiding mixing) |
|---|---|---|---|---|---|
| Climate change | kg $CO_2$ eq | 76.16 | 16.69 | -18.85 | -52.64 |
| Ozone depletion | kg CFC11 eq | 6.13E-06 | | 1.14E-06 | |
| Ionizing radiation | kBq U-235 eq | 1.22 | | 0.24 | |
| Photochemical ozone formation | kg NMVOC eq | 0.26 | | 0.04 | |
| Particulate matter | disease inc. | 3.13E-06 | | 5.19E-07 | |
| Human toxicity, non-cancer | CTUh | 6.89E-07 | | 1.78E-07 | |
| Human toxicity, cancer | CTUh | 1.11E-07 | | 5.63E-09 | |
| Acidification | mol H+ eq | 0.30 | | 0.06 | |
| Eutrophication, freshwater | kg P eq | 2.31E-03 | | 8.83E-04 | |
| Eutrophication, marine | kg N eq | 6.83E-02 | | 2.96E-02 | |
| Eutrophication, terrestrial | mol N eq | 0.82 | | 0.17 | |
| Ecotoxicity, freshwater | CTUe | 1096.76 | | 216.16 | |
| Land use | Pt | 713.27 | | 1268.23 | |
| Water use | m3 depriv. | 7.48 | | 45.44 | |
| Resource use, fossils | MJ | 694.79 | | 93.59 | |
| Resource use, minerals, and metals | kg Sb eq | 9.17E-04 | | 1.12E-04 | |

In Figure 3.11, the normalized results reveal that the brick façade has a high impact on freshwater ecotoxicity and resource use. After weighting, the climate change potential gains importance as the most influential category, increasing the difference in impact between the two façade typologies (Figure 3.12). Considering that the results are normalized and weighted, the EF offers the possibility of obtaining a single impact score result by adding up each category. The single score result and the other relevant results of the study are summarized in Table 3.11.

It is clear from the LCA that using rice straw waste as a raw material reduces emissions of the GHGs carbon dioxide and methane. The comparative LCA indicates that the emission of over 40 kg of $CO_2$e is averted by using the straw to build one square meter of façade panel instead of burning it. Likewise, avoiding incorporating the straw into the soil prevents the emission of 94.21 kg of $CO_2$e. The difference between the emissions generated by burning and by mixing can be explained by the methane emissions generated during the straw's anaerobic decomposition. Methane has a GWP 28 times higher than $CO_2$. From an environmental perspective, neither of these straw management practices can be considered adequate. The only viable and sustainable option is the use of rice straw as a raw material. Moreover, the impact of these practices goes beyond the emissions of GHGs. Although in the case of waste management practices, only the emissions of GHGs were accounted for, other adverse outcomes from these practices are worth mentioning. According to some recent studies, straw burning has significant effects on the local population due to the emission of $NO_x$, $SO_x$, and hydrocarbons. As previously mentioned, this practice is currently banned by the common agricultural policy. At the present time, mixing the straw with the soil is the most common practice, which, apart from producing carbon emissions, hugely damages the local ecosystems by producing eutrophication. Since the paddy fields are directly connected to the Albufera, changes in the water used for irrigation directly affect the lagoon and the species that live in it. Due to its negative effect on biodiversity, eutrophication is considered to be the main problem affecting Spanish freshwater ecosystems (Cobelas et al., 1992). In light of the LCA results, it can be surmised that avoiding the usual rice straw management practices and using the straw as a building material would positively affect climate change and the local ecosystems.

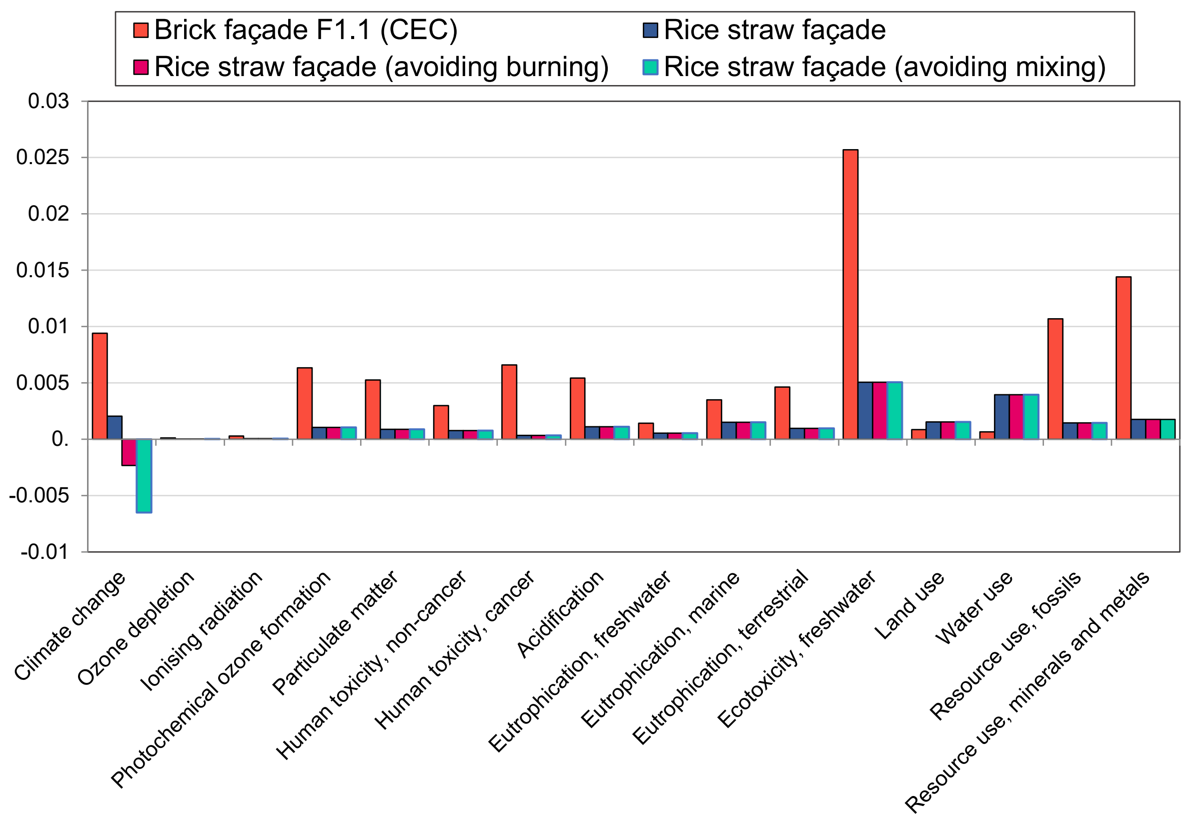


**Figure 3.11.** Environmental footprint normalization

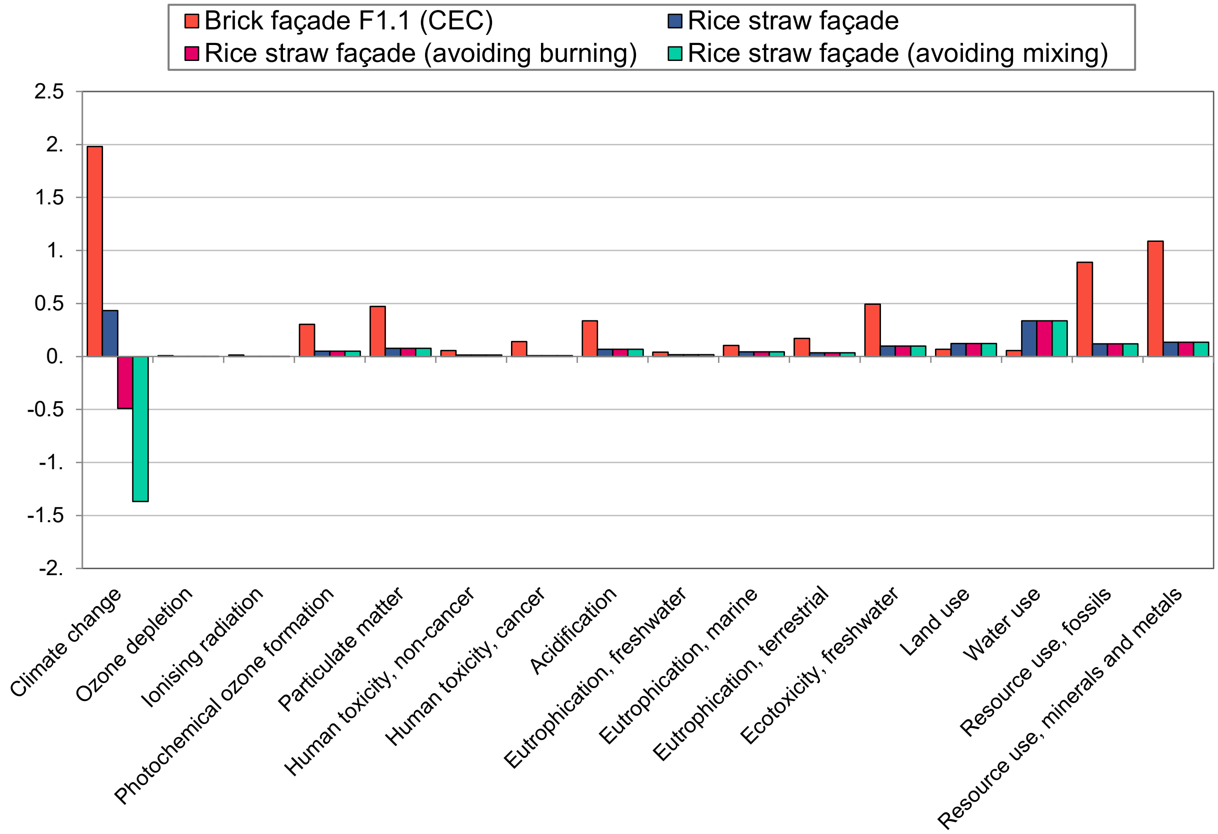


**Figure 3.12.** Environmental footprint weighting

**Table 3.11**
Summary of the acoustic and thermal insulation results

| Typology | EF 3.0 single score mPt | IPCC GWP $CO_2e$ | U-Value $W/m^2{}^oC$ | R,w dB |
|---|---|---|---|---|
| Brick façade F1.1 (CEC) | 6.22 | 76.34 | 0.629 | 49±2.3 |
| Rice straw façade | 1.56 | 16.69 | | |
| Rice straw façade (avoiding burning) | 0.09 | -18.85 | 0.29±0.08 | 47±1.9 |
| Rice straw façade (avoiding mixing) | -1.32 | -52.64 | | |

## 3.5 Further considerations

Overall, the results of this study indicate that the rice straw façade panels may be a sustainable alternative to the most common double-layer brick façades used in Valencia. However, it is necessary to examine other relevant performance indicators before considering any building material adequate.

Fire resistance is one of the main points of concern for many industry professionals regarding straw constructions. Nevertheless, many research studies and standardized fire tests demonstrated that these kinds of construction typologies provide more than adequate fire safety by packing the straw to a density of at least 100 $kg/m^3$. The low amount of oxygen available within the straw slows down the combustion rate in case of fire (Walker et al., 2019). Moreover, literature on the topic consistently shows that rendered straw walls can last up to 90 minutes before the rendered skin collapses and exposes the straw core to the fire (Apte et al., 2008), (Džidić, 2017). That value surpasses the 30 minutes required by the Spanish regulation (CTE) for low-rise buildings.

The structural integrity of the typology is also a subject that needs addressing. The straw panels studied can both be load-bearing and non-load-bearing (Walker et al., 2019). The wood frame would need to be adapted to be an active structural element of the building to use the panels for structural applications. However, in this study, the typologies under comparison are designed merely to perform as the building envelope. One aspect that is also worth considering is cost. While manufacturers claim that the price of straw panels is equivalent or very similar to conventional façade typologies, this statement is subject to variability. Currently, it is possible to obtain the local rice straw for a low price or even for free. However, this situation may change as it gains popularity as a viable raw material. The wood frame also has a relevant impact on the overall cost of the façade. Wood is currently increasing in price as it is becoming a sustainable alternative to concrete.

As for the durability of the panels, it can be assumed that, if properly executed, straw walls can last for more than 100 years (Minke and Krick, 2020). Researchers have shown evidence that straw may be able to withstand relatively high transient moisture contents without suffering serious decay (Thomson and Walker, 2014). Also, a study dealing the hygrothermal and energy performance of different straw bale configurations indicates that straw bale buildings have a robust hygrothermal performance when properly designed (Koh and Kraniotis, 2021). Therefore, straw constructions could be comparable, durability-wise, to the average conventional construction, as most studies consider 100 years a realistic assumption of the service life of buildings (Lavagna et al., 2018), (Marsh, 2017). One remarkable example is the original Nebraska straw bale buildings, built around 1986, which remain functional nowadays (Bruce King, 2007). For the straw panels to last that long, the wall will need to be protected against ground humidity by a waterproofing layer. As mentioned in previous sections, the lime layer will protect the construction against fungus and insects. The level at which those requirements are fulfilled will also determine the possible end-of-life scenarios. Although the end-of-life of phase is beyond the scope of this study, it is worth noting that using bio-based panels has potential benefits after the service life of the building. While materials such as clay bricks or concrete are commonly landfilled (UNEP and ISWA, 2015), bio-based materials such as rice straw can easily be composted or converted into biomass (Sharma et al., 2020), (Singh and Arya, 2021). Currently, rice straw management is a very controversial topic in the region, especially among farmers. Since straw burning has been banned, many farmers have complained about the difficulties that arise from other waste treatments. Managing the amount of residue generated each year is expensive and labor-intensive. Some studies have shown that rice straw can be used in many kinds of construction materials such as composites and concrete (Nguyen and Mangat, 2020), (Pandey and Kumar, 2020). Ideating and generating additional uses for the local rice straw alleviates the pressure on farmers and allows local companies to create innovative products. It may also have significant benefits on the local population. Taking part in the issues that affect local producers might help in creating a sense of community. By feeling that they contribute to the improvement of their community they may be encouraged to tackle other problems. This idea complies with the concept of glocal architecture, based on tackling global and local problems from a joint perspective (Nagashima, 1999). Using glocal materials, it is possible to reduce global threats such as climate change and reduce or even avoid local issues.

# 4 Conclusions and prospects

This study analyzed the environmental, thermal, and acoustic performance of rice straw façade panels in comparison with that of one of the most common façade constructions in Valencia. Additionally, a hygrothermal simulation of the straw façade was run for compliance with the local regulation. Rice straw in Valencia is usually treated as waste, and the most common management practices have been proven to be detrimental to the environment. By using the rice straw as raw material, the adverse environmental impacts resulting from those practices can be avoided. Using an LCA, this study investigated the potential environmental benefits of preventing the carbon emissions resulting from the most common waste management practices. The LCA facilitated a comparison between the impact of rice straw façade production and that of production of double-layer brick façade with stone wool. Two additional scenarios were considered in which carbon emissions were related to the two most common straw management practices of burning and mixing the straw with the soil. Also, the acoustic and thermal performances of both studied façades were measured and compared.

Several conclusions can be drawn. The rice straw façade reduces the thermal transmittance of the double layer brick façade by half, which constitutes a determining factor in reducing the environmental footprint of the operational phase. In the case of the acoustic performance, both façades analyzed had a noise reduction index that meets the local legislation's requirements. Also, the straw façade shows an adequate hygrothermal performance for the local conditions of Valencia. Therefore, it can be concluded that the straw façade performs adequately both in terms of acoustic and thermal insulation. According to the LCA results, the rice straw façade had a lower environmental impact than the brick façade in most categories analyzed. Only in water use and land use did the rice straw façade show a higher impact. Even without considering the adverse environmental effects of conventional waste treatments, the carbon emissions of the rice straw façade are around 80% lower than those of the brick façade. By subtracting the carbon emissions of the waste treatment, building one square meter of this kind of façade avoids the emission of 40.14 kg of $CO_2e$ resulting from incineration of the straw and 94.21 kg of $CO_2e$ resulting from straw being mixed with the soil. In light of these values, it can be stated that the rice straw façade is a carbon-negative construction. From the results of this study, it can be concluded that the rice straw panels can be considered a glocal construction typology due to the benefits for local communities and for local and global environments.

Although straw as a building material has proven to be a viable and sustainable option for many construction applications, there are still several research needs in this domain. One of them is the study of the popular perception of straw buildings. While its use has clear advantages in some cases, many people regard it as unsafe and unreliable. Understanding the origin of those misperceptions and finding ways to overcome it could be the subject of some interesting research studies.

Even though the thermal and the acoustic insulation of the typology studied are adequate for the local climate, it might be interesting to find ways of improving its performance. Optimizing the straw density in the core of the element could be one way of approaching the issue. Altering the straw density could improve the thermal insulation and the sound reduction index. Another viable option would be to combine the core element with additional layers of bio-based panels. While this would increase the price of the façade, it would have positive effects on both the acoustic and the thermal insulation. Also, due to the significant amount of rice straw generated each year in Valencia (up to 90000 tons), augmenting the demand for the material would be beneficial. The development of other straw-based innovative materials would help in reducing the environmental impact of the most common waste management practices.

Studying the long-term effects of the local climatic conditions on already built straw buildings would also be of great relevance. That kind of study could help in understanding ways of avoiding straw degradation and mold formation.

## Funding

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# Chapter 4

## Comparing the environmental impacts of wooden buildings in Spain, Slovenia, and Germany

*Accepted for publication in the Journal of Cleaner Production.
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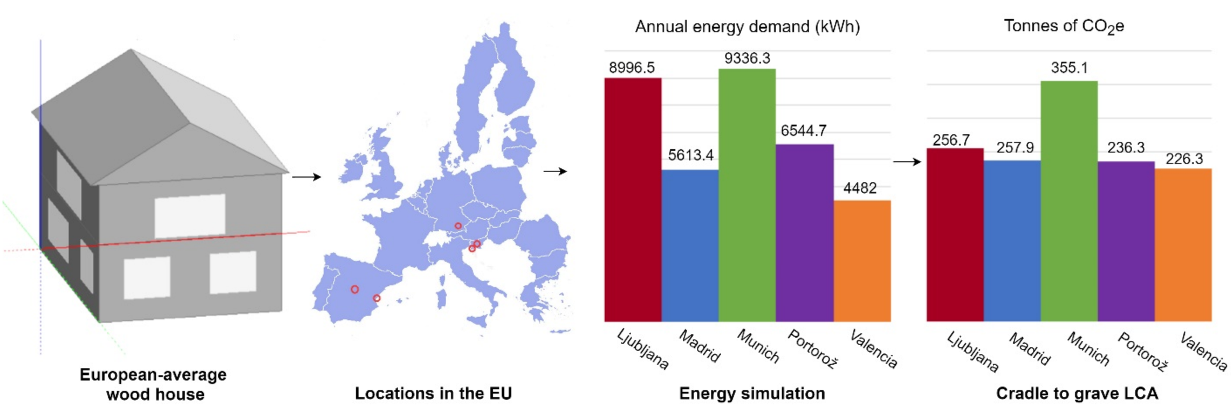
# Abstract

The environmental impacts of a wooden single-family model house were compared in different locations in Europe using Life Cycle Assessment. The chosen locations were Munich, Ljubljana, Portorož, Madrid, and Valencia. The main purpose was to analyze the existing barriers for designing a regenerative wood house and how those barriers change depending on the local conditions. The LCA results show that, despite the highly insulative building envelope, the use phase still contributes between 65% to 76% of the total carbon emissions over the complete life cycle of the house. Carbon emissions and the overall environmental impacts are higher in the locations with a colder climate, due to the energy used for heating. However, the electricity generation mix can sometimes overshadow those differences. Due to that influence, the carbon emissions in Munich are much higher than in Ljubljana despite having a similar energy consumption. The electricity mix effect is also observed when comparing the environmental impacts in Madrid and Portorož, where the $CO_2$ emissions are slightly higher in Madrid despite its lower energy consumption. These results demonstrate the need for taking measures to overcome the impacts that are not possible to eliminate by passively isolating the house.


## Graphical Abstract:



# 1 Introduction

As the third decade of the 21st century begins, climate change is a more pressing threat than ever. Since the first climate emergency declaration in 2016 (Ripple et al., 2020), 25 countries and more than 1250 local governments have made climate emergency declarations. The effects of climate change are becoming more apparent in several areas of the world and are causing severe damage in the most impoverished ones (Climate Centre, 2018). Clearly, current sustainability efforts are not enough. To bring ecosystems back to healthy states, a regenerative approach that includes aggressive steps to achieve environmental restoration along with behavioral change is necessary. The target should be to achieve regenerative sustainability, allowing both society and the environment to maintain a healthy balance and to evolve (COST Action RESTORE, 2018).

Therefore, it is essential to analyze and optimize every industry sector, including the construction sector. The regenerative sustainability paradigm for the built environment was described by du Plessis (2012). du Plessis analyzed and contextualized the role of regenerative design in a historic perspective. While conventional sustainability consists in limiting the impacts over the environment by giving back as much as it is taken, regenerative sustainability seeks to restore ecosystems to a healthy state and then developing a co-creative partnership with nature. The objective is to have a positive impact over the environment by following strategies based on adaptation, resilience and regeneration (du Plessis, 2012). Mang and Reed started developing a framework for designers to successfully apply the regenerative concept to the build environment. Regenerative systems are place specific and the framework includes a requirement to 'build to place, not formula' (Mang and Reed, 2012).

The life cycle of buildings consists of different phases with different specificities that coexist within a complex equilibrium. Building construction, use phase, and end of life are major sources of environmental impacts. It is estimated that half of all extracted materials in Europe are used for building construction and use. Buildings are responsible for around 40% of the total carbon emissions in the world, considering contributions from the production process of the materials, the construction of the building, and its operational phase (Baldassarri et al., 2017). Research on the Life Cycle Assessment (LCA) of buildings has been conducted for over 20 years and it is becoming the staple tool for analyzing the environmental performance of buildings (Bahramian and Yetilmezsoy, 2020) (Lützkendorf, 2018). Currently, the number of studies that analyze the LCA of buildings is growing (Hossain and Marsik, 2018) (Röck et al., 2018) (Abd Rashid et al., 2017). Also, due to the increasing popularity of cross-laminated timber (CLT) buildings, several studies are now assessing the environmental impacts of residential buildings using that material

(Jayalath et al., 2020). Studies on how to successfully build passive houses in different climate zones have already been published (Schnieders et al., 2015) (Yong et al., 2017). However, the differences between the entire life cycle of a wood house in different locations in Europe have not yet been assessed, to our knowledge. It is well stablished that the operational phase of buildings is responsible for the largest share of energy consumption in the entire life cycle (Gustavsson et al., 2010). A recent study conducted by the International Energy Agency (IEA) states that the building sector, including residential and services had the largest increase in energy use (International Energy Agency, 2021). Moreover, the U.S. Energy Information Administration projects that global energy consumption in buildings will grow by 1.3% per year on average from 2018 to 2050 (U.S. Energy Information Administration, 2019). Due to the regional conditions in each location, the energy demand during the operational phase naturally varies. As more is understood about the impact of buildings at all life cycle phases and for all types, the concept of regenerative sustainability is gaining popularity in the building sector (Zhang et al., 2015) (Eberhardt et al., 2019). The concept has even been applied to optimizing urban design (Natanian and Auer, 2020). The challenges that the transition towards a regenerative paradigm represent have also been studied through case studies (Attia, 2016), (Aksamija, 2016). However, there is a lack of consistency on show the strategies should be adapted to different climates.

This study deals with the analysis of the existing barriers as well as the opportunities in the design process of a single-family wooden house with regenerative sustainability goals in the European context. By using the same house design and components it is possible to better analyze how those barriers change exclusively because of the local conditions (i.e., to consider place in a regenerative framework from an impact assessment perspective). Understanding those changes could help in designing better and more optimized buildings.

The objectives of this study were to better understand the environmental impact of single-family wood homes and determine how to improve their design to reach higher sustainability goals given the environmental and energy mix contexts of their location. To achieve these objectives, cradle to grave LCAs of a representative single-family wood-framed house located in five cities in Europe were performed and compared. The locations chosen have both similar and differing climate conditions and different power generation mix. This mix of similar climate conditions and differing energy mixes supports examining the interlink and affect the overall environmental impacts in a given place. The environmental impacts were compared to determine the barriers and opportunities for regenerative construction. The results can be useful to architecture, construction, and engineering (ACE) professionals in understanding optimizing building design for better environmental performance and for researchers to target their activities on solutions which will improve environmental impacts.

# 2 Materials and Methods

A single house design was used and set in five different European cities, Munich, Ljubljana, Portorož, Madrid, and Valencia. The first two cities have continental climates, and the last three Mediterranean climates. Although only two climatic zones were covered, each location has specific characteristics leading to differences in weather conditions, material sources, electricity mix, and use patterns between all locations. Choosing locations with similar weather conditions and from different countries makes possible to analyze the influence that factors such as the electricity mix and the climate conditions have over the total environmental impacts of a house in different parts of Europe. A summary of the average temperatures at each location as well as the heating and cooling degree days is reflected in Table 4.1.

**Table 4.1**
Summary of the weather conditions in each location ("Weather Spark," 2021) ("Heating & Cooling Degree Days - Worldwide Data Calculation," 2020)

| | Hot season temperature (ºC) | | Cold season temperature (ºC) | | Heating degree days (15 ºC) | Cooling degree days (18.3 ºC) |
|---|---|---|---|---|---|---|
| | High | Low | High | Low | | |
| Ljubljana | 27 | 15 | 3 | -3 | 3165 | 137 |
| Madrid | 33 | 18 | 10 | 0 | 1860 | 596 |
| Munich | 24 | 13 | 3 | -4 | 3730 | 47 |
| Portorož | 29 | 18 | 9 | 1 | 1789 | 505 |
| Valencia | 30 | 22 | 16 | 6 | 1024 | 627 |

A building designed to represent an average European single-family wood house was used as a reference for the study (Schau EM et al., 2019). Wood was used for the frame due to its lower carbon emissions compared to concrete (Guardigli et al., 2011). The rest of the building elements consist of conventional materials specified in subsequent sections.

The study implements cradle to grave Life Cycle Assessment (LCA) of the reference house at the five locations. An energy simulation was carried out to analyze the use phase, obtaining the consumption at each location.

## 2.1 Description of the building

The model European reference house is a two-story house with a gable roof conceived to represent the average single-family detached home in Europe. The structure consists of wood, and the building envelope is insulated with several layers of mineral wool to minimize thermal losses. The two biggest façades face north and south, respectively. The north façade has a minimum number of openings to maximize thermal insulation. The first floor is mainly the living/social zone, where there is a living room, kitchen, a storage room, a study, and a small toilet. The second floor is the private/sleeping zone containing two small bedrooms, one master bedroom, and a bathroom. The building plans can be found in Figure A1- A8 in Appendix D and a summary of the building plan is depicted in Figure 4.1.

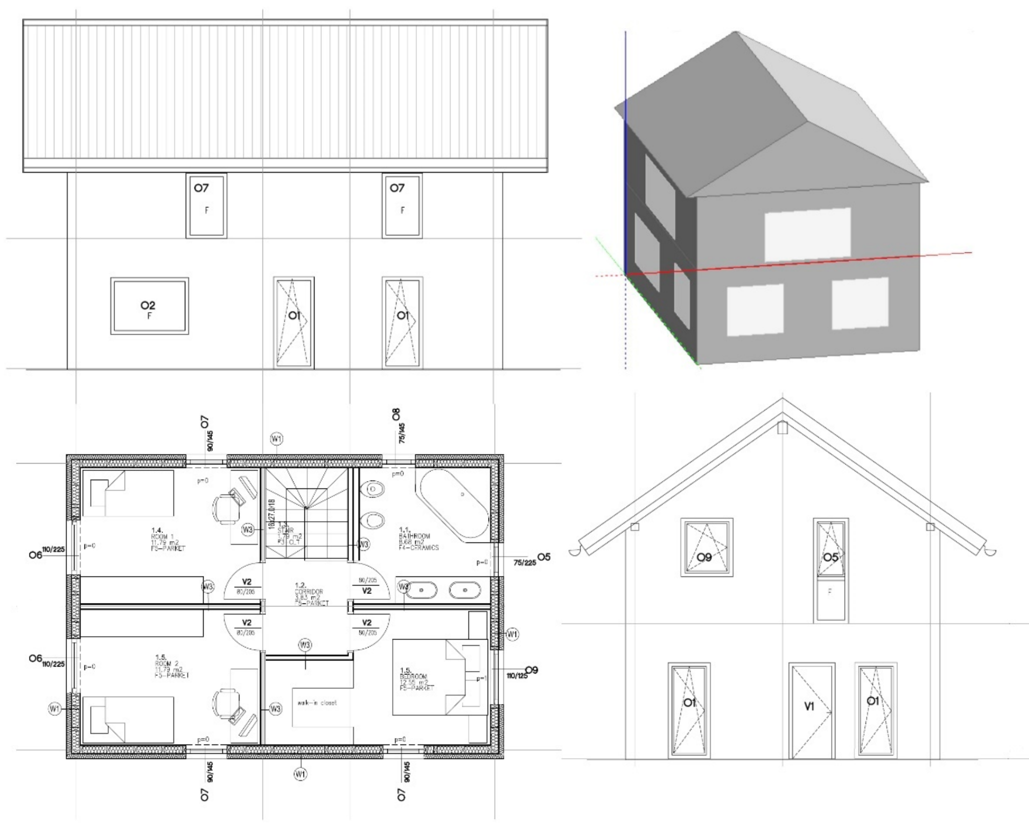


**Figure 4.1.** Overview of the house plans

### 2.1.1 Building layers

The base building layers were selected because they are available in all locations and allow the house to be more comparable between locations. The same thermal insulation was used in every location to allow direct comparison of the relation between the climate conditions and the energy consumption. Comparing the performance of the exact same building in different locations is critical to allow the results to be extrapolated and comparable. By using the same building the influence aspects such as climate change have over the life cycle of the building are easily identifiable. The building envelope is highly insulated (Table 4.2). The materials used in each building layer are specified in Tables A1-A9 in Appendix D. The walls and the roof are insulated with stone wool. The ground floor combines extruded polystyrene (XPS) with a thinner layer of stone wool as XPS is more suitable than mineral wool to be exposed to the moist conditions on the ground floor. Detailed sections of the building envelope can be found in Figures A9 to A12 in Appendix D. The purpose of this design is to minimize the amount of energy needed for heating and cooling. The transmittance of the building envelope was adjusted to comply with building regulations across Europe in the year 2020 ("Zebra2020. Energy efficiency trends in buildings," 2020).

**Table 4.2**
Building envelope

| Building element | U-value (W/m²K) | Surface area (m²) |
|---|---|---|
| W1. Exterior walls | 0.146 | 164.48 |
| W2. Exterior wall ground floor bottom | 0.262 | 22.42 |
| R1 roof | 0.132 | 123.42 |
| F1 ground floor-ceramics | 0.175 | 13.28 |
| F1/A ground floor-ceramics in bathrooms | 0.186 | 10.2 |
| F2 ground floor parquet | 0.174 | 76.52 |

## 2.2 Thermal simulation

To assess the environmental impacts of the house in each location it is necessary to know its energy demand. The amount of energy needed to maintain thermal comfort will vary considerably depending on the climatic conditions in each location. A simulation was run to calculate that energy demand. The building elements considered for the simulations are described in Table A1 to A9 in appendix D.

The energy simulation software used was DesignBuilder 6.1, a well-recognized software tool for analyzing the energy demand in buildings (Design Builder, 2019). DesignBuilder uses EnergyPlus, developed by the US Office of Energy Efficiency & Renewable Energy (United States Department of Energy, 2019), as its calculation engine. The weather data was obtained from The American Society of Heating, Refrigerating and Air-Conditioning Engineers ("ASHRAE," 2017), which is considered the standard for building performance simulation. The steady-state simulation calculates the energy consumption of the room electricity, lighting, heating, cooling, and domestic hot water (DHW). Electricity was used to cover the demand of all the end-uses except for heating, which was covered using natural gas. The activity and occupancy for the energy simulation was modeled using data from Eurostat (European Statistical Office, 2020). Electricity consumption for appliances and lighting was assumed to be equal in each location because of the small differences in the average consumption in the countries under study, according to the latest sectorial profile of the Odissee-Mure project (ODYSSEE-MURE, 2020). Accounting for the different impacts caused by electricity for appliances and lighting is a subject of great interest, yet outside the scope of this study.

## 2.3 Life cycle Assessment

The LCAs were performed following the guidelines described in the ISO 14040:2006 (ISO 14040, 2006) and the EN 15804:2020 (European Committee for Standardization, 2020). The modules considered are A, product phase and construction process, B, use phase, and C, end of life. Considering the modules analyzed, this can be considered a cradle to grave LCA.

### 2.3.1 Functional unit.

The functional unit in an LCA study refers to the element used as the comparative reference. In this case, the functional unit is the entire life cycle of the 100 $m^2$ large dwelling, considering a lifespan of one hundred years.

### 2.3.2 Allocation principle

The allocation principle used in this study is allocation at end-of-life (EoL) according to EN 15804:2020. The methodology was implemented following Baldassarri et al. (2017) and (Lavagna et al., 2018).

### 2.3.3 Life cycle inventory (LCI)

The software used to create the LCI was Simapro v 9.0. Simapro incorporates Ecoinvent V3.5, the most comprehensive database for LCA calculations (Wernet et al., 2016). The impacts generated by each material were adapted to the market in each location by using their country electricity mix. This is a realistic approximation due to the consistency in production technology among European countries. The electricity mix accounts for the different ways to produce energy in each country. Therefore, 1 kWh will have different impacts in each country under study. The electricity mix of each country in the study is described in Table 4.3.

**Table 4.3**
Electricity generation percentage. 2019 statistics. (Eurostat, 2019)("Greenhouse gas emission intensity of electricity generation," 2020)

| | Germany | Slovenia | Spain |
|---|---|---|---|
| Conventional thermal | 56.0 | 30.8 | 42.2 |
| Nuclear | 12.6 | 35.9 | 20.4 |
| Hydro | 3.5 | 31.6 | 13.8 |
| Wind | 19.6 | 0.0 | 19.0 |
| Solar | 8.1 | 1.7 | 4.6 |
| Geothermal & others | 0.1 | 0.0 | 0.0 |
| Kg of $CO_2$ eq. per kWh | 0.406 | 0.248 | 0.276 |

As detailed in previous sections, the processes considered in the LCA are divided into modules, according to the guidelines of the EN 15804 (European Committee for Standardization, 2020) (Figure 4.2).

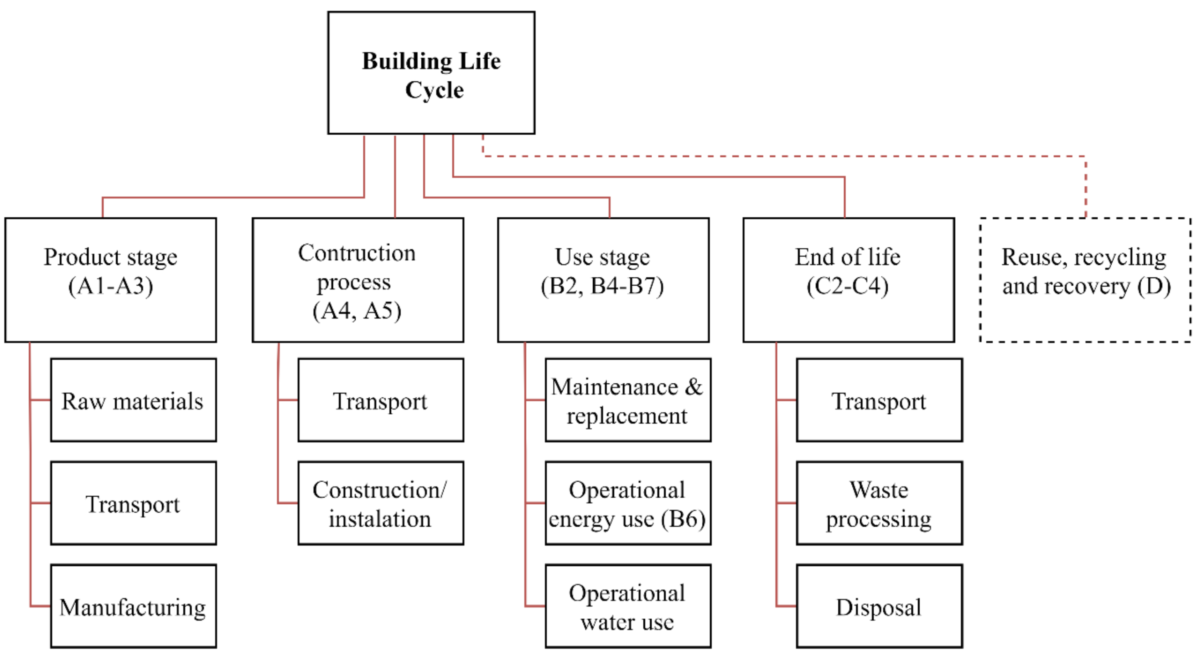



**Figure 4.2.** Building life cycle (with modules A1-D) according to EN15804 (2020), Module D and module B3 (repair) are outside the scope of the study.

Module A: this module contains all materials used for the main building elements (those elements are specified in Tables A1-A9 in Appendix D). Transportation of the materials from the warehouse to the building site were considered to be taken from a 50 kilometer distance. This approximation has been used in several LCA studies (Asdrubali et al., 2013). Other studies also assumed 50 km for massive materials and 100 km for the rest (Lavagna et al., 2018). The materials used for the heating and cooling systems have also been included in the inventory.

Module B: this module comprises the processes that take place during the use phase of the house. In this case, the processes considered are energy consumption and the materials required for maintaining the building. Data on the replacement intervals of building materials was found in literature (Baldassarri et al., 2017): 30 years for mineral insulation, 30 years for internal walls, 30 years for windows and 50 years for finishes. The energy required for heating is assumed to be natural gas. Electricity is used for the rest of the categories. The use of renewable energy sources such as solar panels is neither considered nor modelled in the energy simulation. Modelling how different renewable energy sources might alter the results is beyond the scope of this article. The lifespan of the house is assumed to be 100 years. Although the lifespan of buildings varies significantly, 100 years can be considered a realistic assumption (Lavagna et al., 2018), (Marsh, 2017).

Module C: at end-of-life, incineration is used to model the end of life of the wood used in the house, which is the most common waste management practice for timber products (Hafner et al., 2014). For the other materials, landfilling is selected as the most plausible scenario because approximately 85% the total construction waste is landfilled (UNEP and ISWA, 2015). The distance assumed for transportation to the landfilling and the incineration plant was 50 kilometers (Wilson, 2007).

# 3 Results

## 3.1 Thermal simulation results

Figure 4.3 shows the amount of kWh required each year divided into five categories: room electricity, lighting, heating, cooling, and domestic hot water (DHW). The energy expended to produce heat varies the most, followed by hot water production. Munich and Ljubljana use approximately eight times more energy for heating than Valencia, while Madrid uses only three times more energy for heating; Portorož uses approximately four times more energy for heating than Valencia. The energy used for cooling is significantly higher in Madrid and Valencia – approximately double that of Portorož – while it is negligible for both Ljubljana and Munich. Room electricity and lighting energy demands are constant based on the Odissee-Mure project (ODYSSEE-MURE, 2020). DHW varies slightly due the greater temperature differential between input water and hot water.

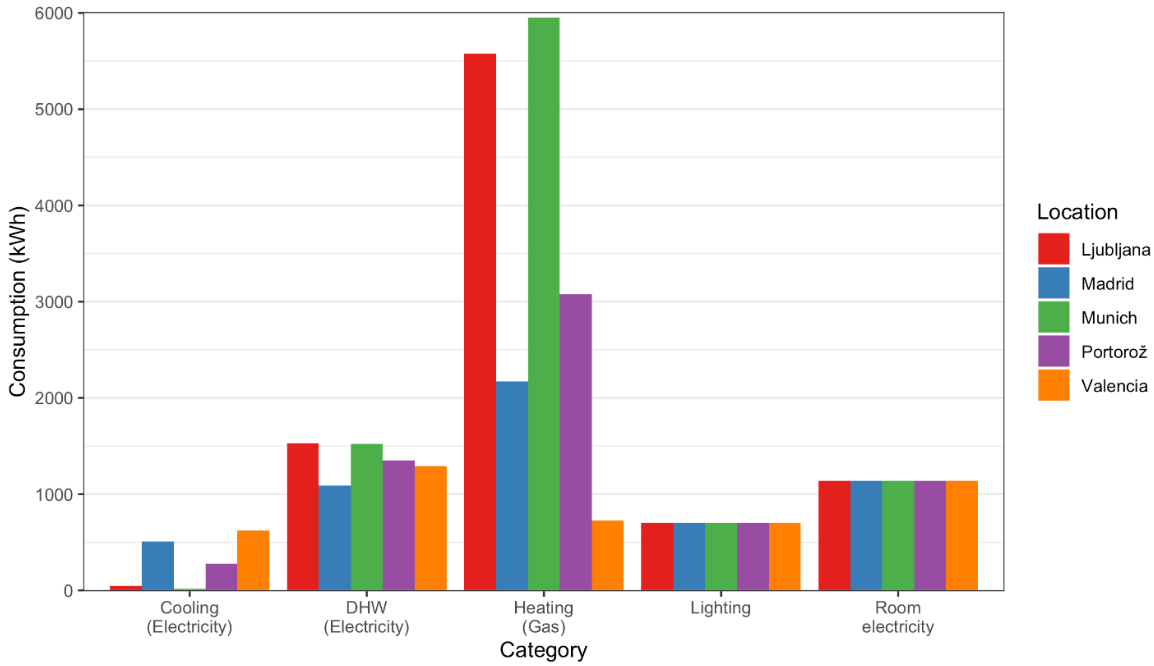



**Figure 4.3.** Energy consumption (kWh) over a one-year period

## 3.2 Impact assessment results

These LCA calculations were carried out using two different highly trusted methods. The first one is the IPCC GWP 100a method. Developed by the Intergovernmental Panel on Climate Change, this method calculated the amount of $CO_2$ equivalent ($CO_2$e) emissions using the 100-year time horizon ("IPCC - Intergovernmental Panel on Climate Change," n.d.). The second method is the Environmental Footprint method (version 2) developed by the Joint Research Centre of the European Commission. This method is recommended to be used in the European Union (European Commission, 2013). Extensive documentation on the Environmental Footprint method as well as its normalization and weighting process of the results was developed (Zampori L and Pant R, 2019).

### 3.2.1 Module differences between locations

The networks representing the contribution of each module to the total carbon emissions in each location are represented in Figures 4.4 to 4.8. The comparison between the carbon emissions is depicted in Figure 4.9. The results show that the house located in Munich generates significantly more $CO_2$e than the rest. It generates 28% more $CO_2$e than the house in Ljubljana despite having a similar energy consumption. The difference between the $CO_2$e emissions in the Spanish and the Slovenian locations is smaller than what the energy consumption might suggest. The fact that the house in Madrid has higher $CO_2$e emissions despite having a lower energy consumption also stands out. This is caused by the different energy sources in each country. The effect of the electricity mix is further discussed in subsequent sections.

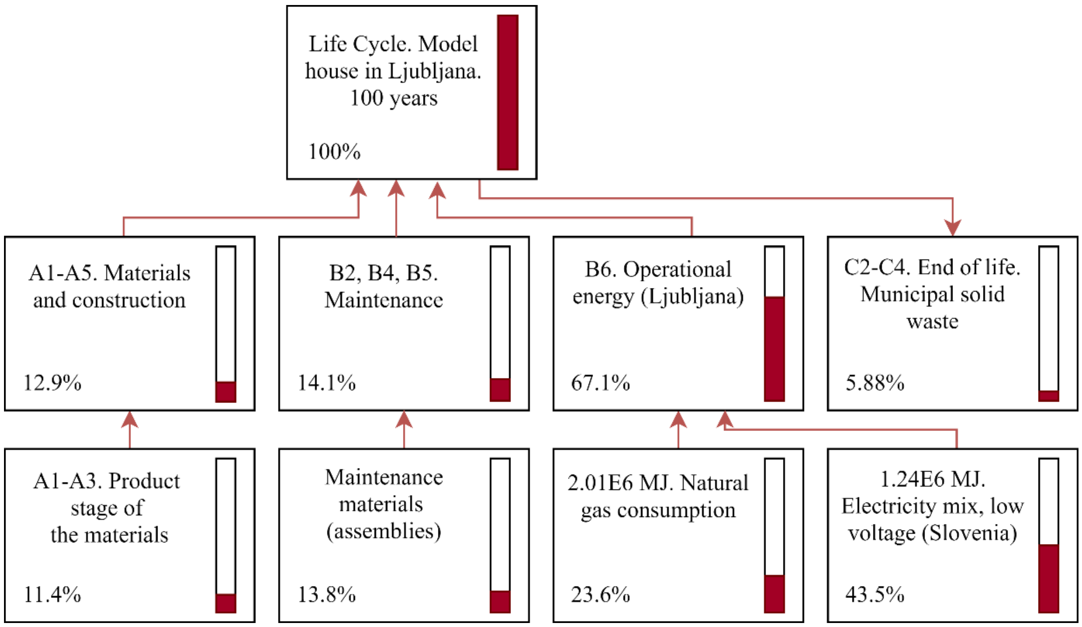



**Figure 4.4.** Contribution of each module to the total carbon emissions in Ljubljana

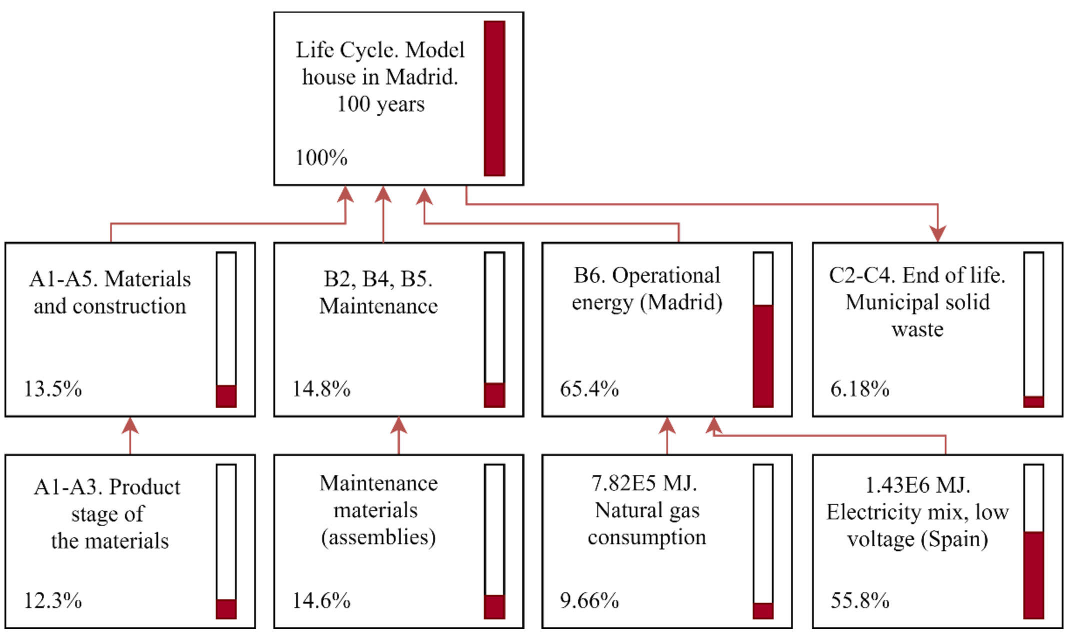



**Figure 4.5.** Contribution of each module to the total carbon emissions in Madrid

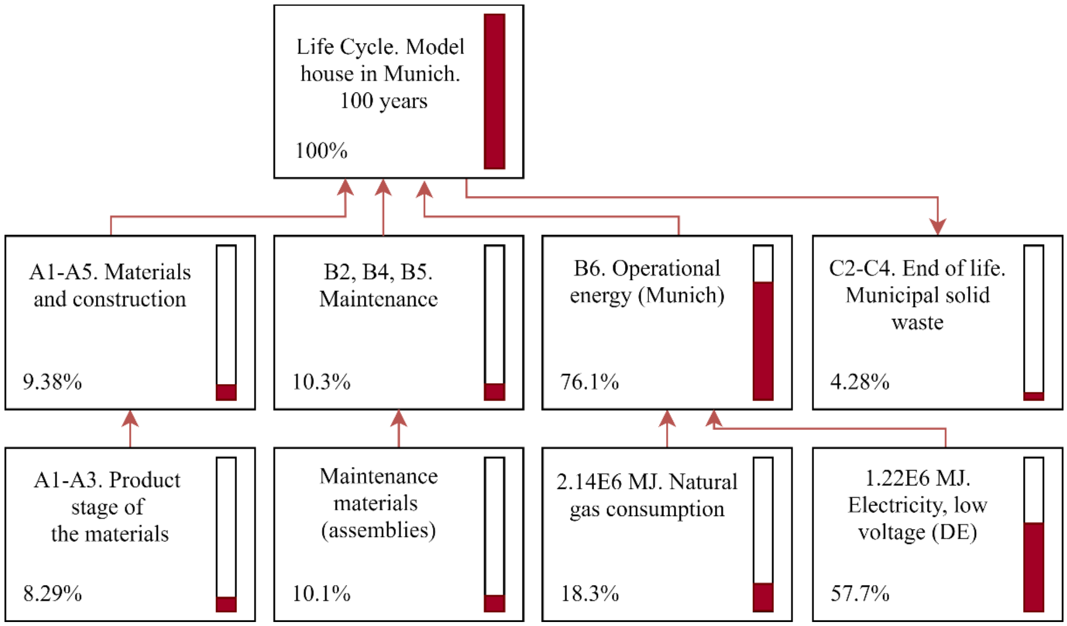



**Figure 4.6.** Contribution of each module to the total carbon emissions in Munich

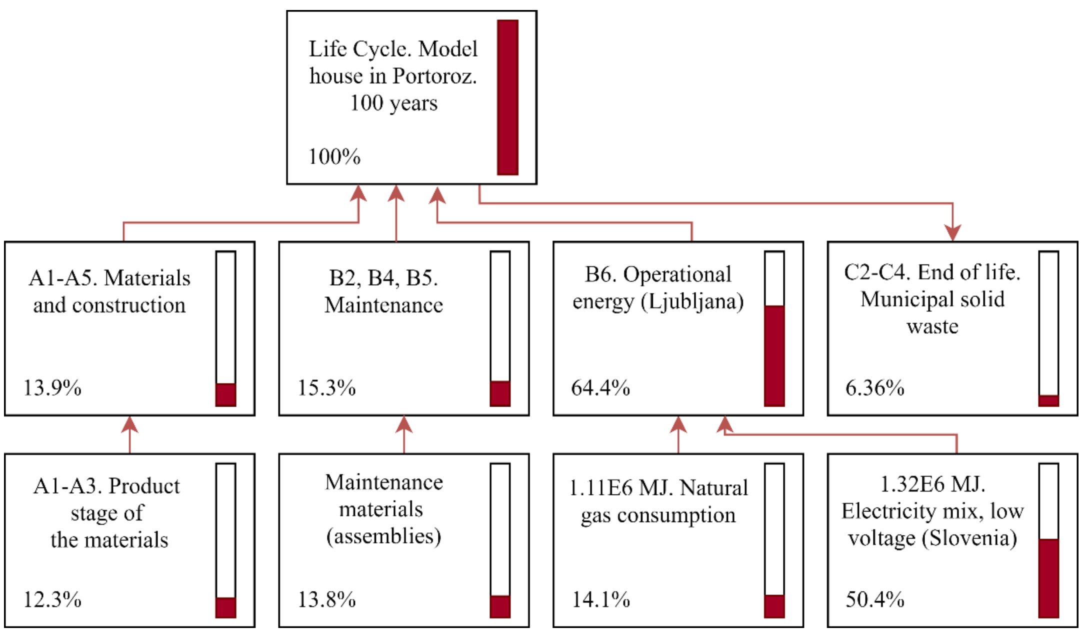



**Figure 4.7.** Contribution of each module to the total carbon emissions in Portorož

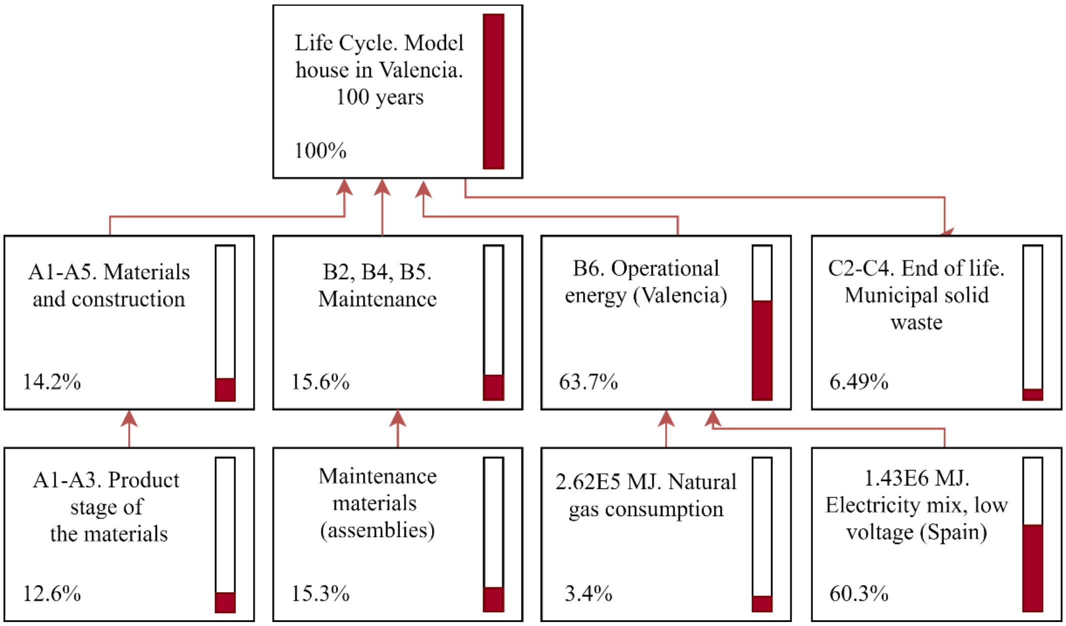



**Figure 4.8.** Contribution of each module to the total carbon emissions in Valencia

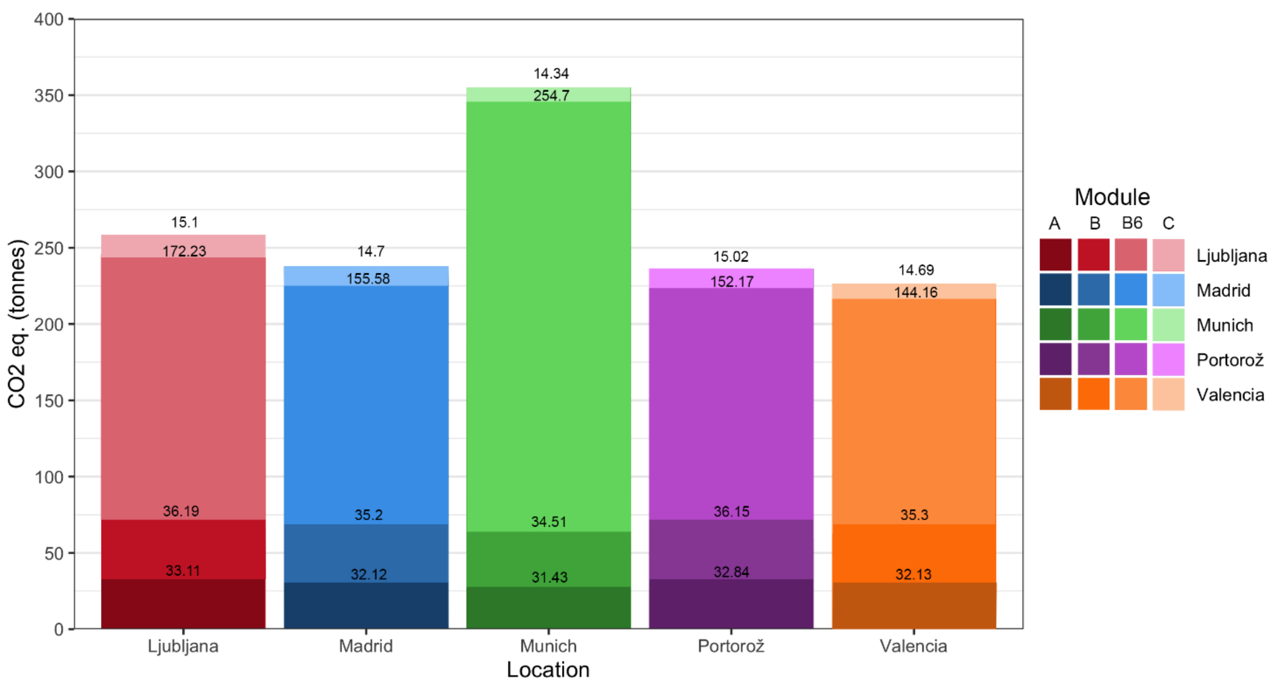



**Figure 4.9.** IPCC GWP method, $CO_2$ eq. emissions

In addition to greenhouse gas emissions, other environmental impacts were evaluated using the Environmental Footprint method. The characterization results are divided into 18 different impact categories. The obtained results show similar tendencies to the previous method in categories like climate change, eutrophication, and acidification (Table 4.4).

In Figure 4.10, the normalized results reveal high impacts related to human health and resource use for energy. After weighting the normalized results, the climate change potential and the use of energy gain importance and reveal Munich as the most impactful location (Figure 4.11). Considering that the results are normalized and weighted, the EF offers the possibility of obtaining a single impact score result by adding up each category (Table 4.5). It should be noted, however, that climate change is highly weighted in the EF method, accounting for 21 % of the total impact (including robustness factor)(Sala et al., 2018). As observed in the IPCC method, the impact score is significantly higher in Munich than in the other cities. In this case, the score obtained in Madrid is lower than the one in Portorož despite its higher climate change potential, due to the influence the other impact categories have.

**Table 4.4**

Environmental Footprint Characterization

| Impact category | Unit | Ljubljana | Madrid | Munich | Portoroz | Valencia |
|---|---|---|---|---|---|---|
| Climate change | t. CO2 eq | 261.79 | 241.72 | 362.26 | 240.50 | 230.63 |
| Climate change - fossil | t. CO2 eq | 260.24 | 239.46 | 358.18 | 239.57 | 228.33 |
| Climate change - biogenic | t. CO2 eq | 0.82 | 0.59 | 3.31 | 0.75 | 0.60 |
| Climate change - land use and transform. | t. CO2 eq | 0.73 | 1.67 | 0.77 | 0.17 | 1.71 |
| Ozone depletion | kg CFC11 eq | 2.33E-02 | 2.55E-02 | 2.31E-02 | 2.11E-02 | 2.43E-02 |
| Ionising radiation, HH | kBq U-235 eq | 2.73E+04 | 3.47E+04 | 1.41E+04 | 2.89E+04 | 3.55E+04 |
| Photochemical ozone formation, HH | kg NMVOC eq | 746.75 | 865.32 | 644.04 | 740.45 | 862.66 |
| Respiratory inorganics | disease inc. | 1.56E-02 | 1.52E-02 | 2.06E-02 | 1.57E-02 | 1.52E-02 |
| Non-cancer human health effects | CTUh | 2.74E-02 | 3.15E-02 | 3.09E-02 | 2.79E-02 | 3.18E-02 |
| Cancer human health effects | CTUh | 4.42E-03 | 4.20E-03 | 4.14E-03 | 4.50E-03 | 4.22E-03 |
| Acidification terrestrial and freshwater | mol H+ eq | 2.74E+03 | 1.84E+03 | 2.05E+03 | 2.86E+03 | 1.86E+03 |
| Eutrophication freshwater | kg P eq | 27.60 | 14.45 | 38.62 | 29.04 | 14.66 |
| Eutrophication marine | kg N eq | 196.56 | 262.82 | 209.72 | 197.81 | 264.67 |
| Eutrophication terrestrial | mol N eq | 3.08E+03 | 3.31E+03 | 6.62E+03 | 3.14E+03 | 3.33E+03 |
| Ecotoxicity freshwater | CTUe | 2.05E+05 | 2.01E+05 | 2.04E+05 | 2.02E+05 | 1.99E+05 |
| Land use | Pt | 1.22E+07 | 1.26E+07 | 1.29E+07 | 1.23E+07 | 1.27E+07 |
| Water scarcity | m3 depriv. | 6.08E+04 | 1.03E+05 | 5.69E+04 | 6.29E+04 | 1.06E+05 |
| Resource use, energy carriers | MJ | 4.37E+06 | 4.31E+06 | 4.78E+06 | 4.16E+06 | 4.17E+06 |
| Resource use, mineral and metals | kg Sb eq | 0.96 | 1.03 | 1.07 | 0.97 | 1.03 |

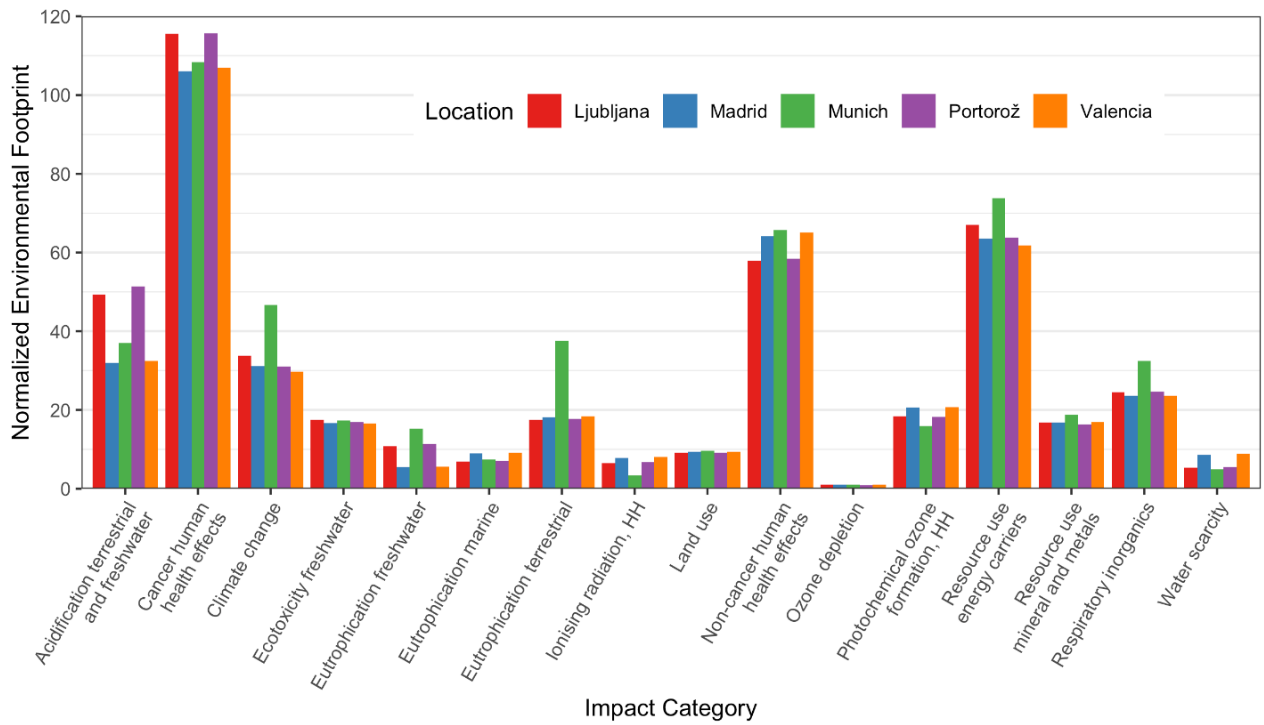



**Figure 4.10.** Environmental Footprint normalization

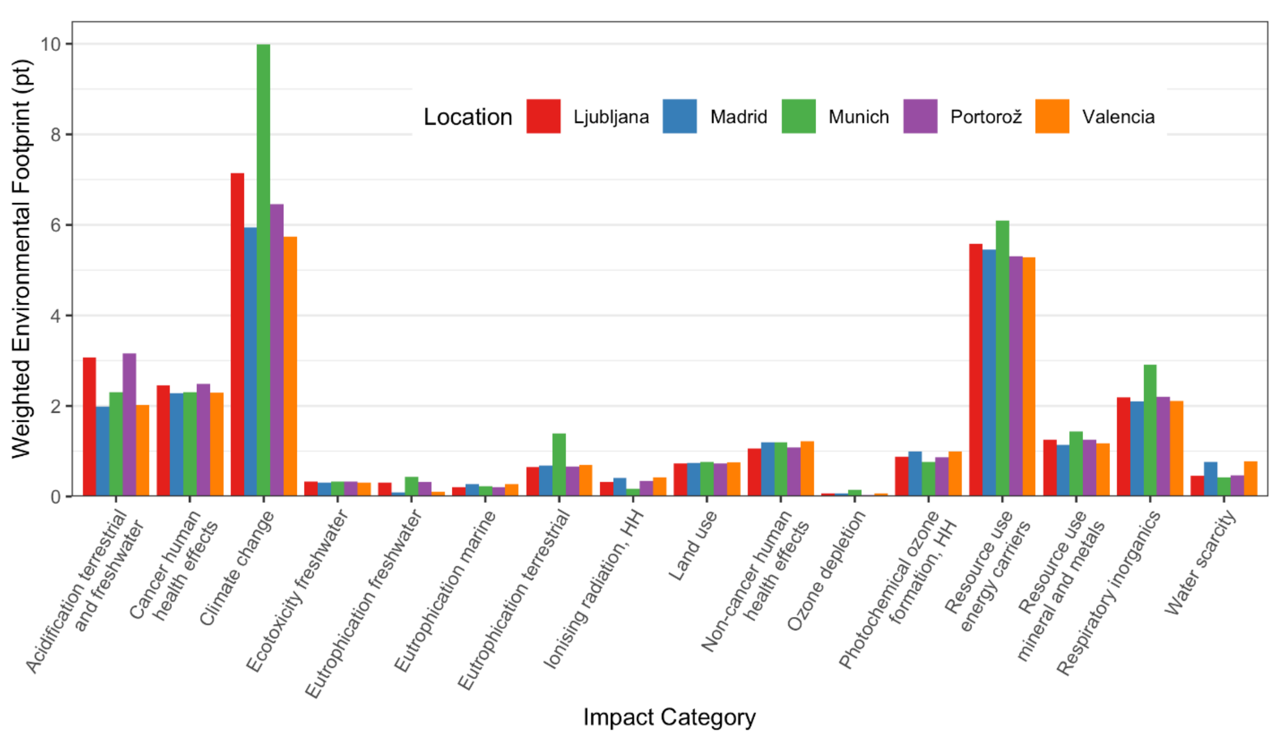



**Figure 4.11.** Environmental Footprint weighting

**Table 4.5**

Summary of the LCA impact results

| Location | Total single EF score (pt) | Total GWP (tonnes of $CO_2e$) | A1-A5 and HVAC. EF single score (pt) | A1-A5 and HVAC. GWP (tonnes of $CO_2e$) |
|---|---|---|---|---|
| Ljubljana | 26.67 | 256.69 | 8.93 | 110.13 |
| Madrid | 24.98 | 237.90 | 8.65 | 89.74 |
| Munich | 30.68 | 355.13 | 9.06 | 113.84 |
| Portorož | 25.97 | 236.30 | 8.37 | 90.70 |
| Valencia | 24.68 | 226.31 | 8.23 | 78.12 |

### 3.2.2 Comparing the A1-A5 and energy consumption for cooling and heating between different cities

The calculations of the house's whole life cycle suggested that the electricity mix of each country plays a big role in the total emissions of the house. As a way of checking if that is the case, the calculations have been performed again, considering only the modules A1-A5 (with the manufacturing of materials, transport, and construction/installation on site) and the energy use for heating (natural gas), ventilation, and air conditioning (HVAC) (part of module B). First, the carbon emissions are assessed again using the IPCC GWP and the EF method. As shown in Table 5, the differences between $CO_2e$ emissions are directly related to the heating consumption in each city. Due to the use of natural gas for heating, the effect of the country's electricity mix is attenuated, only affecting the energy used for cooling. Using the EF method, the single score results follow a similar tendency as the ones obtained using the IPCC GWP except for Madrid and Valencia. In the case of the two Spanish cities, the impacts are higher due to the electricity consumption for cooling and the effect of the electricity mix. The total impact of the building at Portorož is almost the same as in Valencia, despite the significantly lower energy requirement for heating. As it is analyzed in more detail in subsequent sections, these results show that the energy sources have a major influence over the overall environmental impacts.

# 4 Discussion

This study shows how the barriers between regenerative and positive impact buildings change depending on factors linked to location - important aspect of place in the regenerative construction context. As it was expected, due to the high $CO_2e$ emissions associated with energy consumption, the share of impact contributed during each life stage of the house varies depending on the local climate (e.g., warmer in southern places and colder in northern places). However, the electricity use and the associate electricity mix dominate the overall impact. Other factors may overshadow climate conditions in some cases. In Munich, the location with the highest heating demand and corresponding energy use, energy consumption is responsible for 76.1% of the total greenhouse gas emissions over the life cycle. In Valencia, the location with the lowest energy demand, it is responsible for 63.7%. The 12.4-point difference between the two cities, while significant, is small when considering that the annual energy consumption is around 50% higher in Munich. This is caused by the differences in their country electricity mix. Due to the higher $CO_2e$ emissions of the module B6, operational energy use, in colder climates, the percent contribution of module A, product stage and construction process, is lower in locations with higher energy demand. Therefore, module A, with the same materials in an equivalent house, ranges from 9.38% in Munich to 14.2% in Valencia. The same tendency can be observed in module C (use phase) , where it ranges from 4.28% in Munich to 6.49% in Valencia. The percentual contribution to climate change of modules B2, B4, and B5, goes from 10.3% in Munich to 15.6% in Valencia. Despite the use phase contributing more to the total impacts in colder climates, energy consumption still is the main contributor in locations like Valencia. This reinforces the need to use sufficient thermal insulation in warmer climates as well. It is also worth noting that Valencia is the only city where most energy is not used for heating. In this case, around 30% of the energy is used for warming water. Installing a solar DHW system would have a significant effect in reducing the energy consumption depending on the efficiency of the equipment installed, especially in countries with high solar irradiance such as Spain. However, the analysis of the savings generated with renewable sources is outside the scope of this study.

As noted, electricity mix plays an important in the environmental impacts of the use phase. By comparing locations with similar climate conditions with others that have considerably different ones it has been possible to analyze how the energy demand and the sources of energy interlink and affect the overall environmental impacts. For instance, despite the energy consumption in Munich only being around 4% higher than in Ljubljana, the house in Munich generates 28% more $CO_2e$ over its entire life cycle. This can be explained by the different sources of energy each country has. As shown in Table 4.3, Germany generates 56% of its energy in combustion power plants while Slovenia only obtains 30.8% from such plants. Similarly, despite the energy consumption being 10% lower in Madrid, the $CO_2e$ are slightly higher than in Portorož. The fact that 42.2% of the energy in Spain is generated in combustion-based power plants is the most plausible explanation. It also explains why the difference between the emissions in Valencia and the Slovenian locations are not bigger despite the difference in energy consumption. The fact that Slovenia uses a higher percentage of nuclear energy also influences the results beyond carbon emissions. Categories like “Cancer human health effects” and “Acidification terrestrial and freshwater" obtain higher impact scores in both Slovenian locations. It is clear then, that national and regional level decisions about energy sources greatly affect the emissions and the overall environmental impacts generated in buildings. This will be a barrier for regenerative buildings as long as they are dependent on electricity from the grid. Strategies to overcome this barrier are opportunities for significant energy consumption reductions. For example, new policies designed to mitigate climate change should enforce the use of renewable energy sources for electricity production, thereby greening the building life cycle. Increasing the use of renewable energy would likely reduce the $CO_2$e emissions in all locations, and potentially reduce other indicators related to health (e.g., cancer, acidification). Therefore, considering its sizeable effect on the environmental impacts of buildings, the electricity mix can be considered one of the most important barriers towards regenerative architecture. Solution at the building level include, mounting solar panels for heating water (thermal) and producing electricity (photo-voltaic) to make the building more independent from the regional and national electricity mix. Thermal insulation is another key to reducing the energy demand of buildings. Despite the sizeable amount of thermal insulation used in the model house, the energy required for heating and cooling still is quite high. Tackling that problem should be approached both by further increasing the insulation and by optimizing the energy consumption. The results suggest that passive isolation is not enough to design net-positive buildings. Besides increasing passive insulation and using sustainable materials such as wood, it is crucial to install efficient HVAC systems to lower the energy consumption to the minimum. Replacing conventional natural gas-powered heating systems with more efficient technologies such as air to water heat pumps would lead to a reduction in the overall impacts(Bellos and Tzivanidis, 2017) (Slorach and Stamford, 2021). The $CO_2$e emissions of the model house would be minimized in those locations where the electricity mix does not depend on fossil fuels. Moreover, due to the European Green Deal ("The European Green Deal," 2019), HVAC systems powered by electricity will become more sustainable in the future as energy generation transitions towards renewable sources. Despite this clear trend of transitioning towards renewable energy generation in the EU, it will not completely come to fruition until 2050. Energy optimization becomes crucial to overcome the situation. Great opportunities arise from the rapid development of home management systems technologies. Nowadays it is easier and more affordable to install equipment designed for fostering and efficient management of domestic energy consumption. The use of renewable energy generators such as wind turbines or solar panels could be the cornerstone of achieving regenerative sustainability goals, at least while conventional electricity generation relies on fossil fuels and nuclear energy. However, the high cost of these alternatives is an important barrier to entry for much of the population, especially in lower income countries. In the case of air to water heat pumps, despite the decrease in cost over the last decade, the price is still prohibitive for many.

For the end of life, only incineration and landfill were considered. Module D with reuse, recycling, and (energy) recovery is outside the scope, but it is widely recognized that including this module would lower the total carbon footprint and other environmental impacts (Benachio et al., 2020) as the materials from the building could be reused or recycled into new products as well as heat and eventually electricity from incineration could be used to reduce other energy production. This strengthens our arguments that the use phase, and especially the energy use (B6), with its electricity consumption, is crucial for the overall life cycle of the house in different locations and represents a barrier for regenerative sustainability. Nonetheless, construction solutions that provide simple, cost effective, and climate friendly solutions for end-of-life scenarios other than incineration and landfilling offer significant potential in reducing the climate impact of buildings.

One last aspect that is important to bear in mind is climate resiliency. Several studies elaborate on the probable changes that major cities in Europe will undergo in the near future. Their results indicate a foreseeable tendency of cities moving south climate-wise at a rate of 20 km per year (Bastin et al., 2019). Which might lead, for example, to the climate of Munich becoming similar to the current one in Ljubljana and the one in Portorož approaching the Valencian climate (cf., Table 4.1). For that reason, thermal insulation against extremely high temperatures will become crucial for cities such as Madrid and Valencia.

# 5 Conclusions

This study analyzed the existing barriers when designing a sustainable single-family wood house in Europe and how those barriers change depending on the location, giving impact assessment context to the regenerative concept of place. The study used a standard alpine house as the average European single-family house. The house used a wood frame and the building envelope consisted of several layers of gypsum plasterboard and mineral wool and triple glazing windows. The idea behind the study was to compare how the environmental impacts of the house change depending on location. Munich, Ljubljana, Portorož, Madrid, and Valencia were the selected locations for this study. The locations were chosen with the purpose of analyzing the role that the relation between climate and country electricity sources play in the environmental impacts over the life cycle of the building. This was done by comparing locations with similar conditions with others that have considerably different ones. The energy consumption during the use phase was estimated from an energy demand simulation performed using Design Builder. The cradle-tocrave LCA was conducted according to ISO 14040 and including module A-C, but not D, according to EN15804:2020. The Life Cycle Inventory was modeled using Simapro and the Ecoinvent Database. The calculation methods selected were the IPCC GWP 100a method and the Environmental Footprint method.

Several conclusions can be drawn. First, the total environmental impacts between cooler and warmer locations were lower than anticipated. When it comes specifically to carbon emissions, those differences are generally larger. However, the country electricity mix overshadows the effect of the energy demand, which puts the focus on how important is to strive for cleaner sources of energy. This is especially apparent in the case of Ljubljana and Munich, both of which have very different $CO_2$e emissions despite having a similar energy demand. Energy use is the main contributor to climate change in all studied locations with a contribution between 64% to 76%. The electricity mix was identified as a main barrier in lowering the environmental impacts. This indicates significant national and international level changes in energy production may be the most effective solutions to the climate impact of buildings. This is a critical consideration as the ecological transition supported by the European Green deal will not be complete until 2050. Interim solutions, such as passive insulation is crucial to lowering the amount of energy used for HVAC, even in warmer locations such as Valencia. However, passive insulation is likely not enough to provide enough climate mitigation from the building using phase and should be combined with other solutions (e.g., optimized design, Smart Home Management Systems, clean energy generation) to get closer to the regenerative goal. The study also highlights that even in warmer climates such as Valencia where the heating demand is lower, using more efficient HVAC systems would allow for lower carbon emissions. While the use of wood for the frame is a wise choice to lower environmental impacts of buildings (when forests are managed responsibly), using other biobased materials for the rest of the building elements would make a difference in lowering the environmental impact of the house. This study indicates that combining the use of technology and bio-biobased materials will deliver a step towards the regenerative goal.

## 5.1 Further research opportunities

In future studies, the impact of replacing the materials in the building envelope with renewable alternatives will be studied. The materials in the building envelope have an influence that goes beyond the building phase (A module). The materials chosen also to influence the maintenance phase (modules B2, B4 and B5) and module B6 depending on their thermal transmittance. Reuse, recycling, and recovery (Module D) were outside the scope the current study. However, a wooden house has a large potential for material cascading where the materials are reused, recycled, or incinerated for energy recovery. This potential should be further researched to determine optimal end of life strategies for wood-based construction. Further research could focus on this, to understand how the environmental impact of the material of original house could be shared with other subsequent houses or other products made from the (demolished, original) house after its first functional life.

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# Conclusions

This thesis revolves around four different case studies on sustainable building materials and sustainable buildings in general. Conducting this work has allowed me to draw a wide range of conclusions on sustainability and the built environment. Although each chapter contains its own specific set of conclusions, some do not pertain to any chapter in particular, but cover the underlining theme of all of them.

First, it is possible to conclude that Life Cycle Assessment (LCA) can be more than a tool for conducting research. It also has the potential to be a project decision-making tool. LCA can be useful to incorporate sustainability as a factor during the project stage in the same way as the stakeholders make decisions based on aesthetics, thermal insulation, acoustic insulation, or price. Environmental Product Declarations (EPDs) try to be an answer to that need, but they need to be a common practice. Companies do not need to have EPDs of their products. Moreover, most industry professionals and stakeholders, in general, are not always aware of the existence of those kinds of documents. Building regulations need to incorporate the environmental impact of the building as a key element to comply. So far, most environmentally oriented decisions have been taken based on opinions and intuition rather than scientific evidence. The use of tools that objectively measure sustainability allows the establishment of sustainability protocols and increases the overall reliability of sustainability as a science. Building construction consortiums, such as the Valencian Building Institute (FIVE), are working on environmental databases for building products. These databases, which group materials by its purpose on the building , are a viable solution to the problem. Offering a database that includes environmental aspects, similarly to the Catalogue of Building Elements of the Building Technical Code includes acoustic and thermal insulation, would make it easier for the industry professionals to be aware of the actual consequences that each material has on the environment.

Secondly, it has been concluded that it is possible to manufacture bio-based composites that perform similarly to plasterboard while lowering their environmental impacts. The composites studied in chapters one and two are composed of a bio-epoxy matrix and a natural fiber filler. The first study reveals that every combination of natural fiber and bio-epoxy resin lowers the environmental impact of plasterboard. However, the composites have some drawbacks when compared with the most common partition typologies. Besides the lower airborne acoustic insulation, those partitions are also significantly more expensive than those made with plasterboard. New sustainable typologies must be competitive prize-wise to be a feasible alternative in the building market.

It is also demonstrated that agricultural waste can be transformed into high-quality building materials. This has been concluded after studying the LCA and the acoustic, thermal, and hygrothermal performance of façade panels manufactured with the rice straw generated after the harvest in the Albufera paddy fields. The lab measurements and simulations show that the straw panels are a viable alternative to the most common façade solutions. Moreover, the LCA of shows that those façade panels have a positive impact on the environment, as they avoid the emission of up to 52.64 kg of $CO_2e$. As explained in detail in the corresponding chapter, the rice straw generated in the Albufera park is usually treated as waste and either burned or mixed with the soil. These kinds of waste management practices are incredibly detrimental to the environment. Those impacts are avoided by using the rice straw as a raw material for building products. Rice straw is only one example of the many opportunities agricultural waste brings.

Using locally generated agricultural waste to build houses brings many benefits to communities. On the one hand, it avoids the detrimental effects of the management practices, and on the other hand, it serves as a way of generating a sense of belonging for the inhabitants. Houses built using local products can even be a trademark of a town or a city. It could even help to raise awareness about the issues that affect local producers. It is common for farmers to burn straw or other agricultural byproducts. Those practices emit carbon into the atmosphere and pollute the air. Using it would both avoid the impacts related to burning and the impact of manufacturing the conventional building materials. This idea could also be extended to other local materials besides agricultural waste. One interesting example of this is *Posidonia oceánica*. This Mediterranean seaweed is essential for the marine ecosystem of the area. However, when it dies it ends up on the beach sand. Currently, Posidonia ends up being landfilled. If manufacturers found a way of taking advantage, it would be possible to eliminate the impacts associated with it.

Last, it is possible to conclude that conventional sustainability measures cannot reduce the environmental impacts of a single-family house enough to be called a Nearly Zero Emissions Building (NZEB). Despite highly insulating the building and using wood instead of concrete, the environmental impact results for each location are significant. That leads to the conclusion that it is necessary to take more aggressive measures to reach not a point where buildings do not impact the environment, but a point where they contribute to the wellbeing of ecosystems. While wood is probably the sustainable building material of the future, it is necessary to combine it with other sustainable materials. Also, new and efficient Heating, Cooling, and Ventilation Systems (HVAC) need to be connected to Home Energy Management Systems (HEMS). HEMS can automatize domestic devices to avoid spending unnecessary energy. That would lead to a maximum amount of energy generation with minimum consumption. Besides HEMS, buildings should incorporate renewable energy generators such as solar panels or domestic wind turbines. The results show that the use phase is the most significant one in terms of environmental impacts. In cities such as Munich, the operational phase represents around 76% the carbon emissions of the whole life cycle of a house. However, the enormous scale of the environmental impacts generated during the use phase should not distract from the ones generated during the building phase materials. As explained in chapter four, building materials represent one-third of the waste generated in the European Union. It is crucial to find ways of reusing and recycling materials to avoid the undesirable outcomes of excessive landfilling. Moreover, building materials end up having a substantial influence over the use phase. For example, the materials chosen for the building envelope will determine the energy losses and therefore change the amount of energy consumed for heating and cooling.

The building industry must therefore strive for an ecological transition. That idea comprises using bio-based materials, transitioning towards circularity, increasing the passive insulation, using more efficient HVAC systems, optimizing energy consumption, and using renewable energy. As if was explained in a previous paragraph, this must be done with the regenerative paradigm in mind. Another idea to bear in mind is the concept of Glocal Architecture. In a moment when the world is more homogenized than ever, glocality means going back to the roots and tackling local issues while bearing in mind the problems that affect everybody on a glocal scale. That would mean adapting constructions to the local reality and taking advantage of proximity resources, even when those resources are considered waste. It is crucial to promote a kind of architecture that is engaged with its surroundings, that is an answer to the real needs of the dwellers and the environment, not a mere consumer product nor a piece of art. By following those ideas, it is possible to reach a point of symbiosis between the ecosystems and the built environment.

## Main contributions

Each one of the chapters of this thesis has at least one small contribution to the field of sustainable building construction. The first article deals with the development of several new bio-epoxy composite boards with natural fibers designed to replace gypsum plasterboard. The article shows that every bio-composite used has a lower impact over the environment than gypsum plasterboard. The second article demonstrates that it is feasible to use the bio-based composites of the first study to build partitions that lower the impact of gypsum plasterboard and that also maintain an acceptable airborne acoustic insulation. The contribution of the third article, is analyzing for the first time the life cycle assessment of rice straw produced in Valencia. This serves as a way of highlighting the importance of using rice straw as a raw material for manufacturing local products. In the case of the fourth article, the main contribution is proving the need of taking more aggressive measures to successfully build regenerative buildings. Overall, this thesis further emphasizes the necessity to take aggressive measures towards sustainable construction and that those measures must be supported with the Life Cycle Assessment methodology.

## Limitations

There are some limitations to this study that are worth discussing. In the case of the LCA methodology, the main limitation is the lack of available data sourced directly from local producers in chapters one and two. Some pieces of data used to elaborate the life cycle inventory come from the Ecoinvent database, which is the most reputable database for Life Cycle Assessment calculations. In chapter one, the acoustic performance of the composites is not evaluated nor discussed. The reason for this is that the airborne acoustic insulation of individual elements in a partition is not relevant to the overall acoustic performance of the construction. Another limitation is the lack of experimental work regarding the determination of the airborne acoustic insulation of the bio-based composite partitions in chapter two. Also, the hygrothermal study conducted in chapter three is static and does not contemplate transient conditions.

## Future lines of research

After the completion of this thesis, there are several lines of study to pursue. One of the most interesting ones is the definition and characterization of Glocal architecture as a paradigm for regenerative sustainable housing. First it would be interesting to frame the concept and define its boundaries. Answering questions such as, when is a material Glocal? Also, looking for new potential materials that comply with the definition of glocal would enrich the study. The main focus would be to find and analyze new kinds of agricultural waste that are susceptible of being transformed into building materials. Additionally,

# Appendices

# Appendix A. Acoustic and thermal insulation measurement process

**Figure A1.** Straw panels


**Figure A3.** Moving the panels

**Figure A3.** Setting the panels

**Figure A4.** Rendering the walls

**Figure A5.** Rotating microphone inner side

**Figure A6.** Rotating microphone outer side

**Figure A7.** Rotating microphone and sound source

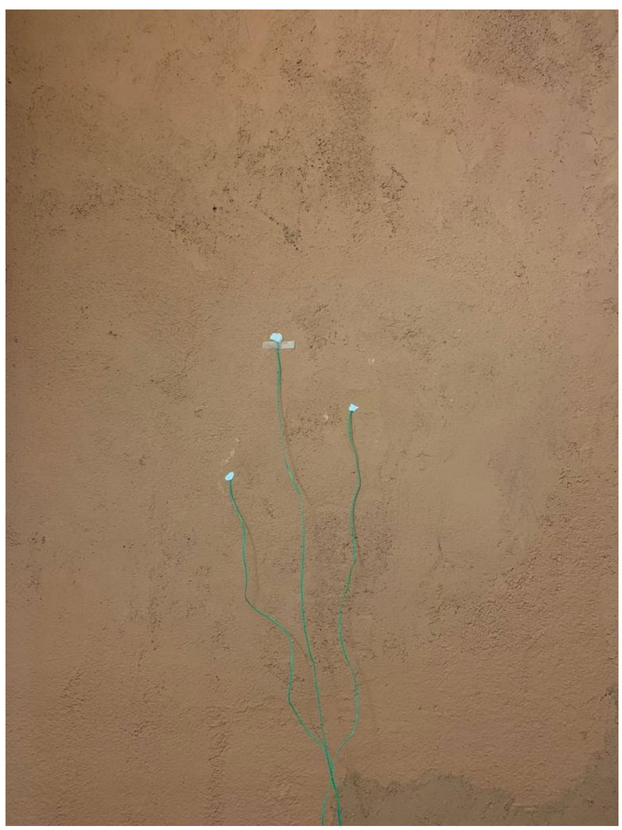

**Figure A8.** Testo sensors inner side

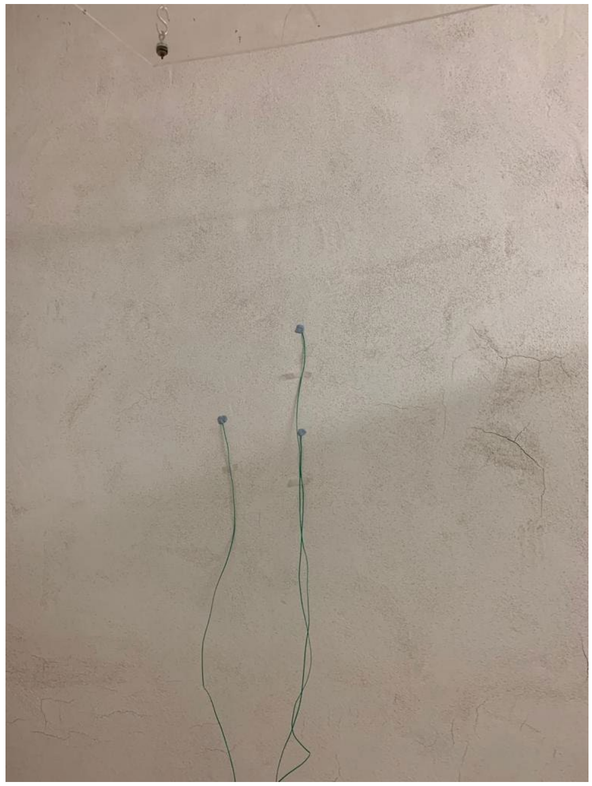

**Figure A9.** Testo sensors outer side

**Figure A10.** Measurement process

# Appendix B. Acoustic measurements

**Table B1**
Rice straw acoustic measurements

| Función LLeq | L1-LLeq Position | | | L2-LLeq Position | | | B2-LLeq | T2-Reverberation time Position | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency Hz | Average dB | 1 dB | 2 dB | Average dB | 1 dB | 2 dB | dB | Prom. s | 1 s | 2 s | 3 s | 4 s |
| 100 | 98.7 | 99.7 | 97.4 | 74.1 | 74.6 | 73.4 | 35.9 | 7.61 | 6.89 | 7.11 | 8.56 | 7.86 |
| 125 | 100 | 100 | 100 | 79.6 | 80.8 | 77.8 | 24.7 | 7.78 | 5.99 | 5.41 | 8.97 | 10.76 |
| 160 | 100.7 | 98.6 | 102.1 | 78.6 | 75.6 | 80.3 | 24.2 | 5.96 | 5.13 | 5.03 | 7.65 | 6.01 |
| 200 | 99.6 | 100.4 | 98.7 | 79.2 | 79.6 | 78.7 | 28.8 | 5.19 | 4.61 | 4.46 | 6.25 | 5.45 |
| 250 | 100.7 | 100.2 | 101.1 | 77 | 76.9 | 77.1 | 23.9 | 5.07 | 5.21 | 5.23 | 5.06 | 4.79 |
| 315 | 100.3 | 100.1 | 100.5 | 71.5 | 70.6 | 72.2 | 27.5 | 5.23 | 5.2 | 5.28 | 5.27 | 5.17 |
| 400 | 100.3 | 100.7 | 99.8 | 64.7 | 65.2 | 64.2 | 24.5 | 4.73 | 5.5 | 4.78 | 4.46 | 4.18 |
| 500 | 101.5 | 101.4 | 101.6 | 60.7 | 60.4 | 60.9 | 16.9 | 4.05 | 4.78 | 4.84 | 3.44 | 3.14 |
| 630 | 101.6 | 101.7 | 101.5 | 57.3 | 57.2 | 57.4 | 14 | 3.73 | 4.48 | 4.45 | 2.96 | 3.01 |
| 800 | 100.1 | 100 | 100.2 | 54.2 | 54.1 | 54.2 | 12.7 | 3.38 | 3.81 | 3.94 | 2.83 | 2.93 |
| 1k | 97.3 | 97.3 | 97.4 | 47.7 | 47.6 | 47.8 | 10.7 | 3.19 | 3.79 | 3.63 | 2.63 | 2.7 |
| 1.25k | 93.6 | 93.6 | 93.7 | 39.3 | 39.3 | 39.3 | 8.5 | 3.06 | 3.54 | 3.74 | 2.59 | 2.36 |
| 1.6k | 93.8 | 93.8 | 93.8 | 35.6 | 35.1 | 36 | 11.7 | 2.96 | 3.51 | 3.45 | 2.5 | 2.38 |
| 2k | 92.5 | 92.5 | 92.5 | 31.2 | 31.1 | 31.2 | 10.1 | 2.58 | 3.15 | 2.95 | 2.06 | 2.17 |
| 2.5k | 87.5 | 87.6 | 87.5 | 23.1 | 23.2 | 22.9 | 9.9 | 2.35 | 2.73 | 2.82 | 1.96 | 1.89 |
| 3.15k | 84.4 | 84.5 | 84.4 | 15.9 | 16 | 15.8 | 10.9 | 2.02 | 2.34 | 2.35 | 1.69 | 1.71 |
| 4k | 79.8 | 79.9 | 79.7 | 11.2 | 11.4 | 11 | 11.3 | 1.75 | 2.05 | 2.08 | 1.45 | 1.43 |
| 5k | 74.8 | 74.8 | 74.7 | 9 | 8 | 10 | 13.4 | 1.53 | 1.77 | 1.82 | 1.24 | 1.27 |

## Appendix C. U-value and interstitial condensation

Available at:

https://ars.els-cdn.com/content/image/1-s2.0-S0959652621027177-mmc3.xlsx

# Appendix D. Building plans and construction details

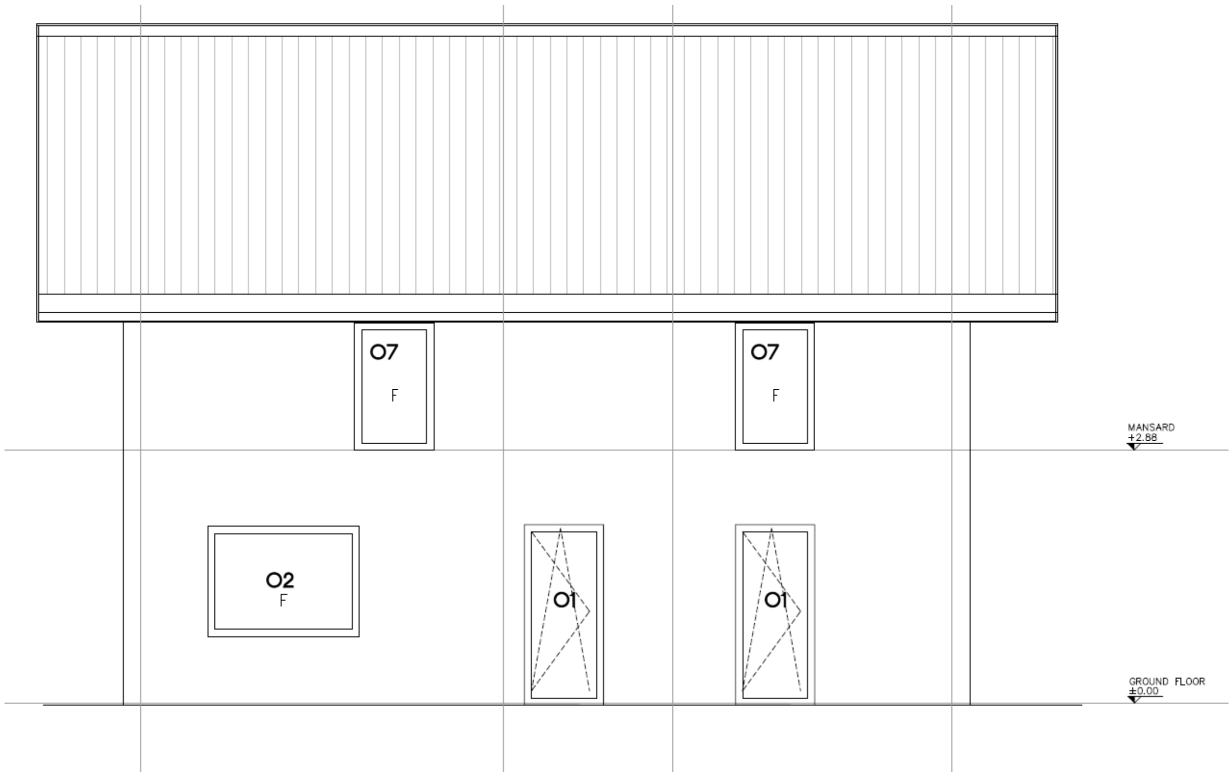


**Figure D1.** Façade South

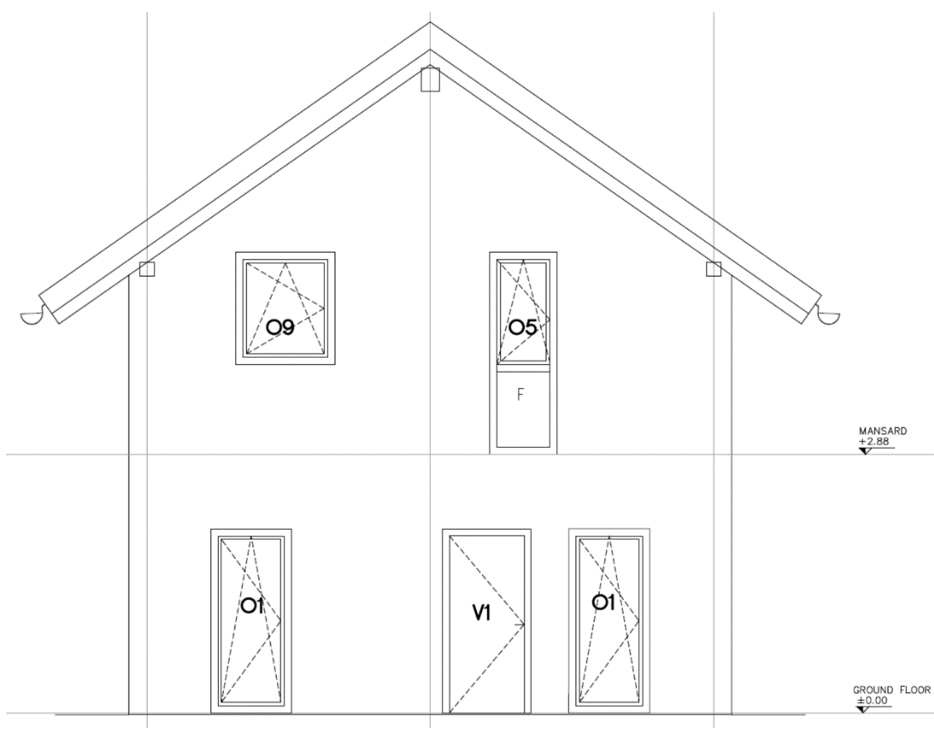


**Figure D2.** Façade East

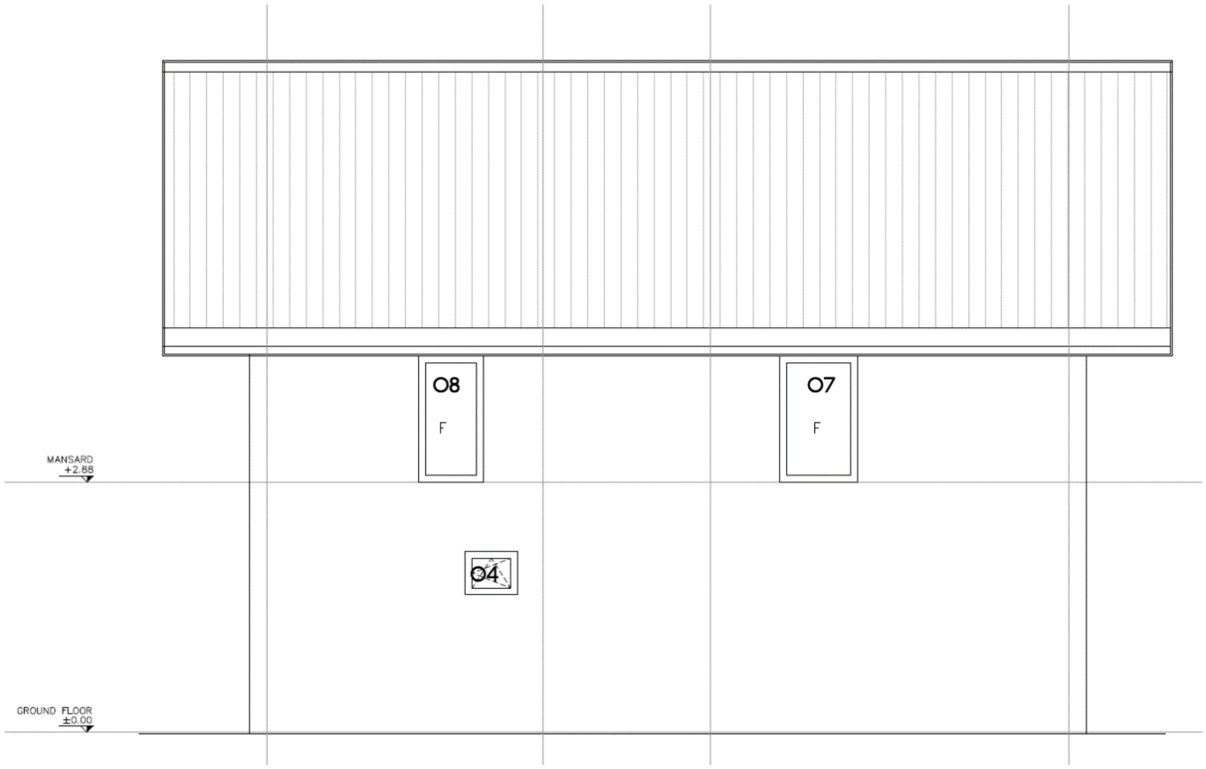


**Figure D3.** Façade North

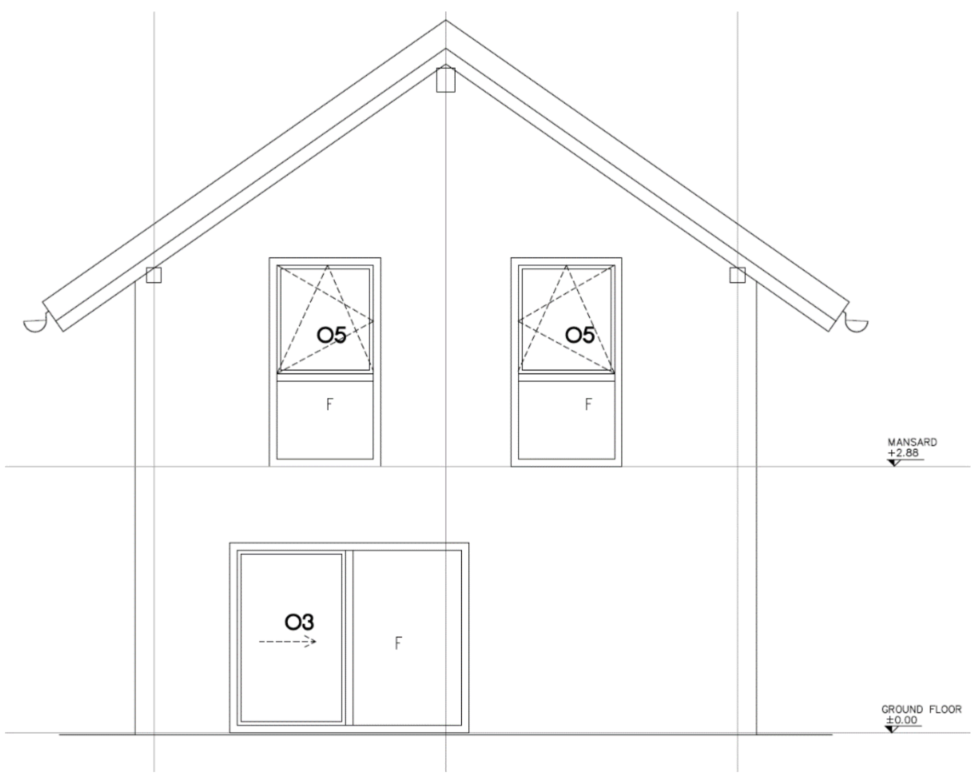


**Figure D4.** Façade West

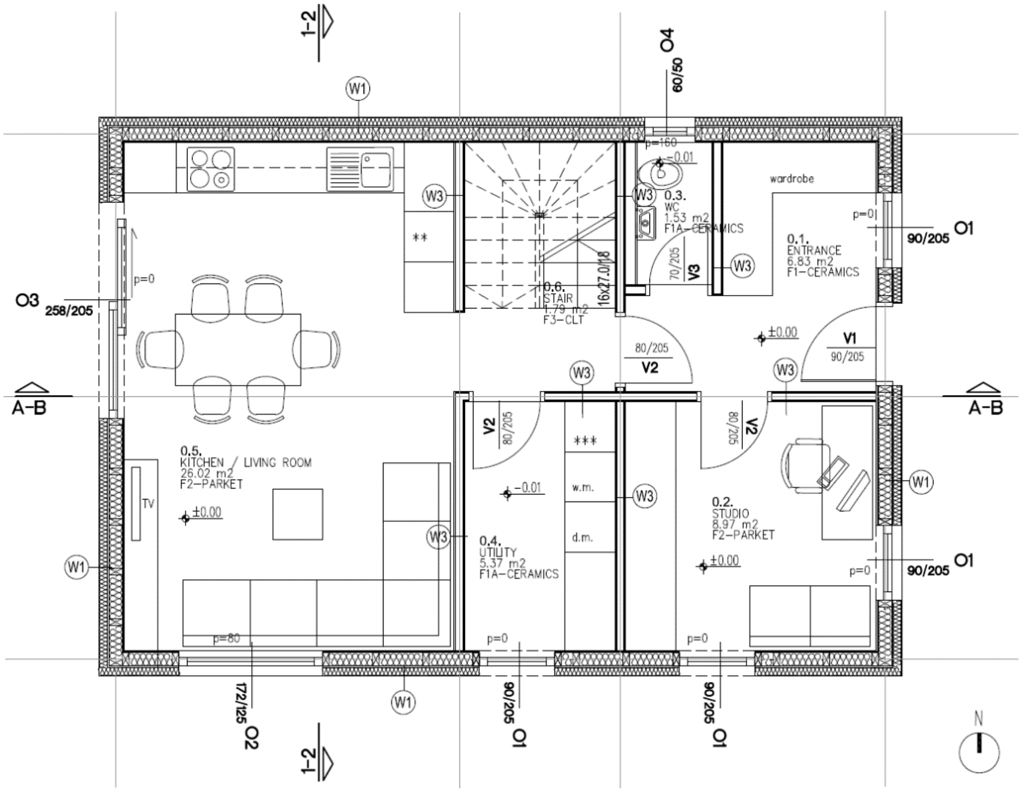


**Figure D5.** Ground floor

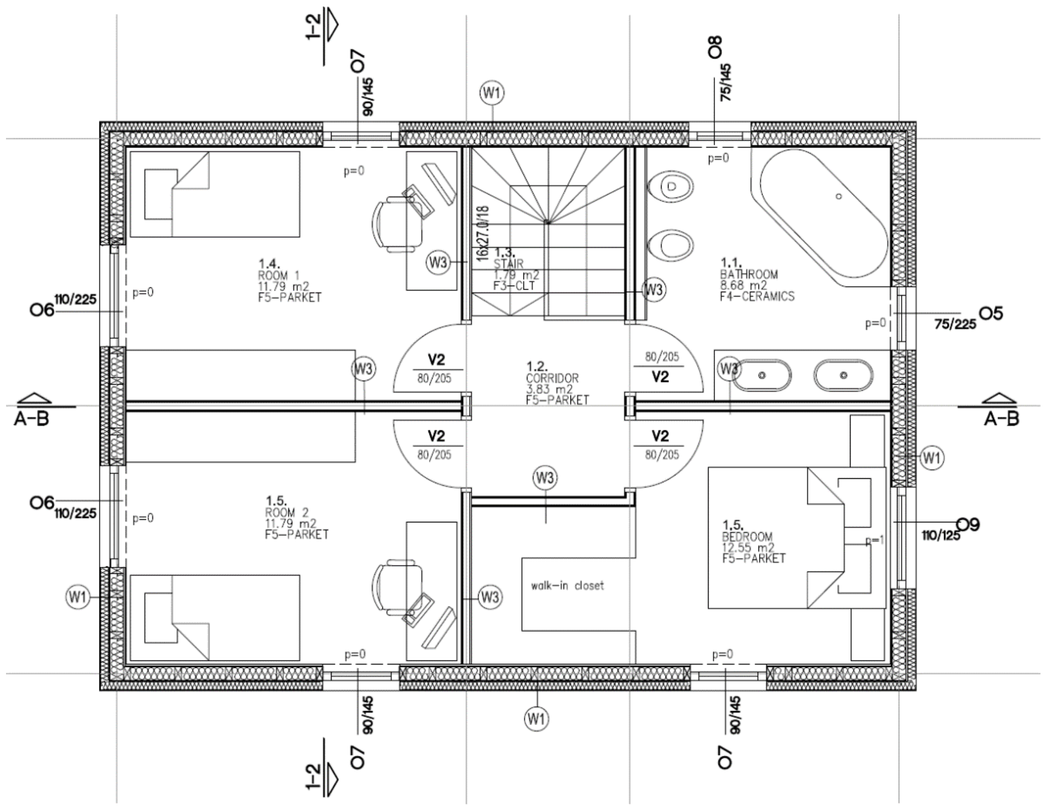


**Figure D6.** First floor

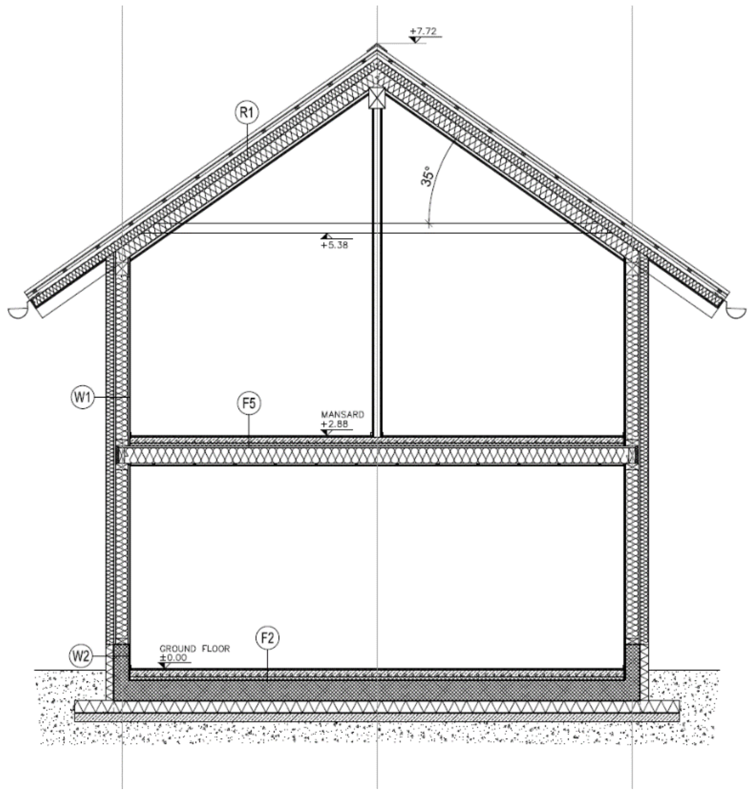


**Figure D7.** Section 1-2

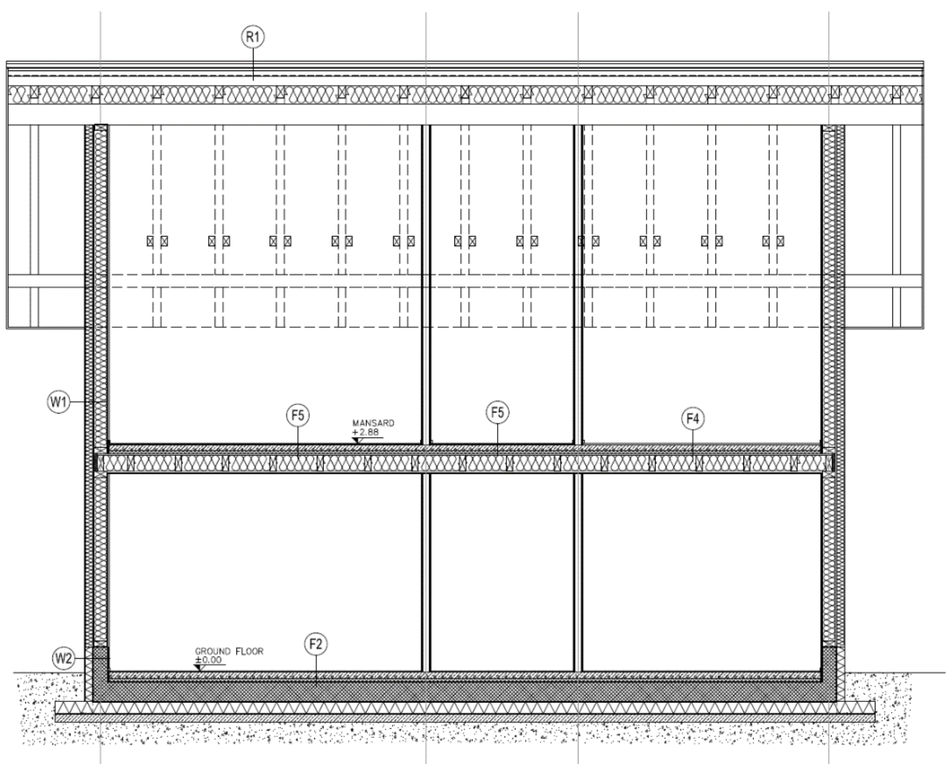


**Figure D8.** Section A-B

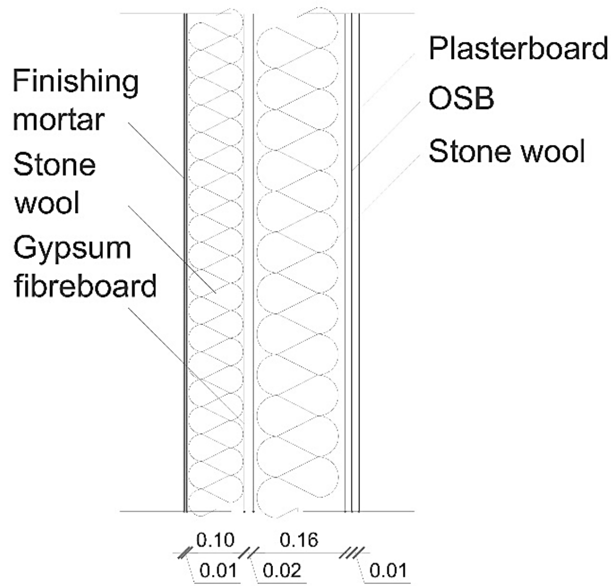


**Figure D9.** Section of the exterior walls (W1)

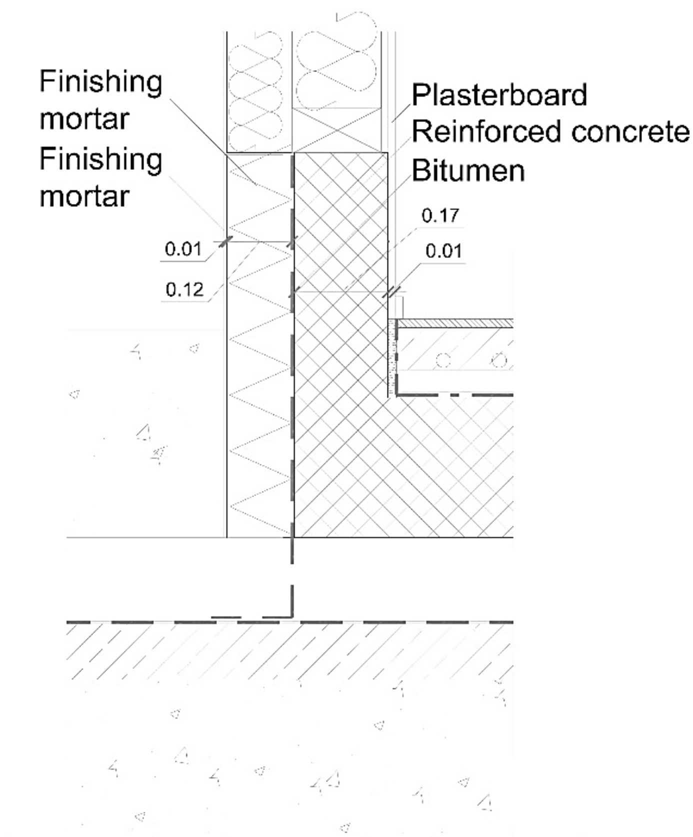


**Figure D10.** Section of the exterior wall ground floor bottom (W2)

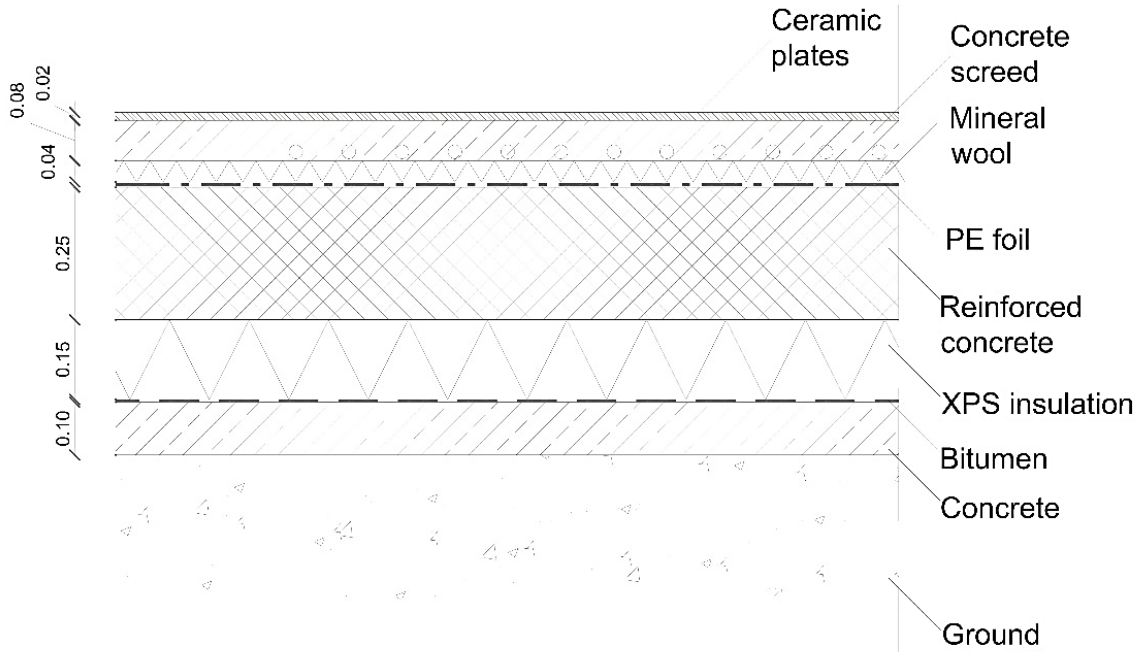


**Figure D11.** Section of the ground floor

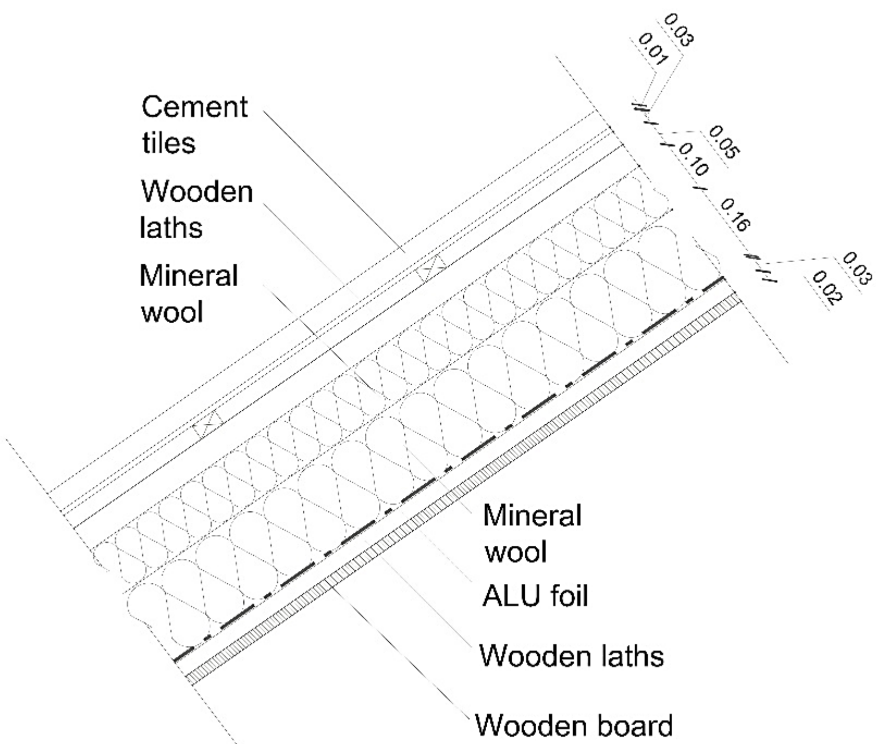


**Figure D12.** Section of the roof (R1)

**Table D1**

W1. Exterior walls U = 0,146 W/m²K

| Material | thickness (cm) |
|---|---|
| Gypsum plasterboard | 1.25 |
| OSB plate | 1.2 |
| Stone wool between the load bearing construction profiles | 16 |
| Gypsum fiberboard | 1.5 |
| Stone wool | 10 |
| Reinforcing mortar, mesh and finishing plaster | 0.6 |

**Table D2**

W2. Exterior wall ground floor bottom U = 0,262 W/m²K

| Material | thickness (cm) |
|---|---|
| Gypsum plasterboard | 1.25 |
| Reinforced concrete | 16 |
| Hydro isolation: polymer-bitumen | 0.4 |
| XPS insulation | 12 |
| Reinforcing mortar, mesh and finishing plaster | 0.6 |

**Table D3**

W3 inner walls

| Material | thickness (cm) |
|---|---|
| 2 x Gypsum plasterboard | 2 x 1.25 |
| Mineral wool | 7.5 |
| 2 x Gypsum plasterboard | 2 x 1.25 |

**Table D4**

R1 roof U = 0,132 W/m²K

| Material | thickness (cm) |
|---|---|
| wooden boards | 2 |
| wooden laths | 3 |
| Reinforced ALU foil | 0.2 |
| Mineral wool between the load bearing construction profiles | 16 |
| Mineral wool between the load bearing construction profiles | 10 |
| Wooden laths | 5 |
| wooden laths in opposite direction | 3 |
| Cement roof tiles | 0.5 |

**Table D5**

| F1 ground floor-ceramics | U = 0,175 W/m²K |
|---|---|
| Material | thickness (cm) |
| Ceramic plates | 1 |
| Glue for ceramic plates | 0.5 |
| Concrete screed | 7.6 |
| PE foil | 0.02 |
| Mineral wool | 4 |
| Reinforced concrete | 25 |
| XPS insulation | 15 |
| Hydro isolation: bitumen | 0.4 |
| bottom concrete | 10 |

**Table D6**

| F1/A ground floor-ceramics in bathrooms | U = 0,186 W/m²K |
|---|---|
| Material | thickness (cm) |
| Ceramic plates | 1 |
| Glue for ceramic plates | 0.5 |
| Concrete screed | 7.6 |
| PE foil | 0.02 |
| Mineral wool | 3 |
| Reinforced concrete | 25 |
| XPS insulation | 15 |
| Hydro isolation: bitumen | 0.4 |

**Table D7**

| F2 ground floor parquet | U = 0,174 W/m²K |
|---|---|
| Material | thickness (cm) |
| Parquet | 1.1 |
| Glue | 0.3 |
| Concrete screed | 7.6 |
| PE foil | 0.02 |
| Mineral wool | 4 |
| Reinforced concrete | 25 |
| XPS insulation | 15 |
| Hydro isolation: bitumen | 0.4 |
| bottom concrete | 10 |

**Table D8**

F4 1st floor ceramics

| Material | thickness (cm) |
|---|---|
| Ceramic plates | 1 |
| Glue for ceramic plates | 0.5 |
| Concrete screed | 7.6 |
| PE foil | 0.02 |
| Mineral wool | 3 |
| OSB plates | 1.5 |
| stone wool between the load bearing construction profiles | 20 |
| wooden laths | 2 |
| Gypsum plasterboard | 1.25 |

**Table D9**

F4 1st floor parquet

| Material | thickness (cm) |
|---|---|
| Parquet | 1.1 |
| Glue | 0.3 |
| Concrete screed | 7.6 |
| PE foil | 0.02 |
| Mineral wool | 4 |
| OSB plates | 1.5 |
| stone wool between the load bearing construction profiles | 20 |
| wooden laths | 2 |
| Gypsum plasterboard | 1.25 |