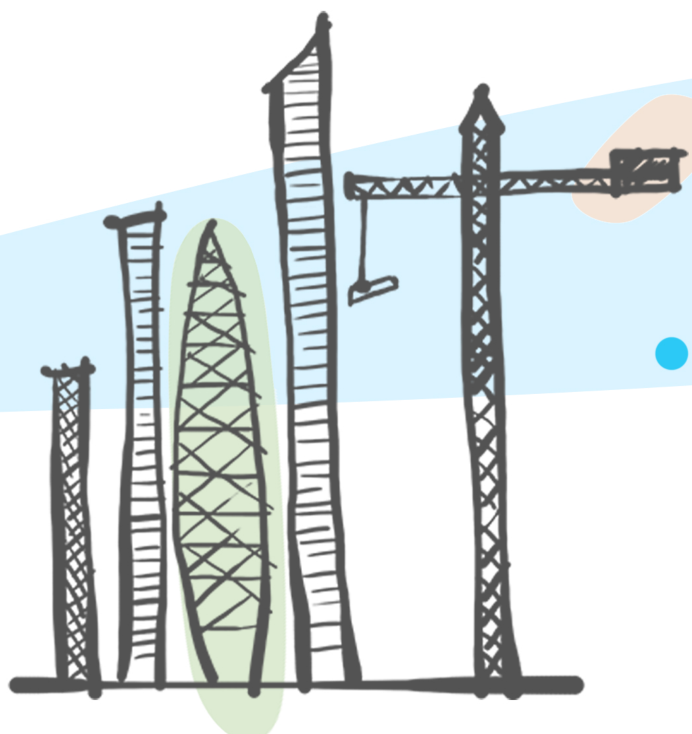
Redesign of a Facade System Based on an Environmental Impact Assessment Framework



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Redesign of a Facade System Based on an Environmental Impact Assessment Framework
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Abstract

The building industry is responsible for 36% of global final energy use (Global Alliance for Building and Construction, 2018), 39% of CO_2 Emissions (Global Alliance for Building and Construction, 2017) and 50% of global waste in just cities (Ellen Macarthur Foundation, 2017). This is mainly due to the linear economy model which is still the dominant model nowadays. This model has been proven to be unsustainable, and it has put an enormous stress in the environment. For this reason, different approaches need to be integrated into the building industry. Designing with the aid of an environmental impact assessment framework is one approach to consider the degradation to the environment, product of a building design. By quantifying the amount of embodied energy and carbon footprint related to a desired acoustic and thermal insulation in a building, designers and engineers can take eco-informed decisions, which not only bring ecological benefits, but also material savings.

The focus of this thesis is on the facade level, which belongs to the "skin" of the building according to Brand (1994). According to Brand's model this layer has an average lifespan of 20 years, meaning that a different approach on the facade level is required in order to reduce the environmental impact during its technical life-span, which is the end goal of the thesis. In order to reach the aforementioned objective, this thesis explores the relevant literature around facades, materials and the environment. Additionally, the relationship between the environment and the built environment is explored, as well as the building industry in the Netherlands with the aim of identifying the most used facade systems. Further study is conveyed for the development of a comparison and selection tool to identify the potentials and weaknesses of the different systems in order to design an environmentally friendly facade.

Keywords

facades - facade systems - framework - materials - environment - environmental impact - sustainability - embodied energy - carbon footprint - acoustic insulation - thermal insulation - u-value - durability

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I also want to give special thanks to Dr.ir. MJ Tenpierik, who helped me in different occasions to deal with the acoustic parameters of the assessment tool, and to help me understand some thermal considerations to take when optimizing a facade. Even though he is not one of my mentors, he supported me whenever I needed his help.

I would also like to thank my parents, my brother and my sister, as well as my friends for believing in me and supporting me at all times. The interest they showed in my work inspired me to push forward my research.

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1) Introduction

1.1 Background

The industrial revolution laid the foundation for how the economy of today operates (Ellen MacArthur Foundation, 2017). This was the first time in history in which products and goods were mass produced. Since raw materials and energy was viewed as infinite and always available a linear economic model was established, as illustrated in figure 1.1. This is still the way in which the economy operates today in the 21st century. This linear economy is based on a take-make-dispose approach in which the raw materials are first extracted from the ground, then products are made with this materials for any intended use, and finally once the products reach their end of service they are disposed as waste.

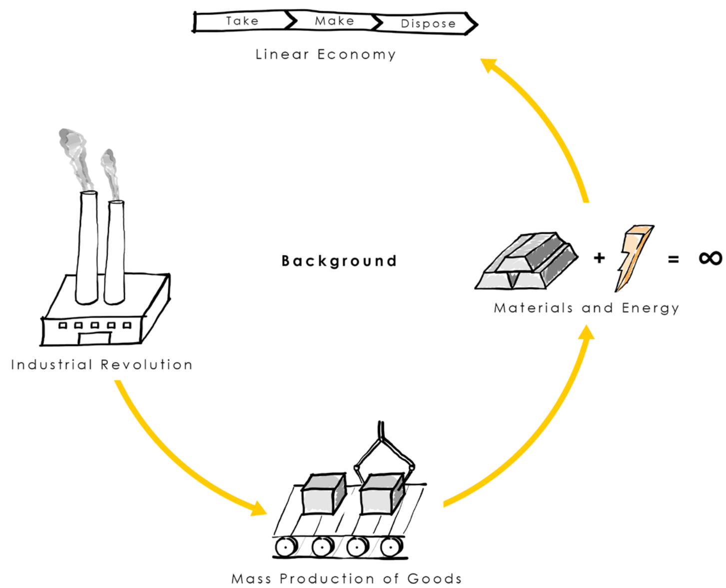


Figure 1.1 Background Scheme

In the building industry this model has prove to be unsustainable, since it is responsible for many forms of environmental degradation and placing many of earth's resources at risk (Allen & Iano, 2019). More specifically the building construction sector accounts for 36% of global final energy use (Global Alliance for Building and Construction, 2018), 39% of CO2 Emissions (Global Alliance for Building and Construction, 2017) and 50% of global waste in just cities (Ellen Macarthur Foundation, 2017), as illustrated in figure 1.2.

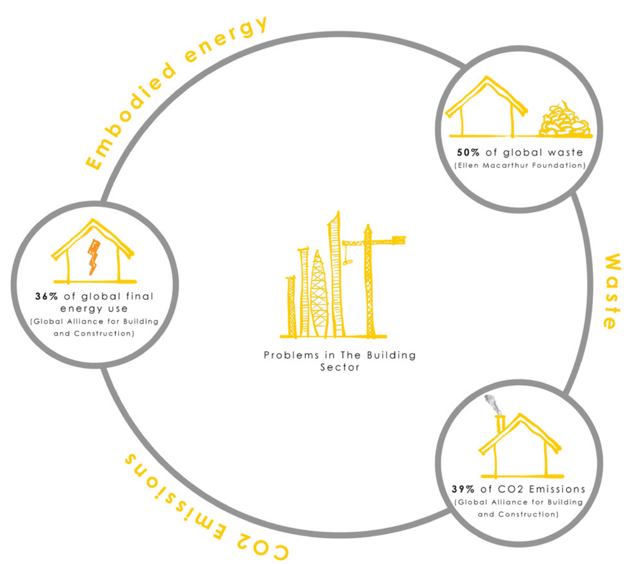


Figure 1.2 Problems in the building sector diagram

In order to reduce the environmental burdens being faced nowadays a different approach in the way products are developed is required. One approach as proposed by Ashby (2013) is to carry out a fast assessment of the life-cycles of a product, providing a framework to implement the necessary design strategies to reduce the eco-impact. Another alternative is to adopt the circular economy approach, which is based on closing the loops of materials (Peck, 2016), this means to keep the materials in use for as long as possible and regenerating the natural systems (Ellen MacArthur Foundation, n.d.). But this research focuses on the first option based on Ashby's method.

1.2 Problem Statement

A building is composed of different parts, each with different service life. Brand (1994) classifies the main parts of a building as 6 shearing layers, also known as building layers (site, structure, skin, services, space plan, and stuff), as seen in figure 1.3. From these layers the building envelope or skin has a relatively low life span or service life, it changes almost every 20 years or so because of wear and tear, technological developments and to keep up with all the ever-changing trends (Brand, 1994).

In order to build a facade a lot of energy is required, almost 25 to 30% of the embodied energy of a building (Cortes, 2019), in addition big amounts of C02 are released into the atmosphere and material is usually wasted during manufacture or construction. Moreover, once a facade reaches the end of its service life or needs renovation it will mostly be disposed of as waste into landfill since most of the waste coming from construction ends up meeting this fate (Verlinde, 2017). This means that new resources from the ground are required to build new facades, which demand a lot of energy and release huge amounts of CO2 as stated previously. Additionally, the environmental impact attributed to a facade system will only worsen when improving the quality of parameters like the acoustic or thermal insulation, as this signifies more material extraction, manufacturing and disposal. Consequently, the environmental impacts we face nowadays are very high. This practice is simply not sustainable in the long run since it will under-manage the natural capital of the planet and its ability to regenerate itself getting in the way of a future economic success (Stuchtey, 2019).

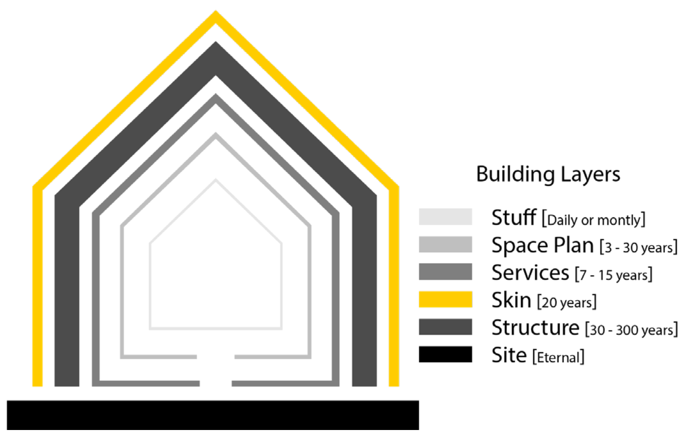


Figure 1.3 Brand’s Shearing Layers of Change

1.3 Objectives

Taking into account the problem statement described previously, the objective of the research is the following:

O) The development of a framework that can evaluate facade systems regarding their environmental impact, acoustic and thermal performance, and used as an optimization tool for designing an environmentally friendly facade system.

With the purpose of reaching this goal, the following sub-objectives have been defined:

S-O1) Identify which facade system predominates in the Netherlands Today.

S-O2) Analyze the identified facade systems in terms of acoustic and thermal performance, and environmental impact.

S-O3) Provide the evaluation criteria to rate and select facade systems with the potential to be improved in regards to their attributed environmental impact.

S-O4) Define the design requirements to decrease the environmental impact of a facade system.

1.4 Boundary Conditions

This research focuses on analyzing the acoustic and thermal performance of the most used facade systems in the Netherlands, as well as relating these parameters with their attributed environmental impact. These properties can be related because the amount of material needed to build a facade in order to achieve a required acoustic and thermal performance varies in the different systems. Therefore, the acoustic and thermal performance of a facade system determines how much material is required, which dictates the environmental impact. The circularity of a system is also related to the environmental impact since it will tell how a system is handled once it reaches its end of service, but it not part of the scope of this research. Once the facade systems are analyzed, the research will be limited to identifying the most promising options to be further studied, which will be used to propose 3 different design options with the objective of providing environmentally friendly facade designs.

1.5 Research Questions

In order to reach the aforementioned objective the following research question has been formulated:

Q) How can a facade system be design or optimized in the most environmentally friendly way without reducing the acoustic and thermal performance?

With the purpose of answering this question, the following sub-questions have been devised:

S-Q1) How can environmental impact, acoustic and thermal performance be related?

S-Q2) How can a facade system be addressed in terms of environmental impact and performance?

S.Q3) How can a framework be provided to identify the opportunities to design or optimize a facade system in order to reduce the environmental impact.

1.6 Approach and Methodology

The thesis consists of three main sections which are directly related among each other, as seen in figure 1.4. The first, second and third sections respectively are based on:

1) Literature review and research

In this part the following topics will be analyzed, which are relevant for the thesis topic and its objectives:

1.1) Materials and their impact in the environment

1.2) Critical Materials

1.3) Environmental impact assessment strategy

1.4) Circular economy

1.5) Circularity in the built environment

1.6) Facade Systems in the Netherlands Today

2) Case study rating and design

This section consists of 4 parts which will be described next:

2.1) The research is extended in this section, but it is focused towards the development of a framework to evaluate and finally rate facade systems in terms of environmental impact, and acoustic and thermal performances. This assessment framework is based on Ashby's method of comparing materials properties, and it is used as a tool to guide the design and optimization of a facade system.

2.2) The facade system representing the highest environmental impact is identified using the previously developed tool. The objective is to determine which component inside the facade system is responsible for the highest environmental impact. Then, provide the guidelines to decrease this aspect, without affecting as much as possible the acoustic and thermal insulation.

2.3) Three design optimization options are proposed with the objective of reducing the environmental impact of the identified facade system, while aiming at keeping similar acoustic and thermal insulation. The design options are compared with the original facade system at different times to obtain insight of their behavior. In other words, this section consists of design informed by research.

2.4) Lastly, the design options are compared with the rest of the facade systems analyzed previously, in order to draw conclusions based on a broader context.

3) Conclusions

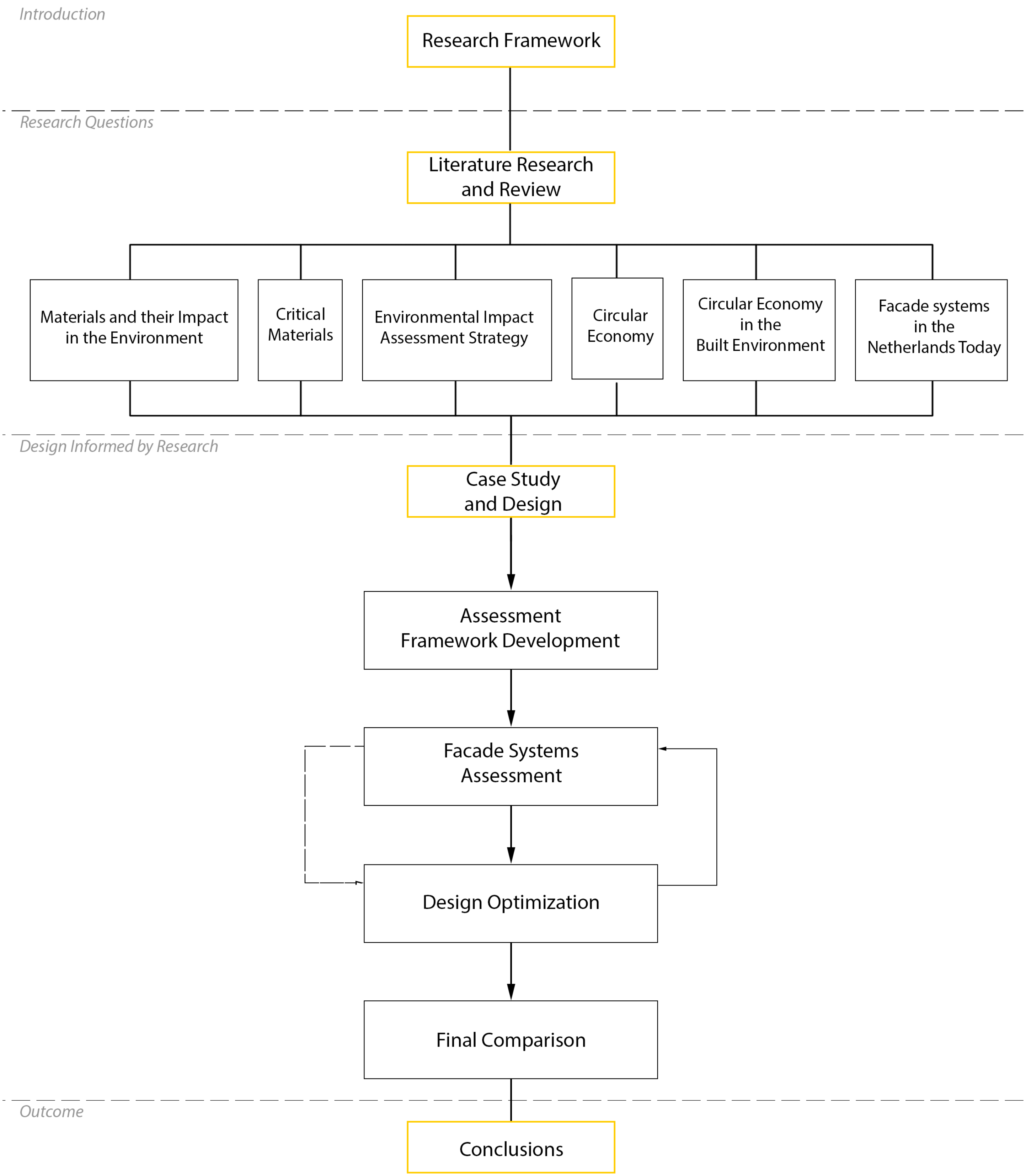


Figure 1.4 Methodology Diagram

1.7 Relevance

Societal Relevance

Human beings need shelter from the harsh conditions of the environment and services that could satisfy their basic needs. In order to address these requirements materials are gathered from the soil in order to be processed and transformed into construction materials that will be assembled in what is known as buildings (Allen & Iano, 2019). The practice used nowadays to construct buildings demand for a lot of Earth's natural resources, either renewable or non-renewable, and with the exponential increasing of population more pressure will be put on natural resources. The same practice just described is not only depleting Earth's resources, but is also having an important negative impact in the environment by creating pollution and releasing CO2 to the atmosphere.

By providing a framework that could be used as a tool to evaluate the environmental impact a facade system contributes, they can be designed or redesigned in a more responsible way with the environment. This will not only benefit human beings by preserving a clean atmosphere and the necessary resources to keep their lifestyles as it is now, but it will also save many other species in Earth who are being endangered by the destruction of their habitats or by harsh climate change conditions. The circular economy principle is another alternative to start designing in a way that will take care of the environment by keeping the materials used to create products in constant use, avoiding disposal at all cost. By applying this principle into the facade of a building, which require a lot of material because of their required performance, the environmental impact could be reduced in a significant way.

Scientific Relevance

The development of a framework to put together and compare the environmental impact with the performance of a facade system based on Ashby's method is a relevant tool for facade designers a it can give an approximation on how well the system performs and how much environmental impact it can cause based on the required performance. This kind of comparison tool is also useful for many other parts of a building, like the structural system or technical systems, but this thesis is limited to the application of the tool on facades.

2) Materials and their Impact in the Environment

2.1) A Brief History of Materials

Since the beginning of mankind, there has been an important connection with materials. There have always been basic human needs that have been satisfied by the use of certain materials, like the need to wear clothing in order to protect the body from exterior elements, or the use of certain tools in order to document history in the form of art or to obtain and process food, among many other activities. In fact materials were so important that many of the ages of man are named after the dominant material at the moment, like the Stone Age, Copper Age, Bronze Age, and Iron Age. It is the use of materials that enabled mankind since its early beginnings to develop from the man in the cave into the modern man. The problem is that as the time progressed mankind has developed a stronger dependence on materials, specially the ones coming from nonrenewable sources (Ashby, 2013).The next paragraphs will present a brief history of how materials evolved, and how are materials being used nowadays, which gives the background to understand how they are related to the environmental issues being faced today.

The first tools of mankind were made of stone and bone, this materials date from the prehistory about 300,000 years ago. Many of the materials used in the distant past have been proven to be durable, like stone, mud bricks, straw, bark, wood and animal skins, among many others. Many of this materials are still used today in modern construction (Ashby, 2013). Up until this point all the materials that were used for any kind of human activity have something in common, that is that they were natural materials. As a consequence the impact imposed on the environment was practically null.

Later on the potential of metals was discovered, mainly due to their strength and ductile behavior. The first metals to be shaped into tools were gold, silver and copper, which occur naturally in nature. But at some point in history the combination of different metals to make a superior product was discovered, this process is known as alloying. This discovery stimulated many subsequent technological advances. This set the grounds for the development of important alloys that contributed at the same time to the evolution of society. Some examples in chronological order are bronze, which allowed the creation of better tools and weapons for mankind or iron, which was very important for agriculture and allowed the construction of new types of structures or steel which had and still has an important role in structural designs (Ashby, 2013). It is important to note that these discoveries allowed mankind to push their boundaries further by enabling them to realize activities in a way that never seen before. It is this behavior that slowly started making humanity more dependent on materials, specially man made materials. This pattern of demanding every time more from materials to expand mankind's boundaries set the ground for big and fast steps in the development of materials.

In the 20th century, the demands for the aircraft industries to produce lighter alloys brought as a consequence a shift into metals based on aluminium, titanium and magnesium. Later on polymers became very important due to their cheap prices, color and shaping capabilities. Not of less importance the new application of silicon in this century created many fields of electronics and computer science. Finally by the end of the century the shift was changed into nano materials, since it was discovered that material behavior depended on scale (Ashby, 2013). Figure 2.1 shows the material time-line, which gives in detail the year of discovery or importance of materials.

What is important to realize from the way mankind together with materials evolved, is that the further back in history the more dependence on renewable resources, and the other way around, the closer in history to nowadays, the more dependence on nonrenewable resources. As Ashby (2013) states, by the end of the 20th century, our dependence on nonrenewable resources was almost total, making humanity today 96% dependent on nonrenewable resources. One of the main problems being faced with materials today is that of their impact in the environment. Huge amounts of energy are require to extract and process materials into products, as well as huge amounts of CO2 emission being released into the environment by doing so. The next section will present how materials are being used in the construction industry as well as the environmental impact related to this activity.

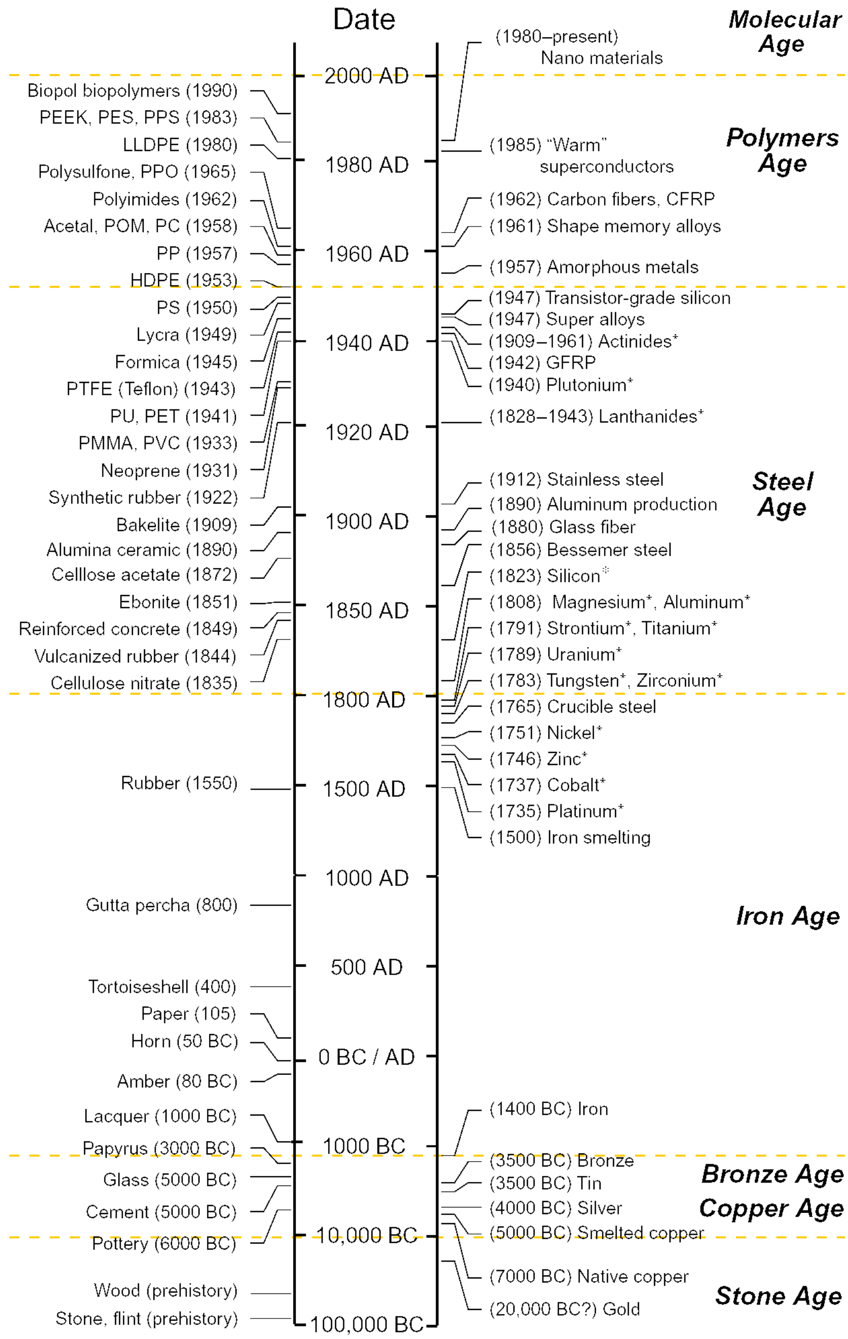


Figure 2.1 Materials Timeline

2.2) Materials in the Construction Industry

As mentioned in the previous section, materials are essential to humanity, specially to keep human activity in the way it is today. Without the technological advances of materials, life as it is known today, would have been very different. In order to keep up with the demands of this century, the amount of material required to process all the products being used today is enormous. As declared by the United Nations (2019), the consumption of materials worldwide, as well as the material footprint per capita have increased considerably. The worldwide material consumption has increased a 254% since 1970, from 27 billion tons to 92.1 billion tons. These number will keep increasing as there is a link between population growth and resource consumption and depletion (Ashby, 2013). The problem with this alarming rate at which materials are consumed is not only the risk of depletion in the future, but their impact in the environment.

Extracting and processing any material uses huge amounts of energy and at the same time releases big amounts of CO2 into the environment. The materials of the construction industry are produced in the greatest quantities. Amongst the mostly produced are: Wood, steel, concrete, asphalt, brick and glass (Ashby, 2013), as illustrated in figure 2.2.

As material production is directly related to its use or consumption, figure 2.3 presents in the form of pie charts the material usage by family in the construction industry. From these charts it is evident that the predominating materials are concrete and brick, which belong to the group of ceramics, no mater if they are measured by weight or by volume.

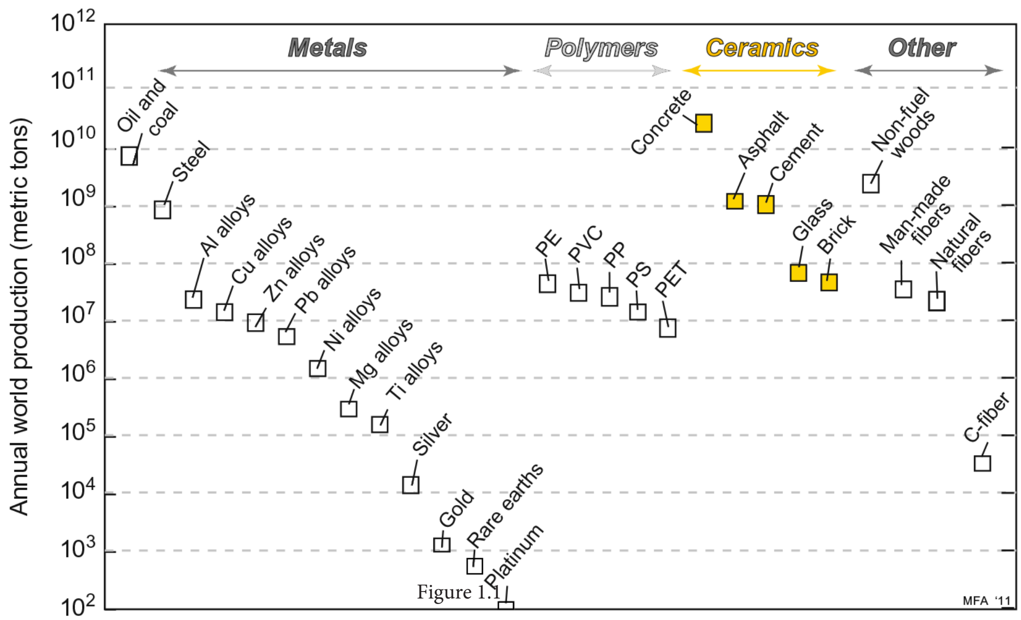


Figure 2.2 Annual world production of industrialized materials. Adapted from Ashby (2013).

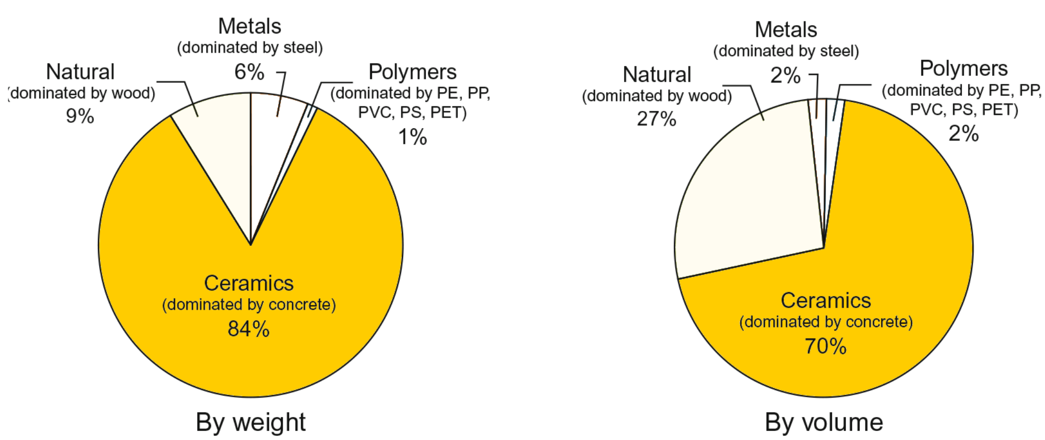


Figure 2.3 Materials used in the construction industry. Adapted from Ashby (2013).

What can be deducted from this data is that the construction industry is one of the sectors responsible for the greatest consumption of materials. Since materials are directly related to energy use and CO2 emissions, this sector alongside with the industrial and transportation sectors are held accountant for the largest impacts in the environment. To be most precise in the numbers, the construction industry accounts for 36% of global final energy use (Global Alliance for Building and Construction, 2018), 39% of CO2 Emissions (Global Alliance for Building and Construction, 2017).

2.3) The Materials - Energy - Carbon Triangle

In order to make and use materials the first factor that should be taken into account is energy, since it has the highest implications in the environment. The global consumption of primary energy is approximately 500 EJ (10^{18}J). This derivatives mainly from the burning of three nonrenewable resources: Coal, gas and oil. The dependence on these resources needs to be addressed as soon as possible due to three emerging pressures (Ashby, 2013):

1) To reduce the diminishing reserves of oil and gas.

2) To reduce the CO2 emissions and other concerning greenhouse gases into the atmosphere.

3) To reduce the dependence of importing fossil fuels and the tensions that their dependence create.

The burden this poses into the environment is only expected to get worse, as the worldwide demand for energy is expected to triple by 2050 (Ashby, 2013).

As it can be deducted from this chapter materials are energy intensive, and they are directly related to energy. The more a material is processed or used, the more is the required energy. At the same time energy is also related to carbon dioxide emissions (CO2), most of the time, the more the energy required to process a material or to realize other activities, the largest the CO2 emissions. The problem in this relationship is that nowadays changes in one of the parts has important implications in another which are important to understand and consider. Obtaining carbon-free energy is material intensive, at the same time materials are energy-intensive, and energy, as it is made today, is carbon-intensive. These clashing objectives are explained graphically in figure 2.4, with the materials-energy-carbon triangle.

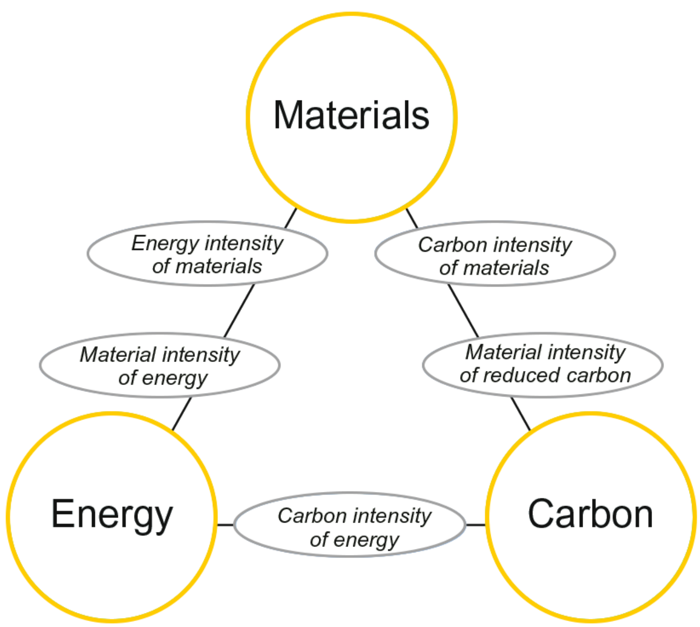


Figure 2.4 The materials-energy-carbon triangle. Adapted from Ashby (2013).

3) Critical Materials


Promethium
Pm
61
145
Lutetium
Lu
71
174.97
Erbium
Er
68
167.26
Holmium
Ho
67
164.93
Neodymium
Nd
60
144.24
Lanthanum
La
57
138.91
Terbium
Tb
158.93
Praseodymium
Pr
59
140.91

3.1) What are Critical Materials?

The current dominant economic system in the world is the linear economy. This system as Webster (2019) describes, depends on cheap materials cheap energy and cheap credit. This became specially true after the second world war, since materials were produced in abundance as a response to all the restrictions, rationing and destruction brought by it. Even nowadays with the current technology, high quality resources are hard to extract, and with the ever increasing demand for materials the cost is increasing gradually. This has brought and still brings high environmental and resource supply problems.
Peck (2016) provides the definition of critical materials as provided by the EU in the following way:

"To qualify as critical, a raw material must face high risks with regard to access to it, i.e. high supply risks or high environmental risks, and be of high economic importance. In such a case, the likelihood that impediments to access occur is relatively high and impacts for the whole EU economy would be relatively significant." (EU, 2010).

Critical material problems are being faced today and as Webster (2020) states, billions of new customer will enter the market in the next 20 to 30 years. This will put enormous pressure on the resource base, therefore continuing with the linear ways is no longer an option. If materials keep being handled in a linear way scarcity and price volatility might become a serious threat in the near future, and the environmental impact will be devastating.

3.2) Critical Materials and Design

In order to design a product the choice of materials are made at the design stage. The way a product is designed can decide its length of life or service life, as it affects its potential to be repaired, reused, re-manufactured or recycled, which as explained previously, has direct implications in the environment. If the product's service life is shorter, the critical material consumption will become worse as well as the environmental impact (Peck, 2016).

The beginning of this section gives an idea of how important the design of a product is since the first stages, if the end goal is a functional product which comes with the least environmental burdens as possible. The application of circular economy principles are one way to deal with the problem of critical materials, and it is one of the most known series of strategies to be adopted in order to keep materials flowing inside the economy and reduce the environmental impact, but other strategies to deal with critical materials as presented by Peck (2016) are of the same importance in order to reach the same goal:

1) Less material
2) Lightweight materials
3) Robust and long lasting materials
4) Design for repair
5) Use of local materials
6) Standardized Design
7) Reduced decoration

These strategies were applied by Britain as a response to dealing with the material scarcity faced during the second world war, and they played a significant role since it helped the British government to overcome the crisis.
This were not the only strategies exercised by the British government during this time of crisis, but they are the most important concerning the critical material problems being faced today in the world, as many of the other strategies applied were extreme measures specifically created to solve the scarcity problems created by World War II.

3.3) Critical Materials and the Built Environment

In the previous sections it could be understood that the critical material problems are not just about scarcity, but about ensuring the security of supply, this is specially true for metals (Peck, 2016), which play an extremely important role in today's built environment.
Before the 19th century, metals were not as important as they are today, they were mainly used as connecting devices, and had little structural relevance (Allen & Iano, 2019). Nowadays an enormous range of ferrous and non-ferrous alloys are used within the construction industry. The most common metals used by the industry are iron, steel, aluminium, lead and zinc (Lyons, 2014).

Metals are energy intensive materials, they use up to 7 to 8% of the total energy to be produced, and these numbers are expected to rise, as well as their demand. This means that supply of metals in the near future can become critical if they keep being managed in the same linear way. This will mainly be caused because the mines from which metal supply is extracted nowadays will be depleted in around 20 years. This does not mean that Earth is running out of metals, but it means that new technology and huge amounts of new energy are required in order to dig deeper to find more metals (van der Voet, 2019). As a consequence this will increase the environmental impact and it could bring material supply shortages.

The facade industry is directly connected with critical material problems, as many metal alloys are applied in the production and construction of facade systems. Metal alloys like aluminium and steel are widely applied by the facade industry, and though in many cases efforts are already being exercised to recover the value of many metals used to build the different components in a facade system, the most applied circular principle is recycling. With the problems of some materials becoming critical within the facade industry, it is easy to ask if other materials that cause lower environmental impacts and are at less risk of becoming critical could be applied instead. The answer to this question is provided by Peck (2016), in which he argues that switching to another element or material is not an easy task and this will simply make the substituted element critical. In order to address the critical material problems Peck (2016) suggests 4 substitution strategies, as presented in figure 3.1.

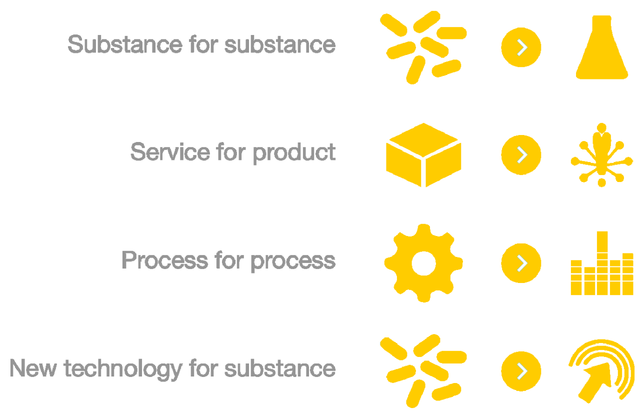


Figure 3.1 Substitution strategies. Adapted from Peck (2016).

The strategies can be understood as follows:

1) Substance for Substance: This will be the least desirable option since it requires changing a material for a different one, which is not an efficient solution as explained previously.

2) Service for Product: This involves services such as repair, reuse, and all the other re-life options.

3) Process for Process: This concerns the changes to the process approach of products.

4) New Technology for Substance: New technology can help replace a product's approaches and services.

4.1) The Linear Economy in Buildings

The building construction sector in responsible for placing many of Earth's resources at risk, as well as contributing to the degradation of the environment (Allen & Iano, 2019). Today the building and construction sector are responsible for 36% of global final energy use (Global Alliance for Building and Construction, 2018), 39% of CO2 Emissions (Global Alliance for Building and Construction, 2017) and 50% of global waste in just cities (Ellen Macarthur Foundation, 2017). This is a direct consequence running the built environment in a linear way.

4) Environmental Impact Assessment Strategy

4.1) How to Assess the Environmental Impact?

From the previous chapters it can be understood how the extraction and dependence of materials and their making into products has impacted in an unfavorable way the environment. Since the beginning of the ages of man the impact caused by mankind in the environment has progressively worsen. The industrial revolution which introduced the mass production of products, without any kind of environmental awareness, and the explosive population growth seen in the recent years have just aggravated the situation. It is not long since mankind began to realize the consequences of the way we obtain and shape resources on the environment.

It was just in 1987 when the United Nations published the report Our Common Future, which provided the concise definition of sustainable development, which is defined as follows:

> “Building to meet the needs of the present generation without compromising the ability of future generations to meet their own needs” (Allen & Iano, 2019).

Some time after the release of this report some awareness in the ways the environment is being affected by human activity was raised. In the building industry the practice of sustainable design and construction, commonly known as green building, has slowly grown ever since. Progressively the understanding in the relation between buildings and the environment has increased, and many standards for assessing the sustainability of materials and construction practices have grown in number (Allen & Iano, 2019).

In order to design in a sustainable way, access to information about the environment and material impact is required. Information regarding building materials and their impact in the environment can be gathered form different sources. One of this sources is the Product Data Sheet (PDS), which is self-reported information about a product, which is provided by the manufacturer. This information provides the description of a product, its material composition and physical properties, together with the guidelines for its use. Other sources of information about the environmental impact of a product are the ecolabels, which are a third-party environmental rating system, that reports how sustainable a product can be. More complete and reliable sources of information about the ecological impact of certain products are the Environmental Product Declarations (EPDs). These assessment method usually describes the environmental impacts through the complete life-cycle of building materials and products. These documents are made by the product manufacturer, and they contain important data like renewable and nonrenewable energy consumed, CO2 equivalent global warming potentials, and fresh water consumed. Additional data offered in these documents quantify material consumption, smog production, ozone depletion, waste materials generated, and many other parameters (Allen & Iano, 2019). EPDs are produced based on the life- cycle assessment (LCA) calculations, meaning they are a short version of the famous LCA(Hillege, 2020). Life-cycle assessments, also known as cradle-to-grave analysis is one of the most accepted and comprehensive methods for quantifying the environmental impacts related with materials and buildings (Allen & Iano, 2019).

All of the aforementioned assessment methods provide numerical information about different parameters that contribute to any sort of environmental degradation when developing a product, but these numbers are left into the interpretation of the designer. The previous data is useful to do a comparison of one product over another, but these numbers alone, provided by these kind of documentation, are of little use to a designer whose end goal is to create a product or build a building, while keeping the environmental footprint as low as possible. The objective of lowering the environmental impact in the building industry is not only reduced to the products offered by already established suppliers and manufacturers, but on the contrary, an environmentally friendly product can be obtained by a well informed choice of materials, which can guide the designer to choose or optimize a material or combination of materials, since material use is directly associated with environmental impact. As Ashby (2013) suggests, a tool that designers need in order to make the fastest, cheaper and environmental friendly decisions is an eco-audit. The eco-audit tool, which is used later in this thesis to evaluate certain facade systems will be explained in the coming section.

4.2) The Eco-Audit

While LCA are very detailed, they are not necessarily completely precise. The two main difficulties encountered with LCA results (Ashby, 2013):

1) The resulting numbers of this kind of assessment is uncertain for the designer, and sometimes many of the different categories are not measured in the same units.

2) LCA are very expensive.

There is an alternative tool that can assess the environmental impact associated with the life-cycle of a material or product from cradle to grave, in a fast and cheaper way. This is the eco-audit tool. The eco-audit is a fast tool that offers the possibilities of exploring the consequences of certain choice of materials, their use pattern and end-of-life scenarios (Ashby, 2013). An eco-audit report focuses mainly on the embodied energy of a material or product and its CO2 emissions, which can be obtained as a total or by life phase, as shown in figure 4.1.

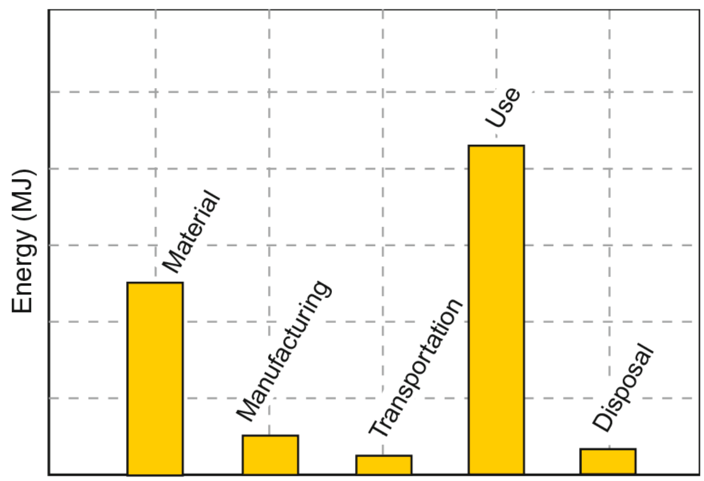


Figure 4.1 Breakdown of energy associated with a material or product life phase. Adapted from Ashby (2013).

4.3) The Strategy

Since the main goal of this thesis is to develop a framework that can evaluate facade systems regarding their environmental impact and performance, to be used as an optimization tool to design a facade in an environmentally friendly way, the strategy adopted for this end is based on the assessment approach developed by Ashby. Ashby's approach is composed of 3 main steps:

1) Adopt simple metrics of environmental stress: The most logical metric choices to evaluate the environmental impact are energy consumption and CO2 emissions, since they are related and better understood by the public in general.

2) Distinguish the phases of life: Breakdown of energy and CO2 of the different life phases of a product (material creation, manufacturing, transport, product use and disposal), to later point out the phase of most concern. The phase of life that dominates should become the target of redesign, since the fractional reduction makes the biggest contribution. When differences are great, precision is not essential, but it is the ranking what matters the most.

3) Base actions on the energy or carbon breakdown: A series of actions can be implemented at the different stages of life of a product or material. Depending on the dominant phase they can be as follows:

a) Manufacturing: - Choose materials with low embodied energy
- Minimize material use.

b) Manufacturing: - Reduce processing energies
- Reduce processing CO_2.

c) Transportation: - Optimize transportation mode or look for a more efficient one
- Reduce distance.
- Reduce mass.

d) Use: - Minimize mass
- Increase thermal efficiency
- Reduce electrical losses.

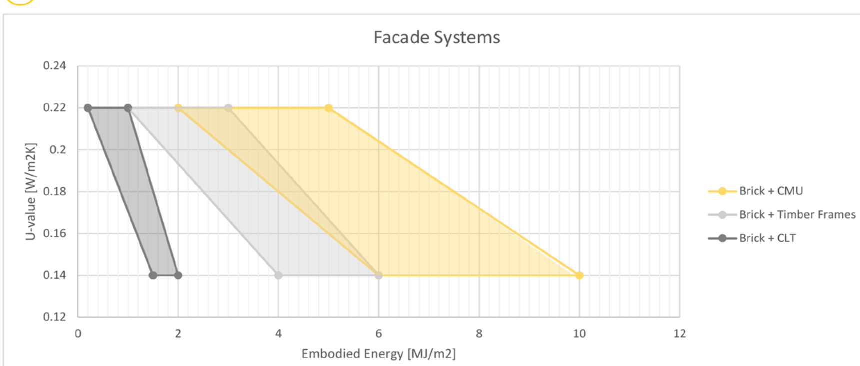
e) Disposal: This phase can take many forms, which makes interpretation somehow more difficult.

Since multiple facade systems will be considered in this thesis, the assessment strategy proposed, which is based on Ashby's environmental assessment approach, is illustrated in figure 4.2, and it is as follows:

①

Facade System			
	System	Thermal Performance (U-value)	Embodied Energy
1	Brick + CMU	0.22 - 0.14 [W/m2K]	5 - 10 [MJ/m2]
2	Brick + Timber Frames	0.22 - 0.14 [W/m2K]	3 - 6 [MJ/m2]
3	Brick + CLT	0.22 - 0.14 [W/m2K]	1 - 2 [MJ/m2]

②



③

Redesign (Brick + CMU)	
Materials	Embodied Energy [MJ/m2]
Brick	2 - 5
Insulation	1 - 4
CMU	2 - 3

Figure 4.2 Assessment strategy approach.

1) Adopt energy consumption and CO2 emissions, per m2 of wall, as metrics to evaluate the environmental impact of a facade system.

2) Identify the environmental impact associated with performance: Since the amount of materials in a facade system are mostly determined by the required acoustic or thermal performance, it is important to assess the environmental impacts caused by them. By comparing these performance against embodied energy or CO2 emissions, per m2 of wall, the impact can be obtained for the different facade systems. This comparison tool is important to take decisions when many options are present, as identifying the most concerning or potential systems to be later optimized becomes clear. In this manner a database is established with different facade options, which could grow over time with the addition of different facade systems.

3) Redesign based on the data interpretation: The data obtained from the previous step helps designers to compare and select a potential system to be optimized. Once a system is selected, all the data related to the environmental impact of each of the individual materials that compose a m2 of the facade system can be analyzed. This makes the redesign decisions easier as it points out which materials are causing the greatest problems. Therefore by optimizing the most troubling part in the system, the greatest positive contribution will be achieved.

4.4) Building and Product Examples

Lately, many architecture and engineering firms have been doing great efforts to reduce the environmental impact when designing buildings or products, as well as looking at ways of quantifying the harm done to the environment related to certain materials or components. This section presents 3 practical examples in which sustainable ideas have been applied in the building sector, in order to decrease the environmental impact.

1) EC3

Several architecture and engineering companies have gather together in a effort of creating a free digital calculator that measures the embodied carbon in a construction. Some companies like Autodesk, Microsoft and the American Institute of Architects collaborated in the development of this tool (Aouf, 2020).

This tool obtains the carbon footprint data of different materials from environmental product declarations (EPDs). With these values and other data on material properties, the tool is practically a big database that aims at making the carbon reduction measurable (Aouf, 2020), as show in figure 4.3.

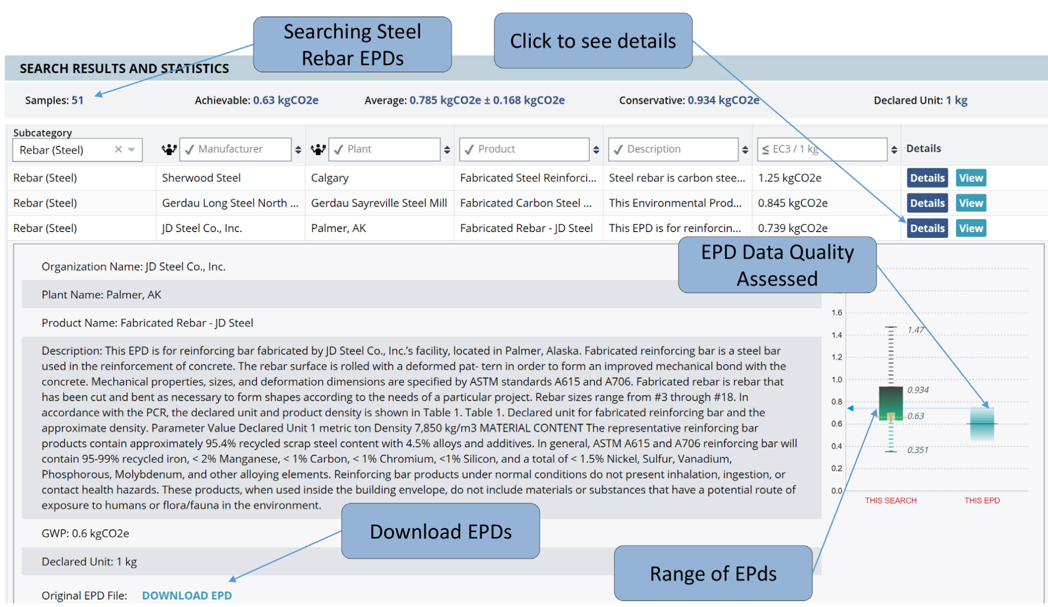


Figure 4.3 EC3 embodied carbon calculator. Retrieved from Aouf (2020).

2) Canada's Earth Tower

This mixed-use tower designed by the architectural firm Perkins + Will, is going to be built in Vancouver, British Columbia. The high-rise is 120 meters tall, and it will be the world tallest hybrid wood tower to the date (McKnight, 2019). In order to reduce greenhouse effects, the tower will use locally manufactured timber for the facades and the columns, and a concrete core which will provide stability to the structure of the building. Timber is a material which is normally considered to have negative carbon footprint for its property to sequester CO_2 particles from the environment. Additionally, the weight of the building will be reduced by using composite floors (Perkins & Will, n.d.). The strategies taken in order to reduce the weight of the building and reduce the massive materials like concrete to the minimum, are strategies that will help to reduce considerably its embodied energy and CO_2 emissions. Moreover, using local materials will reduce the transport distances of the building components, reducing even more the environmental impact.

In addition to the construction materials, the tower will be equipped with systems to reduce energy consumption, like heat recovery systems and photovoltaics. The aim of the architectural firm is to obtain the Passive House Certification (McKnight, 2019).

Figure 4.4 Exterior and interior renders of Canada's Earth Tower. Retrieved from McKnight (2019).

3) The K-Briq

Developed by the Scottish startup Kenoteq, a brick that is made of 90% construction waste is more sustainable than the traditional clay bricks used in the construction industry. Most of the reduction in the carbon emissions and embodied energy of the brick come from the small efforts in the manufacturing process. These bricks don´t need to be fired, and as a consequence they en up generating less than a tenth of the carbon emissions in the production stage, when compared to the regular bricks. Moreover, the k-briqs offer better insulation properties than the traditional clay bricks (Aouf, 2020). These improves the overall thermal insulation of a facade, and decrease the need for extra insulation, which increases the weight and environmental impact in a building.

Figure 4.5 Different views of the k-briqs. Retrieved form Aouf (2020).

5) Circular Economy

5.1) What is the Circular Economy?

There is no record or evidence as to when this well known concept of a circular economy was first originated, but it became popularized in China in the 1990s in response to fast economic growth and resource limitations. Nowadays the concept has been adopted and properly introduced by other organizations like the European Commission and the Ellen MacArthur Foundation (Winans, Kendall, Deng, 2017).
There more than 100 published definitions of a circular economy, since the concept is applied by many groups of researchers and professionals (Het Groene Brein, n.d.). A clear definition in a few words of what is the circular economy, is provided by WRAP (n.d.) and it is as follows:

> A circular economy is an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life.

The circular economy is an alternative to the linear economy model which dominates today. The practice of a linear economy consists of taking raw materials from Earth's soil, transporting them to a manufacturing site in which they are transformed into products, and taking them to the consumers that will later on dispose the materials as waste at the end of service of the product, as can be seen in figure 5.1. This model is simply unacceptable nowadays and for the coming times, as it has already brought serious environmental degradation and it has contribute to the scarcity of resources. As a consequence issues like global warming, resource price volatility and waste generation are being faced. In addition the last step of the linear model (dispose) leads to the destruction of all the energy and labor once applied to build the disposed product (Beurskens & Bakx, 2015).

Figure 5.1 Linear economy diagram. Adapted from Wautelet (2018).

In a circular economy the value of the resources, materials and products are maintained in the economy for as long as possible (European Commission, 2016). This is possible because the products are designed in such a way that they can be brought back to life by falling in the different technical cycles, as seen in image 5.2. As a consequence this model can alleviate the resource supply risks faced nowadays, as well as reduce the green house gas emissions (GHG) and the generated waste, all of which is translated to reduction of environmental impact.

The European Commission (2016) also presents more advantages to the circular economy model than just the reduction of the environmental impact and securing the supply of resources. Other advantages are a boost of 7% in GDP in the European Economy, the increment of new business opportunities as well as business competition, and the creation of jobs in the EU.
The circular economy as described by the Ellen MacArthur Foundation is based on four principles that will be explained in detail in the following section.

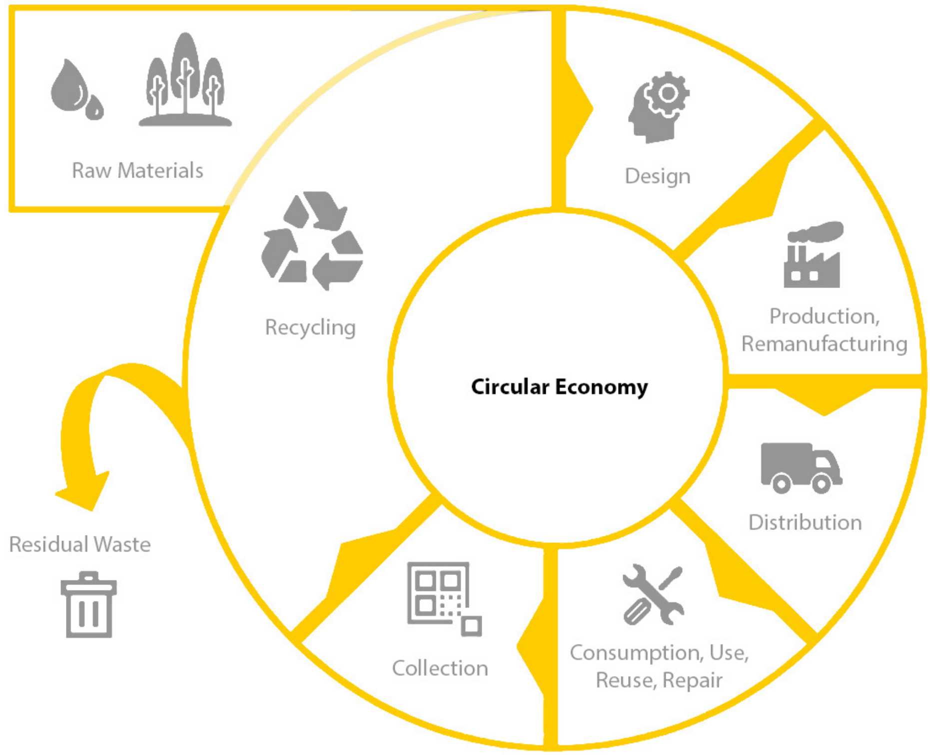


Figure 5.2 Circular economy diagram. Adapted form EIT (n.d.).

5.2) Principles of the Circular Economy

The concept of the circular economy described previously depend on four main principles as described by Peck (2019). These principles are:

1) Design Out Waste: This first principle is centered on the thought that 'waste equals food'. This is based on the idea that in nature there is not such thing as waste, the waste left by one species becomes the food of another. By applying this principle to products they could be kept at their highest values at all times.

2) Build Resilience Through Diversity: The second principle is based on the idea that in biodiversity many species contribute to the overall health of a system by supporting it at all times, even in the times of crisis. An economy can become stronger by sharing strengths and having a greater disposal of resources to draw on.

3) Work Towards Energy from Renewable Resources:
The third principle is centered around the idea that living systems are mostly based on power coming from renewable resources like gathering energy from the sun. The objective is to create flows of materials and information by powering everything with renewable resources.

4) Think in Systems: The fourth principle refers to the ability of understanding how people places and ideas are connected and how economic, environmental and societal gains can be generated.

5.3) Longer Lasting Products

The service life of a product can be made to last if it is robust and if it is designed to be repaired, reused, re-manufactured or recycled. These two steps are at the core of designing in a circular way, and the later can be understood in the Butterfly Diagram, as shown in figure 5.3.

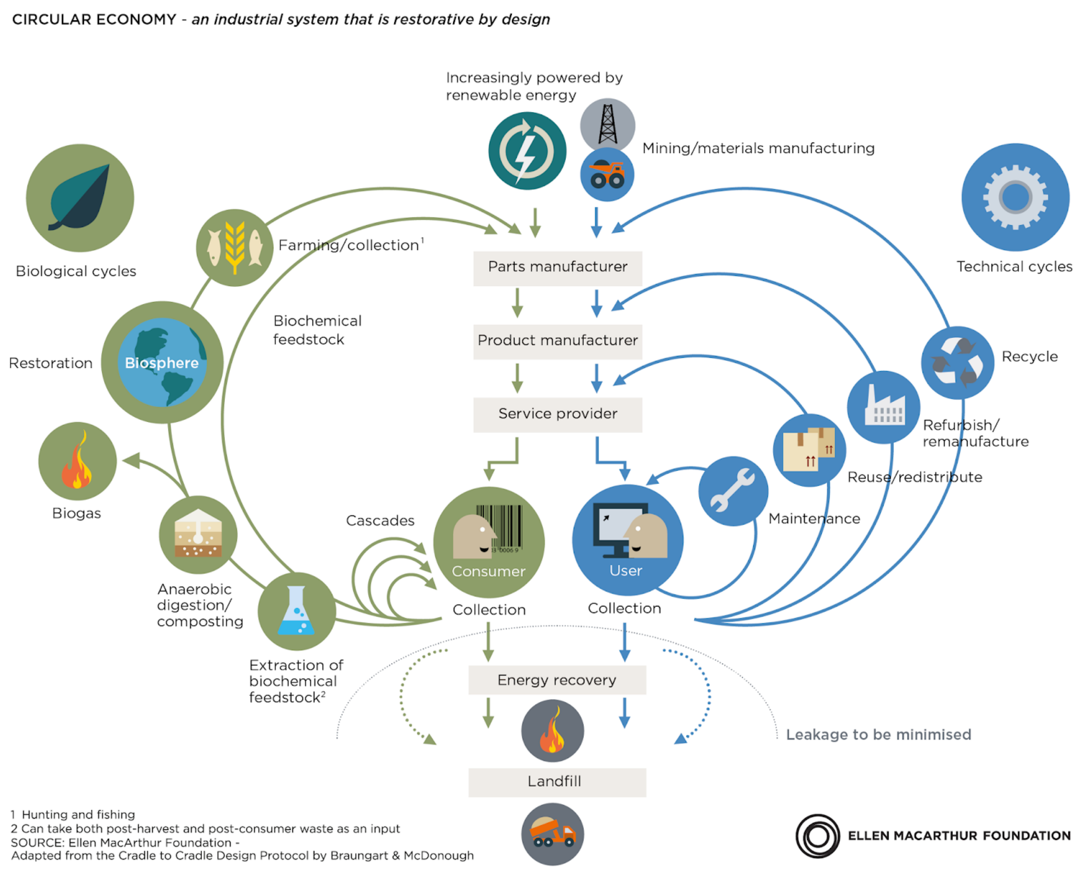


Figure 5.3 Butterfly diagram. Retrieved from the Ellen MacArthur Foundation (n.d.).

In a circular economy, the materials can follow two cycles as shown in figure 5.3. These are the Biological cycle and the Technical cycle. They both follow different processes as discussed next:

a) Technical Cycle: Materials in this cycle are also called synthetic materials and they mainly include fossil fuel, plastics and metals. Their main characteristics are that these materials have limited availability, they cannot be created easily and they are used instead of being consumed. In this cycle materials maintain their original value after they are used, as they are recovered from residual flows (Het Groene Brein, 2015).

b) Biological Cycle: Materials in this cycle are biological, some examples are timber, food and water. The main characteristic of the materials in this cycle is that they can be regenerated through biological processes. In order to preserve the environment and the natural resources in this cycle, the circular economy avoids toxic substances that could contaminate the ecosystem and excessive consumption. If these steps are followed renewable organic material can be regenerated (Het Groene Brein, 2015).

As can be observed in figure xx, the technical cycle is composed of different cascading circles, these are better known as 'loops'. In the circular economy it is best to design in a way in which the materials can cycle in the smaller circles or closest loops, because the profitability of the system increases as the loops decrease.

The different loops in the technical cycle can be understood as follows:

a) Maintenance: This is the innermost loop or smaller circle of the technical cycle. In this loop the products and materials are designed so that they are easily maintained and repaired, as a consequence the lifespan of the product or material is extended.

b) Reuse/Redistribute: In the second loop the products and materials are designed so that they are directly reused or redistributed multiple times in their original condition.

c) Refurbish/Re-manufacture: The third loop focuses on designing products so that its value can be easily restored. Although this two concepts are very similar they refer to different processes. On the one hand, refurbishment is focused towards repairing a product in a cosmetic level, this means that the product is not disassembled and the components are not replaced. On the other hand re-manufacturing refers to disassembly of a product to its component level, in which damaged or old components are replaced to return the value of the product to an almost new condition.

d) Recycle: The fourth and outermost loop is considered to be the last resort option of the technical cycle. This process consists of disassembling a product to its component level and reducing the components back to their basic material level, from which they are remade into a new product. This process brings as a consequence the loss of the embodied energy and labor applied in the making of the product, and the new costs required to remake a product.

6) Circular Economy in the Built Environment


Design Event
Pavilion?
Pavilion
Design Event

6.1) The Linear Economy in Buildings

The building construction sector in responsible for placing many of Earth's resources at risk, as well as contributing to the degradation of the environment (Allen & Iano, 2019). Today the building and construction sector are responsible for 36% of global final energy use (Global Alliance for Building and Construction, 2018), 39% of CO2 Emissions (Global Alliance for Building and Construction, 2017) and 50% of global waste in just cities (Ellen Macarthur Foundation, 2017). This is a direct consequence running the built environment in a linear way. In order to understand why the built environment contributes to such environmental detriment, it is important to understand how materials and products are managed in the linear economy, as show in figure 6.1.

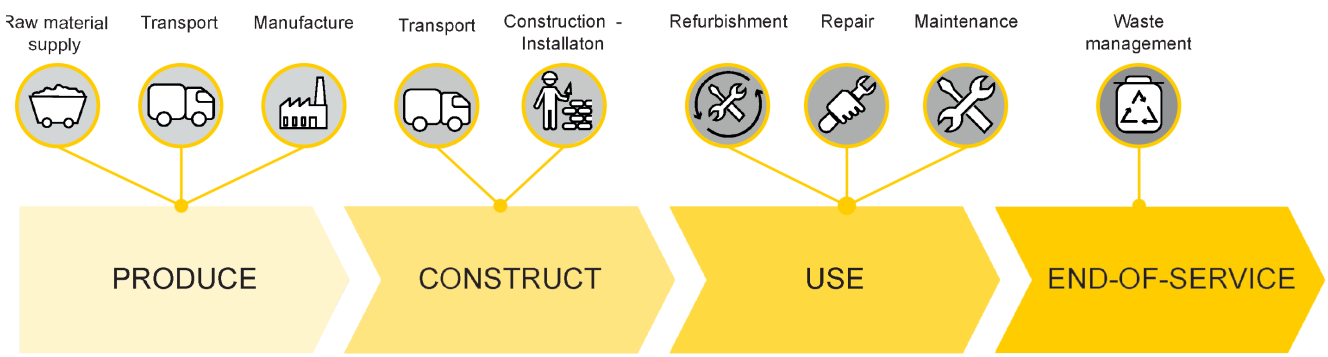


Figure 6.1 Linear economy in the construction industry. Adapted from Klein (2019).

As illustrated in figure 6.1, today's product life-cycle in the built environment follows 4 phases (Klein, 2019) which will be explained in detail next:

1) Produce: In this first phase building components are produced. First the raw materials are extracted from the soil, followed by their transportation to the manufacturing site, and finally the materials are made into products in the factory.

2) Construct: During this phase the building is assembled on site or by prefabricated elements built off-site. During this step the components produced in the factory are transported to the construction site, from which they are installed afterwards.

3) Use: This is the longest in the overall lifetime of a building, it can last from 40 to 60 years in average. During all these years the building components already installed will start to wear and tear, for this reason they will have to be maintained, repaired and refurbished many times until the products reach their final stage in a linear economy, the end of service.

4) End-of-Service: This is the final phase of the life-cycle of products inside the built environment in a linear economy, and it is by far the worst since all the energy and labour applied in all the previous steps will be lost forever in the form of waste. As can be noted from figure 6.2, the central activity of this phase is the waste management which gives only three options:

a) Recycling
b) Energy recovery by burning
c) Landfill

6.2) The Circular Built Environment Framework

If products are designed in such a way that they can have longer lifespans than what they normally have, and if they are designed so that they can be upgraded and reused, re-manufactured or recycled, then it is safe to say that the products are circular. These two principles of keeping products in use for longer and give them a second or more lives are the foundations of the circular economy. In a circular building environment, all the construction phases are kept in a loop as seen in figure 6.2, with the purpose of reducing waste, giving products and materials a longer service life, as well as recovering and reusing their value at the end of their lifespan.

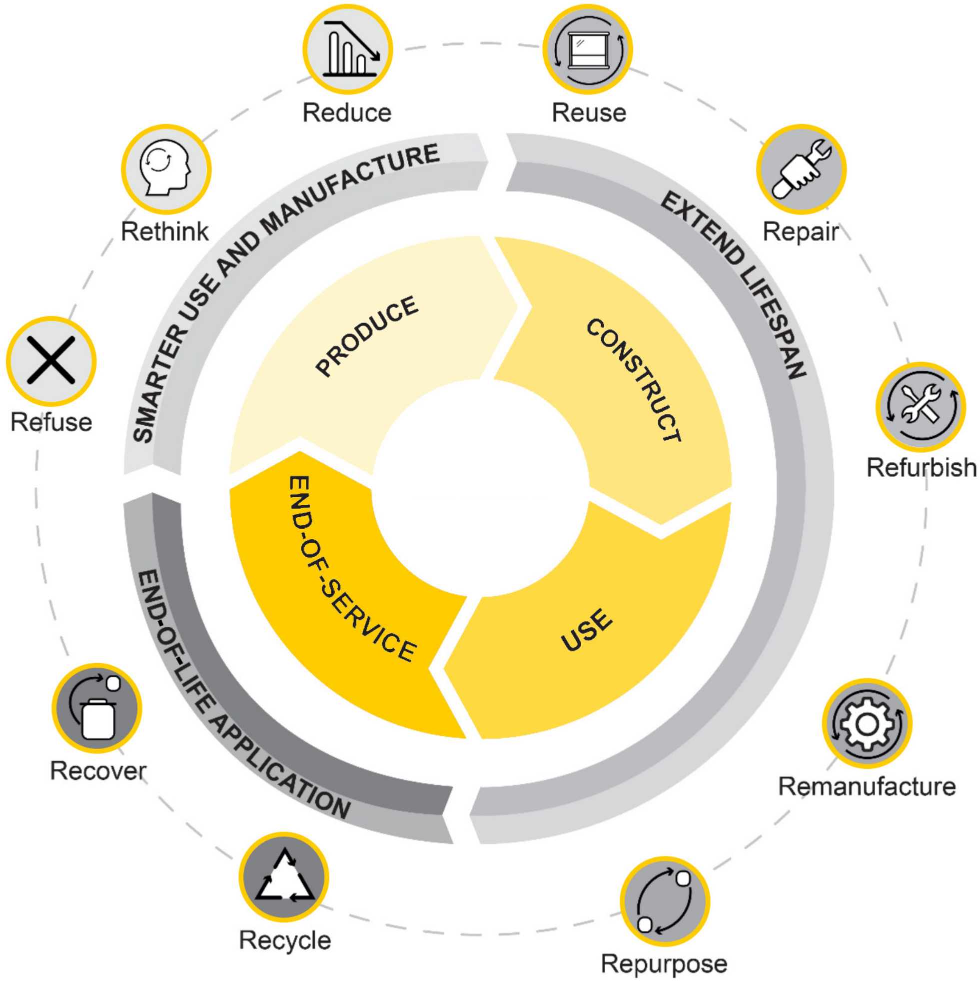


Figure 6.2 Circular economy in the construction industry. Adapted from Klein (2019).

In order to make the building industry circular two features need to be addressed (Billow, 2019):

1) Renovating the gigantic stock of buildings reaching their end of life.

2) Creating new concepts for today´s buildings, so that they can be adapted to the future and with the possibility of being redesigned, upgraded or disassembled without creating waste.

Design for disassembly is a recurrent theme in the circular built environment, since it is at the core of the circular economy. This is because it allows products to be taken apart in an easy and effective way to be later repaired, reused, re-manufactured or recycled. As stated by Cruz, Chong & Grau (2015), design for disassembly is essential for closing the loops of materials. If building products, parts or components cannot be disassembled or are hard to demount, it is highly probable that the product will end up as waste even if it is made of parts that can be reused, re-manufactured or recycled.

By applying strategies to disassemble a product, the manufacturing process can become cheaper. Some of these strategies as presented by Autodesk (2015) can be:

1) Use fewer parts, as there will be less to take apart.

2) Avoid fasteners, as they usually make products nearly impossible to take apart. Instead:
   a) Use common and similar fasteners.

   b) Screws are better and faster to install than nuts and bolts.

   c) Using snap-together hooks or tab-and-slot fasteners are one of the best solutions, as they don't require any tools.

   d) If the use of adhesives is really necessary, use common, similar and non-toxic adhesives that are heat reversible or easy to dissolve.

3) Provide disassembly instructions into products.

6.3) Building Layers

When looking at the construction and building environment it is important to understand that buildings should not be seen as one single product, but a system of various layer and components (Brand, 1994), as seen in figure 9. This thesis is focused towards the facade, which is part of the "skin" of a building. The skin is one of the building layers as proposed by Stewart Brand in his book "How Buildings Learn", and it is comprised of the facade and the roof.
There is a still lot of improvement to be done in the way facades are designed today. Similar to the time in which Brand came up with the concept of the shearing layers of change in buildings, the lifespan of facades nowadays is still around 20 years or so. This change is mostly driven by changes in trends over the years, but adapting or taking apart a facade while maintaining its value to be reused or recovered is very seldom applied.
The building layers with their corresponding service life as described by Brand (1994) can be seen in image 6.3.

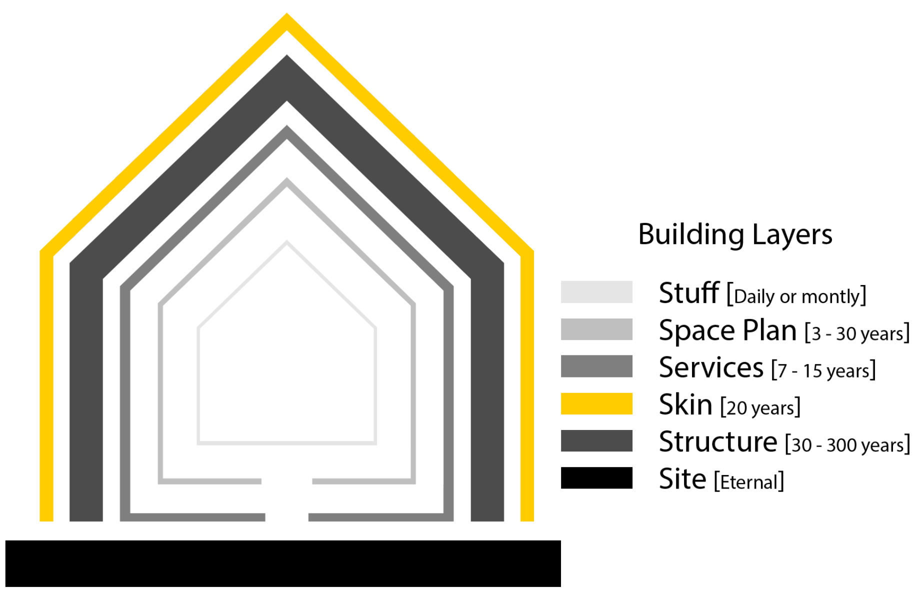


Figure 6.3 Brand's shearing layers of change

7) Facade Systems in the Netherlands Today

7.1) Contemporary Dutch Facades: An Overview

This section is based on identifying which facade systems are being built the most in the Netherlands nowadays, with the purpose of pointing out the predominating one, since optimization of this system with the objective of decreasing the embodied energy and CO2 emissions will have the greatest contribution to the environment.
The Netherlands is a country of contrast thanks to its architecture, on the one hand, the traditional Dutch house architecture can be seen everywhere, which consists of narrow buildings, with narrow windows around 5 stories high, and brick facades, on the other hand, in many places tall high-rises and contemporary architecture built with the latest technology in the construction sector can easily be spotted. This is true specially for some cities like Rotterdam, which was almost entirely destroyed after World War II by its bombardment during the German invasion. As result, this city has experience the influence of many modern and contemporary buildings.

Due to the aforementioned contrast in architecture, the facade systems in the Netherlands are diverse. But among this diversity one material dominates the picture. This material is brick. This material is deeply integrated into Dutch history, as it was firstly introduced in the Netherlands in the middle ages, most precisely around 1200 (Lubelli, 2018). Brick in the Netherlands is still the predominant construction material used for facades and streets (Wingender & Grootens, 2016). Therefore, the predominating facade system in the Netherlands is brick masonry. This statement is also validated by Design and Engineering department of the Dutch construction company Heijmans based on their given data (see Appendix for a copy of the survey conducted).

In the Netherlands, brick masonry is mostly the external layer of a whole assembly known as cavity wall. It should be noted that the majority of brick masonry facades in the Netherlands are based on this cavity principle, in which there is an outer layer a cavity and an inner layer with insulation. Cavity walls were introduced at the beginning of the 1970s, and their main purposes are to prevent the spreading of moisture from the external wall to the internal one, keep out warm and cold, and provide good sound insulation (Wingender & Grootens, 2016).
Different literature focusing on buildings in the Netherlands also portray brick masonry as the predominating facade system. Examples of these literature can be found in a series of well know journals in the Dutch architecture community known as, Architecture In The Netherlands - Yearbook, which always presents a selection of over 20 different projects each built in the Netherlands from around the given dates. From the last two volumes in these series the following facade systems were identified:

1) Brick Masonry
2) Precast Concrete Walls
3) Curtain Walls - Stick System
4) Concrete Masonry
5) Window Wall
6) Curtain Wall - Unitized System
7) Point Fitting System
8) Timber Frames
9) Timber Panels
10) SIPS (Structural Insulated Panels)
11) Sandwich Panels

Since brick masonry is mostly applied in cavity walls, a combination of at least two systems are always present. In this thesis the most common combination of systems will be explored, keeping always the same architectural look and feel of brick on the outside. More specific, the facade system assessment framework will evaluate the environmental impact, per m2 of wall, related to the different combinations of systems from the same facade system on the outside layer (brick masonry), to the different possible combinations on the inside layer, whose amount of material is dictated mainly by their acoustic, and thermal requirements. The step following the assessment outcome is that of optimization by redesign.

7.2) Identified Facade Systems

This section will present in detail the most common combinations of brick facade on the outer layer, in a cavity wall construction and multi-layered systems in the Netherlands. Assuming the brick masonry system is constant on the outer layer of the assembly, the different systems are divided into 4 main groups based on the inner layer: Panel systems, masonry systems, frame systems and board systems. The last group is composed in the same systems as the previous categories, but the cavity is replaced by an emerging technology in the Netherlands known as E-Board.

1) Panel Systems: The inner layers are composed by prefab components like prefab concrete panels and CLT panels.

1a) Brick and Prefab Concrete Panel Cavity Wall: This facade system is composed of a brick outer layer, with a 40 mm cavity, and prefab concrete sandwich panels on the inner layer. The concrete sandwich panels contain an insulation layer in the middle, in order to provide thermal and acoustic protection. Additionally, the inner face of the prefab sandwich panels are treated with gypsum plaster.

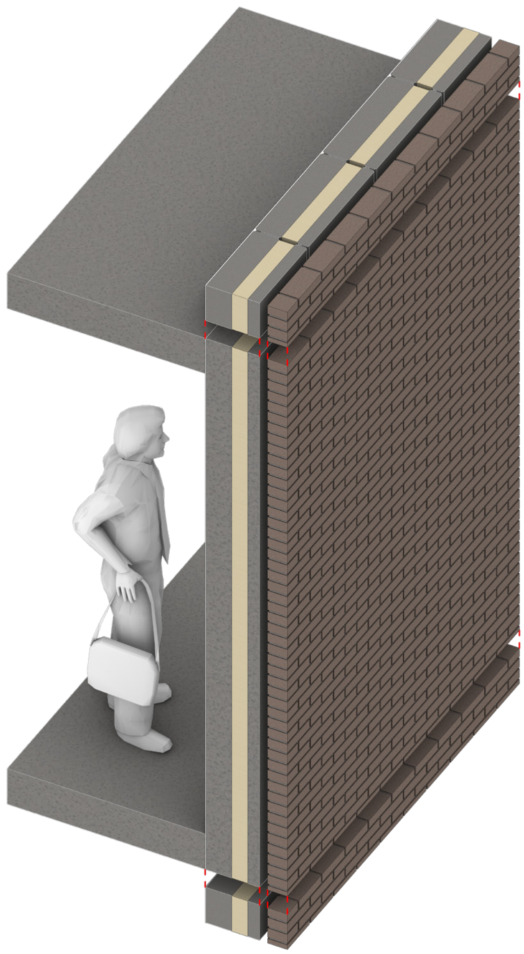


Figure 7.1 Axonometric of brick and prefab concrete panel cavity wall system.

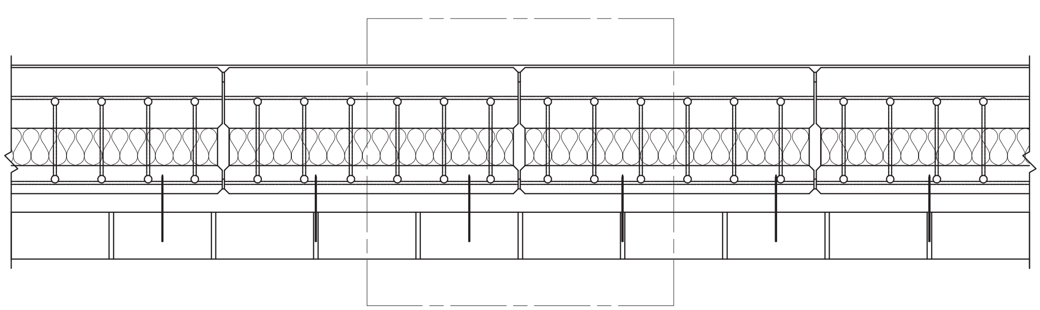


Figure 7.2 Top view of brick and prefab concrete panel cavity wall system.

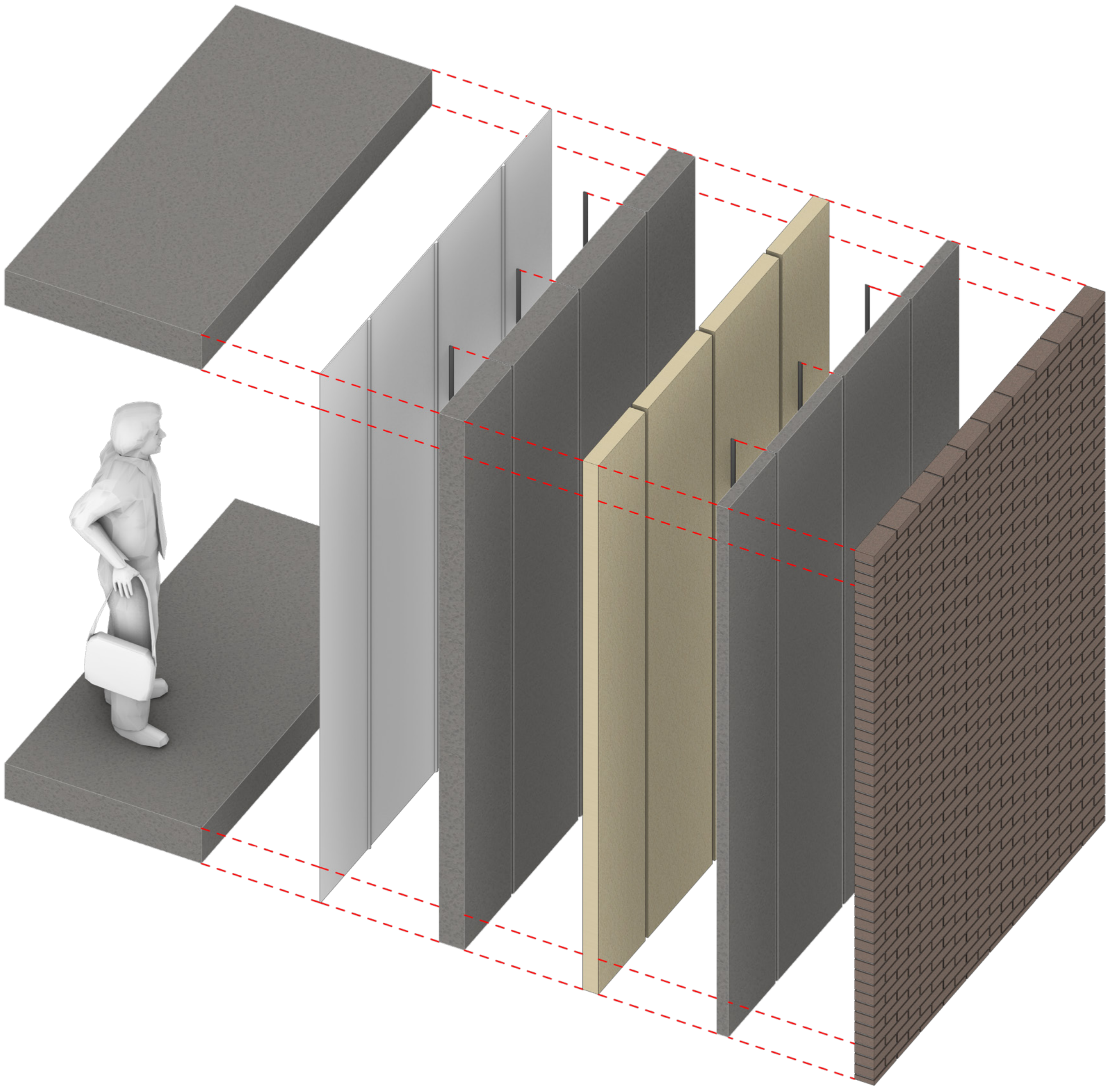


Figure 7.3 Exploded axonometric of brick and prefab concrete panel cavity wall system.

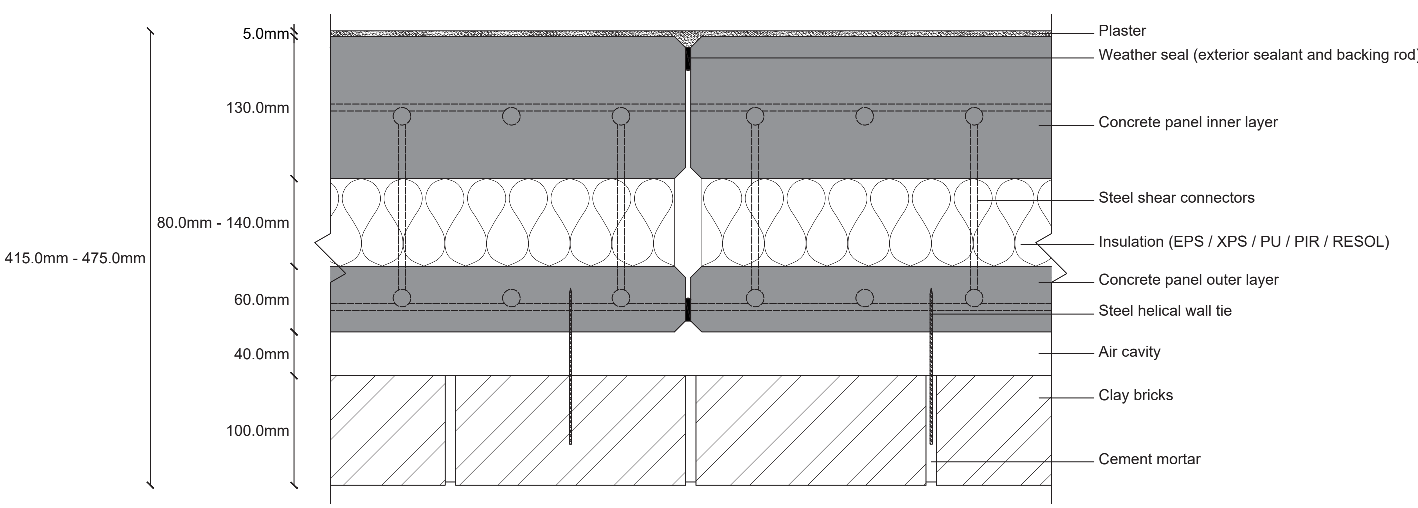


Figure 7.4 Top view detail of brick and prefab concrete panel cavity wall system.

1b) Brick and CLT Cavity Wall: In this facade system, the outer layer is composed of clay bricks, this are then followed by a 40 mm cavity, which separates the thermal insulation and the cross laminated timber (CLT) panels that make up the inner layer. The outer face of the CLT panels are covered with a very thin sheet of vapor retarder, which avoids internal condensation inside these elements. The inner face of the timber panels are covered with thin gypsum boards.

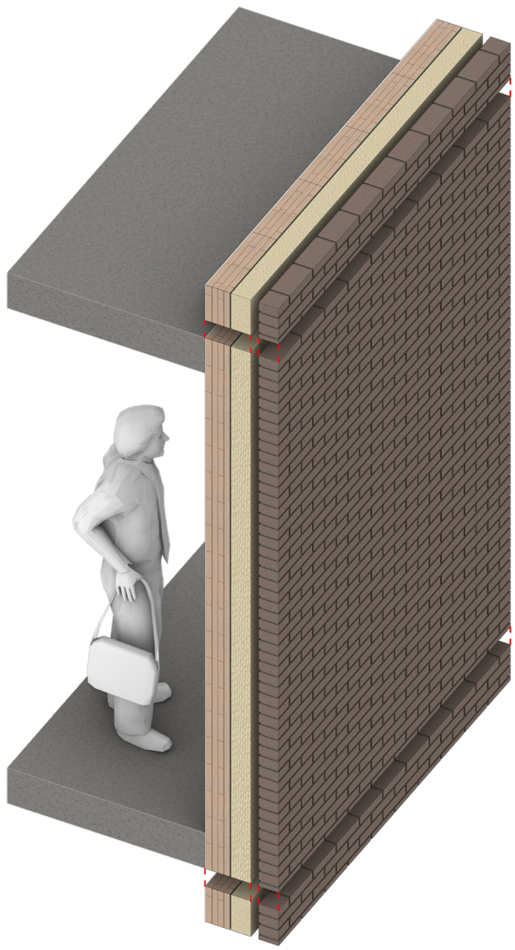


Figure 7.5 Axonometric of brick and CLT cavity wall system.

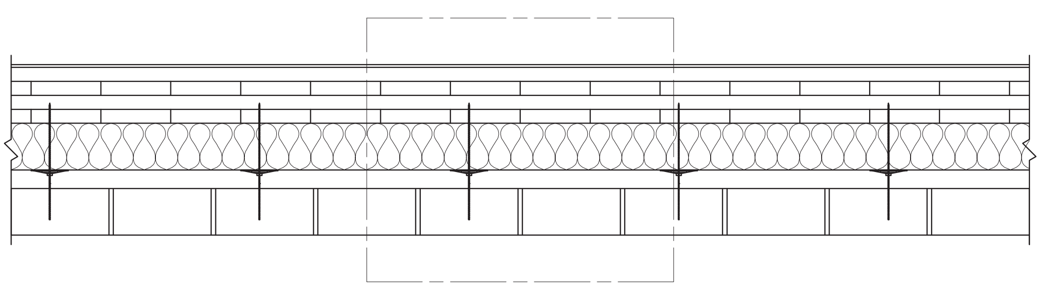


Figure 7.6 Top view of brick and CLT cavity wall system.

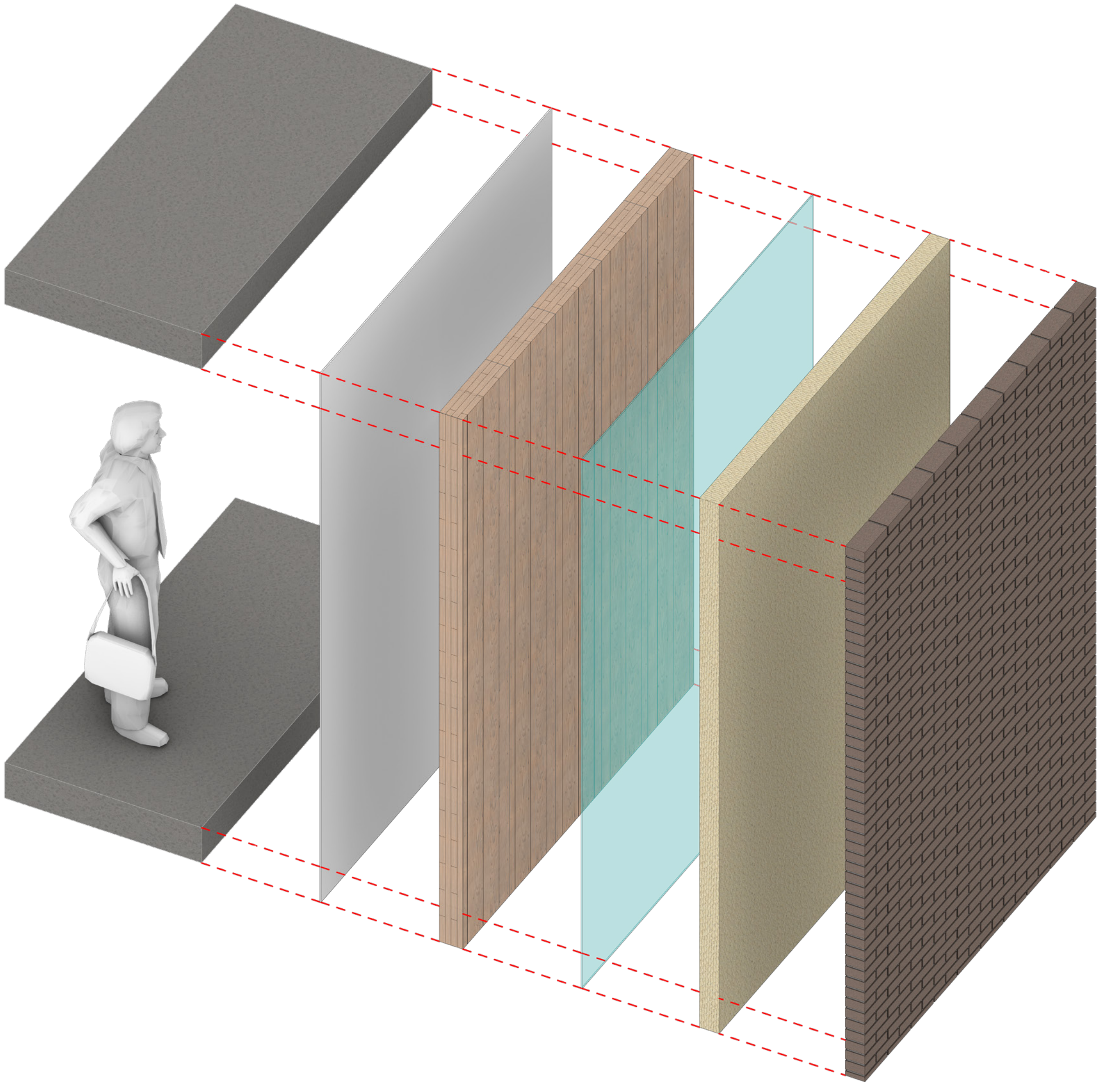


Figure 7.7 Exploded axonometric of brick and CLT cavity wall system.

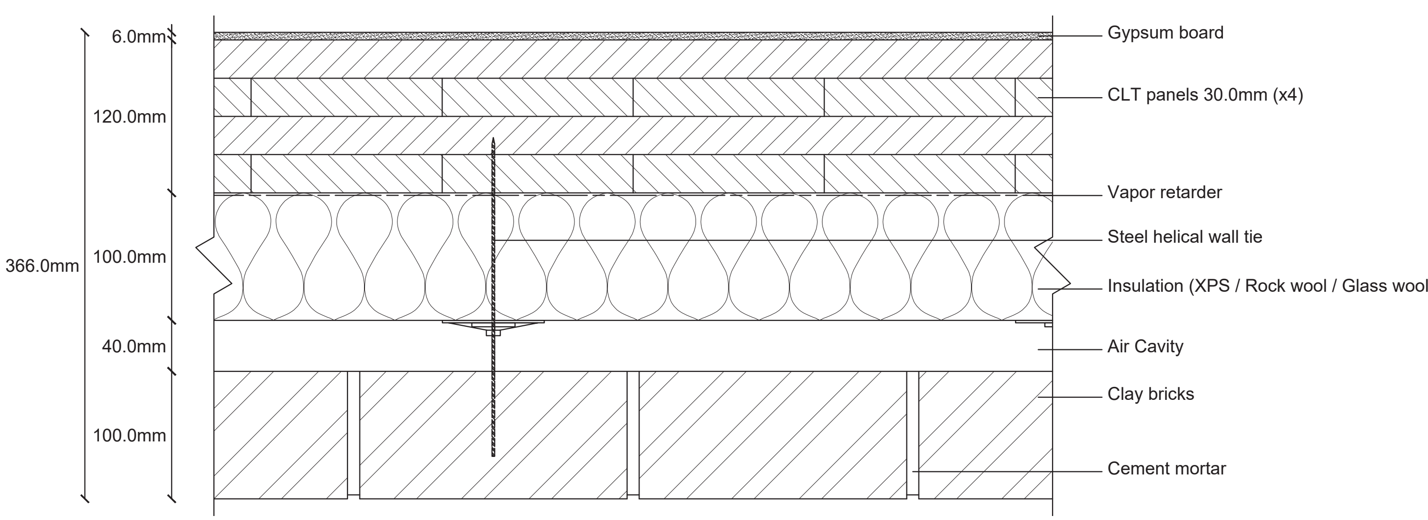


Figure 7.8 Top view detail of brick and CLT cavity wall system.

2) Masonry Systems: The inner layers are comprised of masonry facade systems like sand lime blocks (Kalksandsteen in dutch) and Concrete Masonry Units (CMU).

2a) Brick and Sand Lime Block Cavity Wall: This facade system is purely built by using masonry techniques, as both the inner and outer layers are assembled using this method. A clay brick wall makes up the outer layer, which is separated from the inner layer by a 40 mm cavity. The inner layer consists of a thermal insulation layer, followed by sand-lime blocks, which are composed of sand, gravel, quicklime (calcium oxide), and stone powder (Bundesver band Kalksandsteinindustrie e.V., 2016). These blocks are put together by using mortar, in the same way a brick wall is built. Similarly to the previous systems, the inner face of the lime-sand blocks are covered with gypsum plaster.

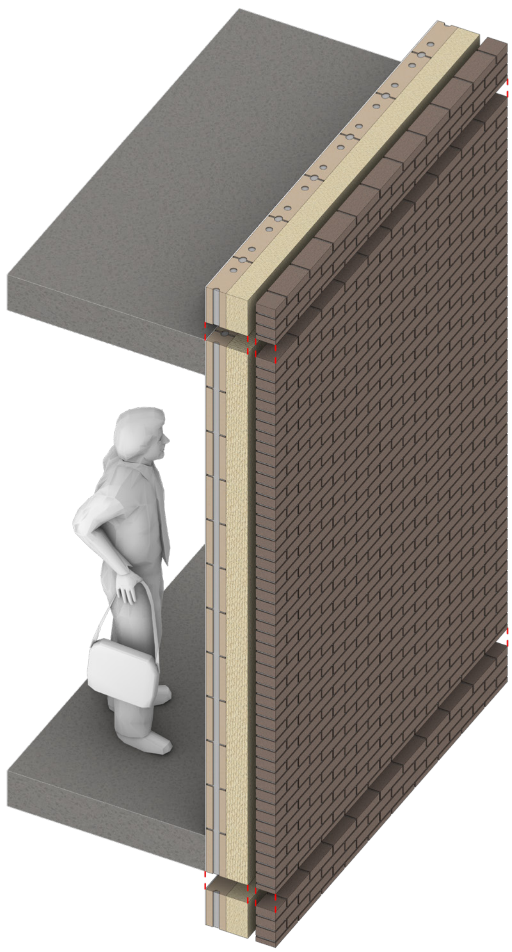


Figure 7.9 Axonometric of brick and sand lime block cavity wall system.

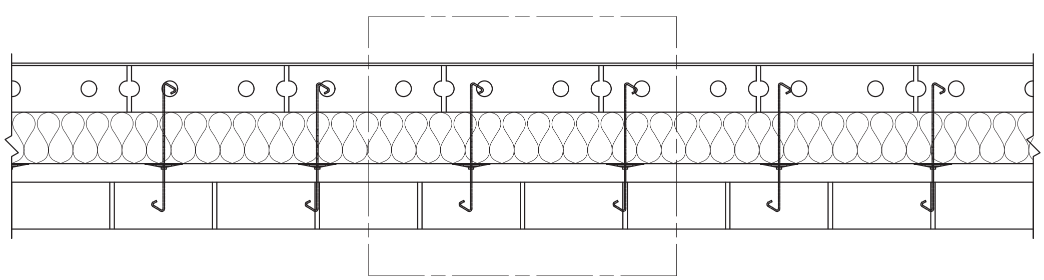


Figure 7.10 Top view of brick and sand lime block cavity wall system.

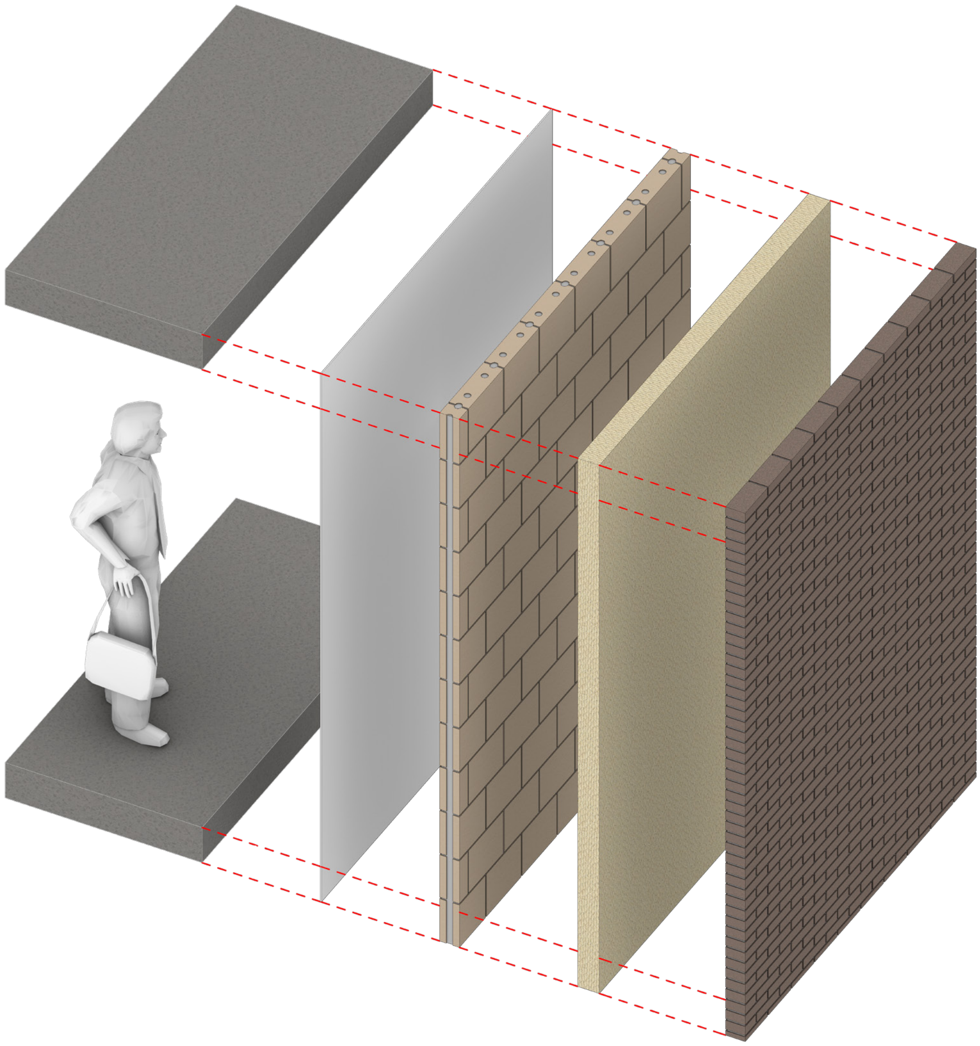


Figure 7.11 Exploded axonometric of brick and sand lime block cavity wall system.

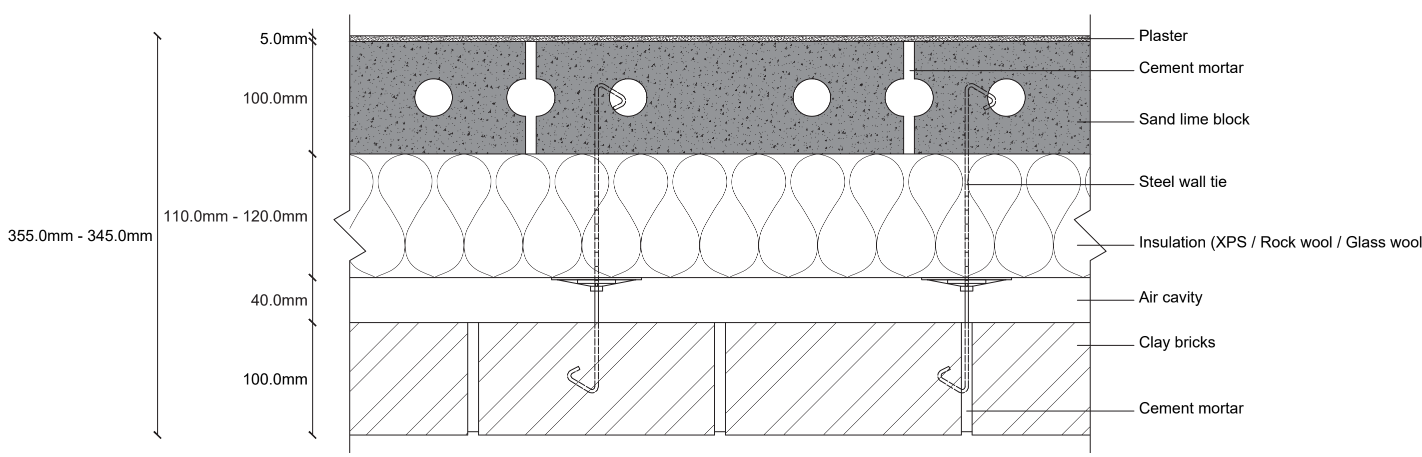


Figure 7.12 Top view detail of brick and sand lime block cavity wall system.

2b) Brick and CMU cavity wall system: In the same way as the previous facade system (brick and sand-lime block cavity wall), both the inner and outer layer of this system are built using masonry techniques. The outer layer is composed of brick with a 40 mm cavity, that separates it from the inner layer. This layer is composed of thermal insulation, followed by concrete masonry units (CMU). Finally, the inner face of the CMUs are treated with a layer of gypsum plaster.

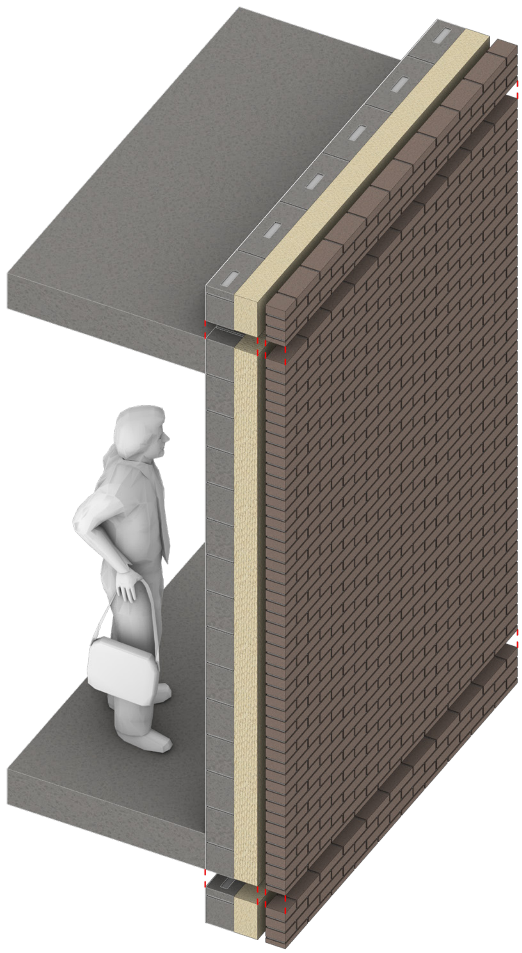


Figure 7.13 Axonometric of brick and CMU cavity wall system.

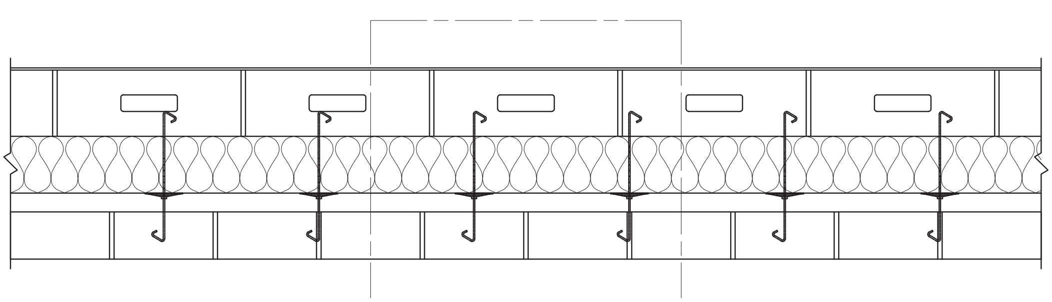


Figure 7.14 Top view of brick and CMU cavity wall system.

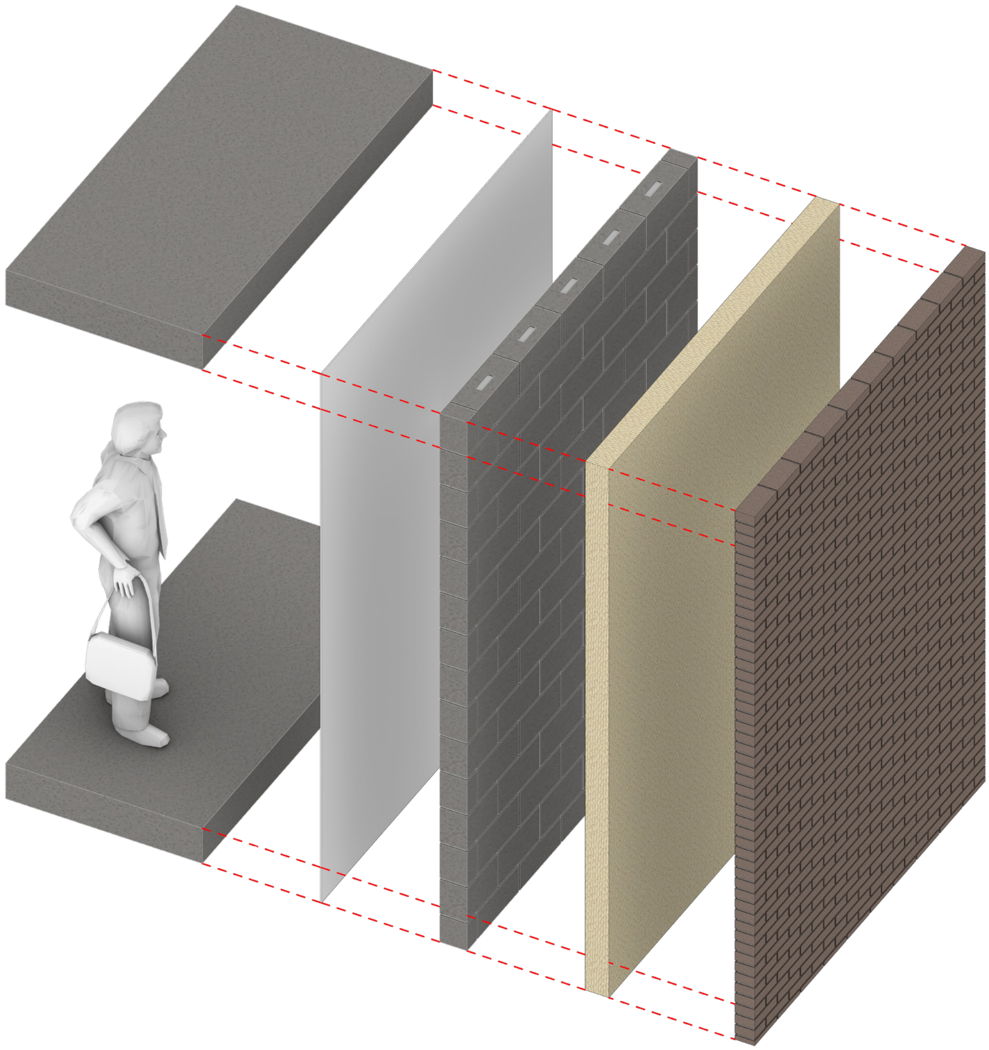


Figure 7.15 Exploded axonometric of brick and CMU cavity wall system.

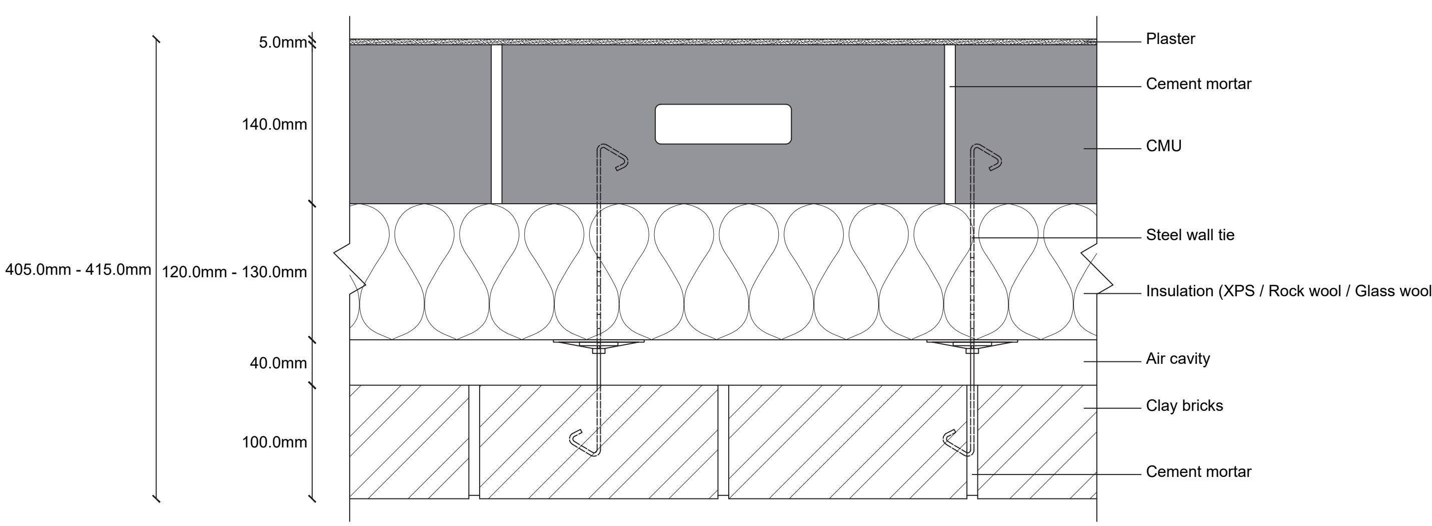


Figure 7.16 Top view detail of brick and CMU cavity wall system.

3) Timber Frame Systems: This category includes the timber frames facade system.

3a) Brick and Timber Frames Cavity Wall: This facade system the outer layer consists of clay bricks, which are separated from the inner layer by the same cavity width as the previous systems (40 mm). The inner layer is composed of 2 layers of oriented strand board (OSB), which are connected by timber studs. The empty space in between the OSB layers are filled with thermal insulation. In the same way as in the CLT facade system, the inner face of the timber frame is covered with gypsum boards.

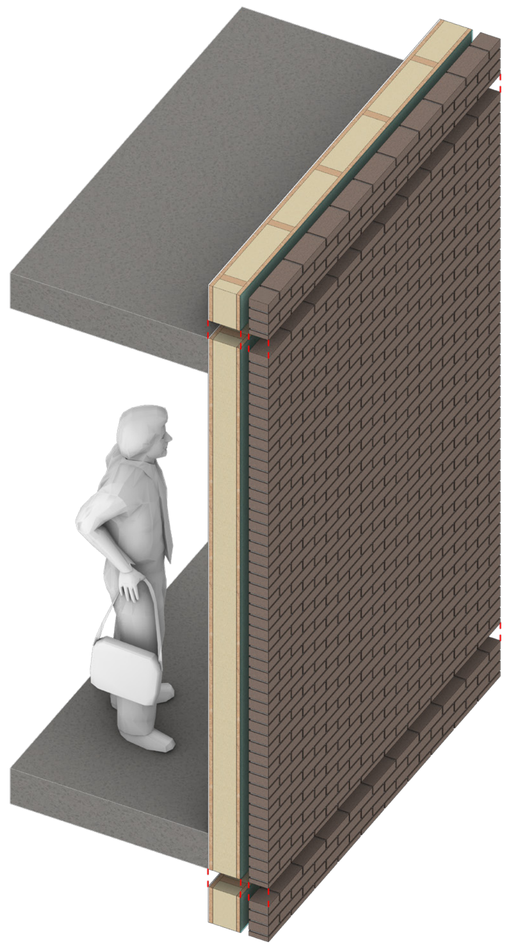


Figure 7.17 Axonometric of brick and timber frame cavity wall system.

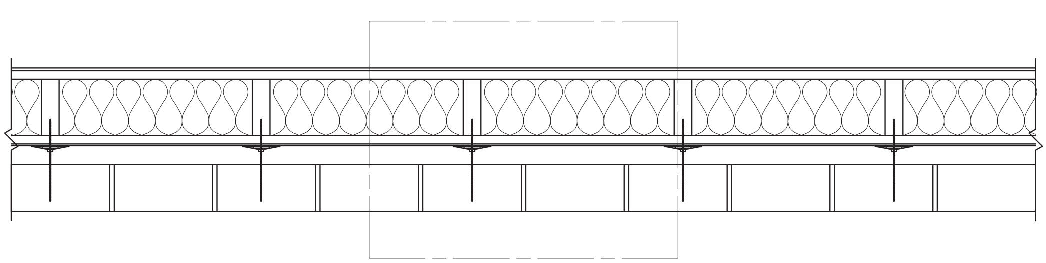


Figure 7.18 Top view of brick and timber frame cavity wall system.

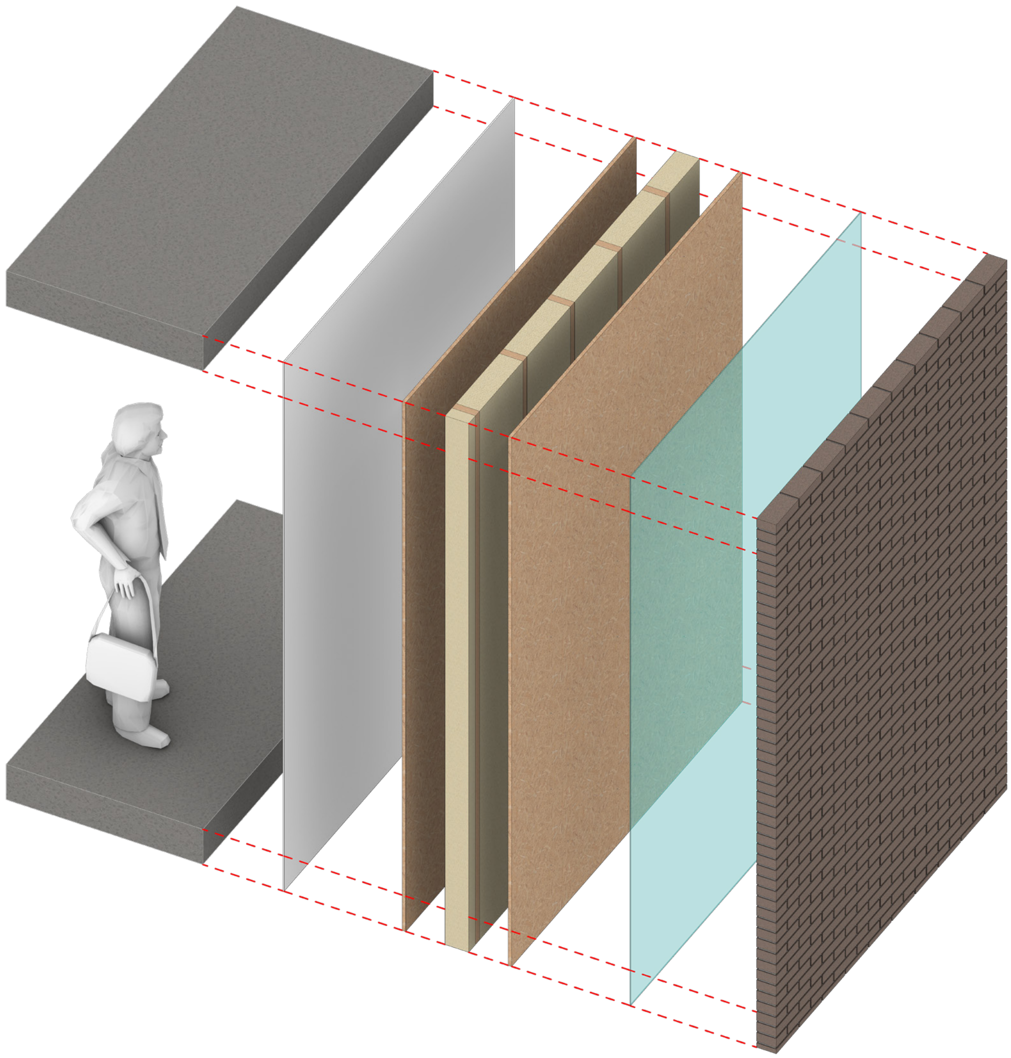


Figure 7.19 Exploded axonometric of brick and timber frame cavity wall system.

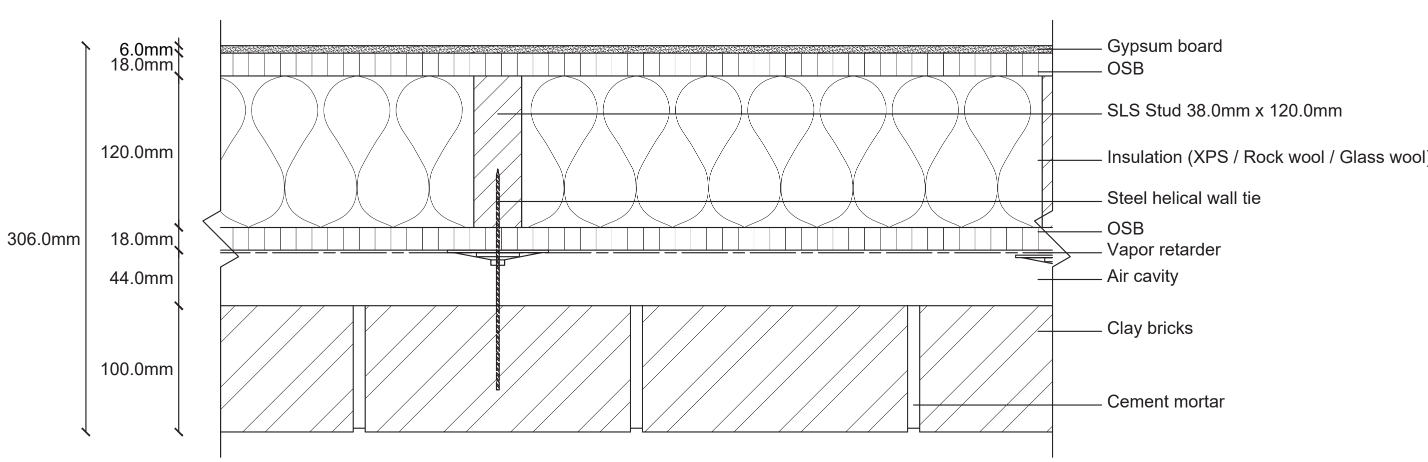


Figure 7.20 Top view detail of brick and timber frame cavity wall system.

4) Board Systems: In this category the air cavity is replaces by E-Board, which is a technology used in the Netherlands mainly produced by Vandersanden. It consists of an EPS (expanded polystyrene) layer from which brick slips are connected by mortar. Helical wall ties connect the EPS layer with the inner layers.

4a) E-Board and Prefab Concrete Panel Wall: This multi-layered facade is composed of an outer face made up of clay brick slips, which are connected to the inner prefab concrete panels by an EPS insulation layer.

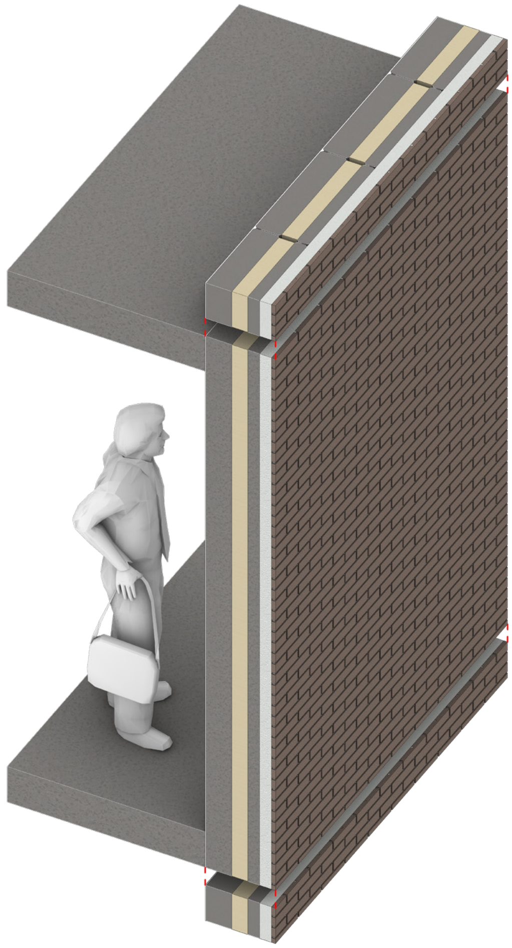


Figure 7.21 Axonometric of E-board and prefab concrete panel wall system.

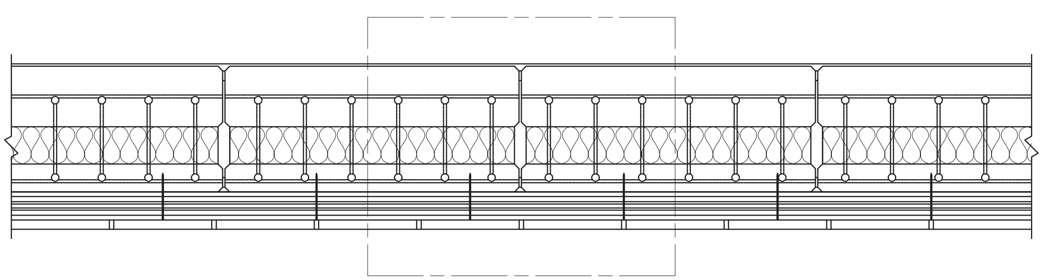


Figure 7.22 Top view of E-board and prefab concrete panel wall system.

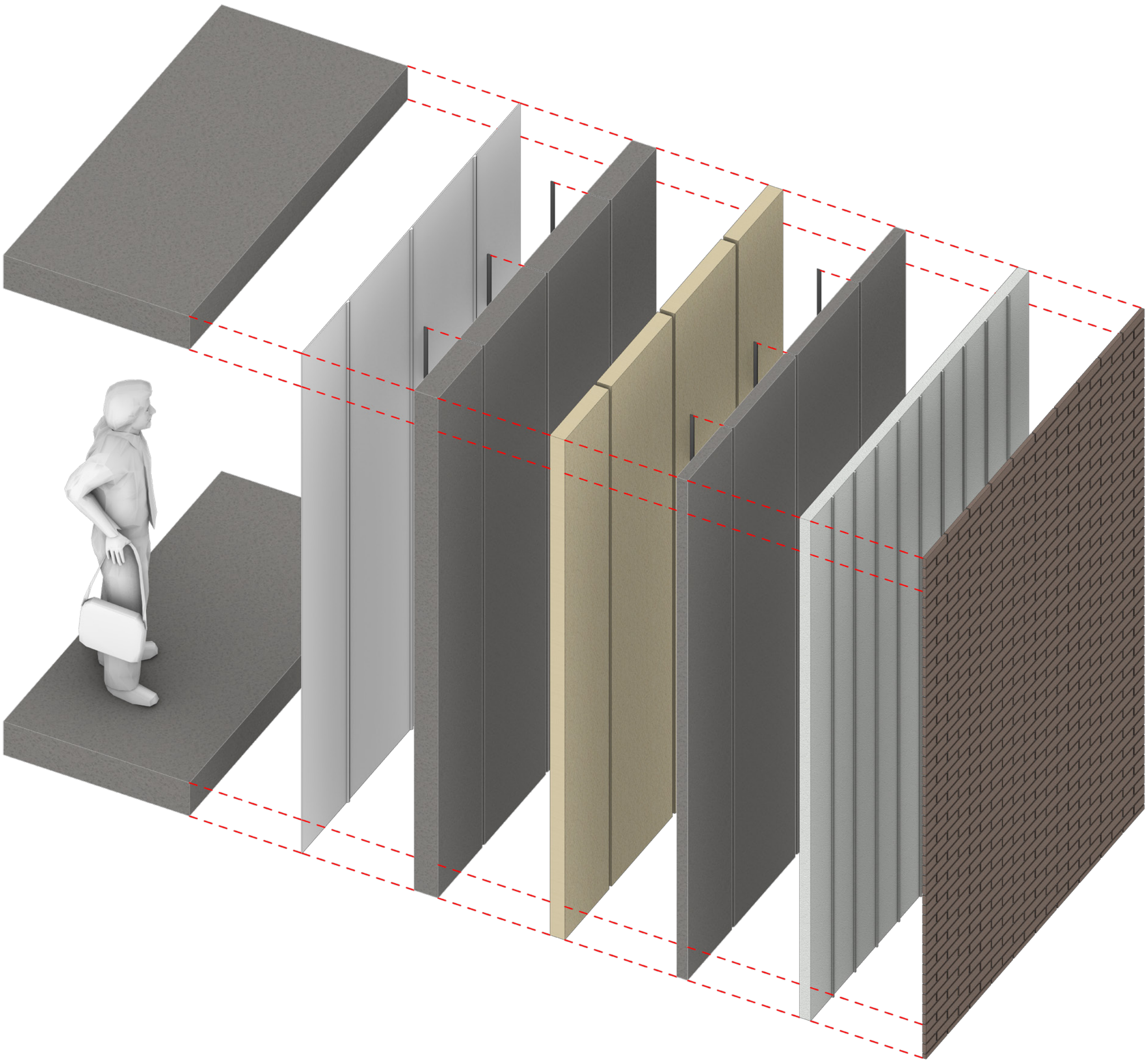


Figure 7.23 Exploded axonometric of E-board and prefab concrete panel wall system.

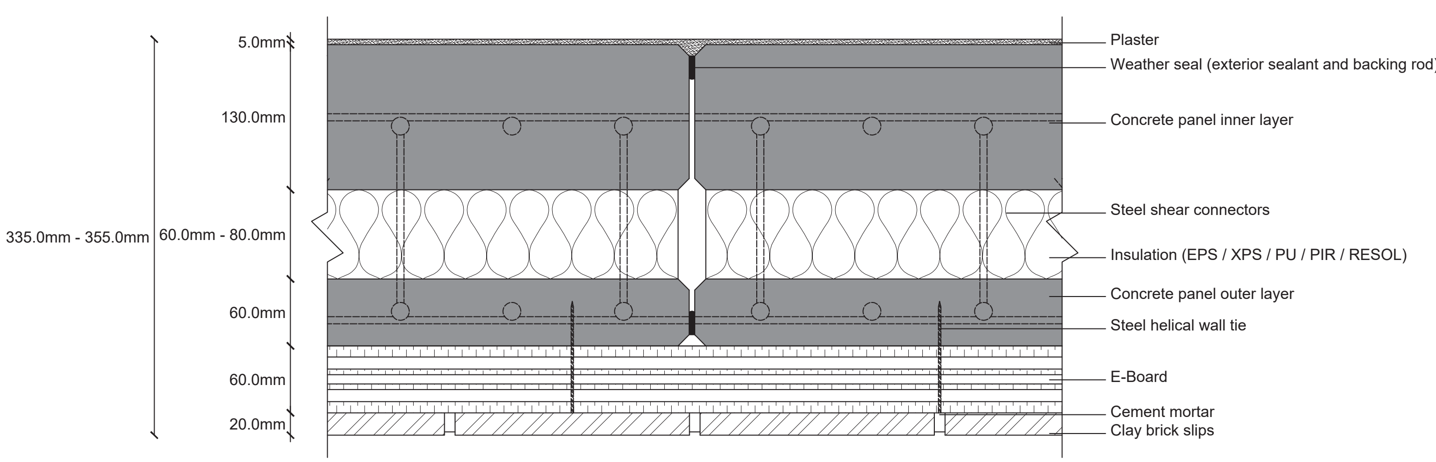


Figure 7.24 Top view detail of E-board and prefab concrete panel wall system.

4b) E-Board and CLT Wall: In this facade system an outer layer of clay brick slips are connected to the inner layer of CLT panels, by the EPS insulation layer or e-board.

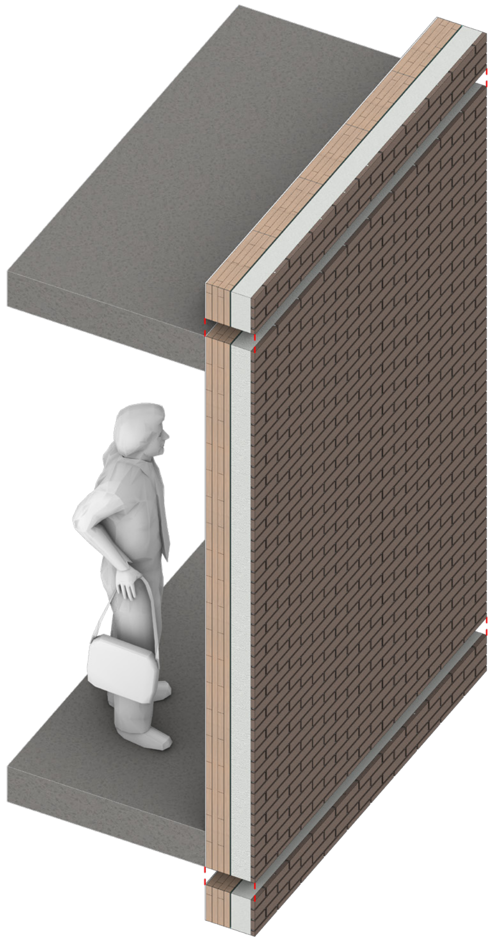


Figure 7.25 Axonometric of E-board and CLT wall system.

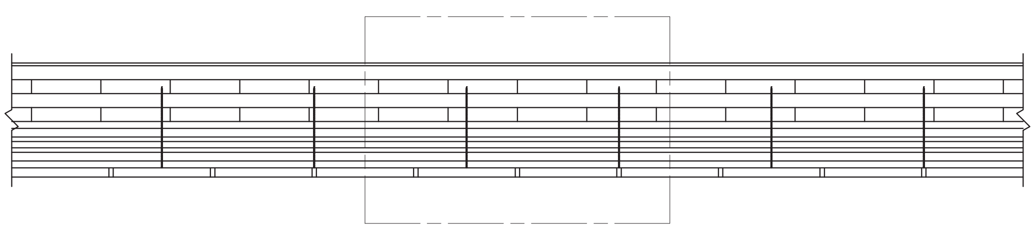


Figure 7.26 Top view of E-board and CLT wall system.

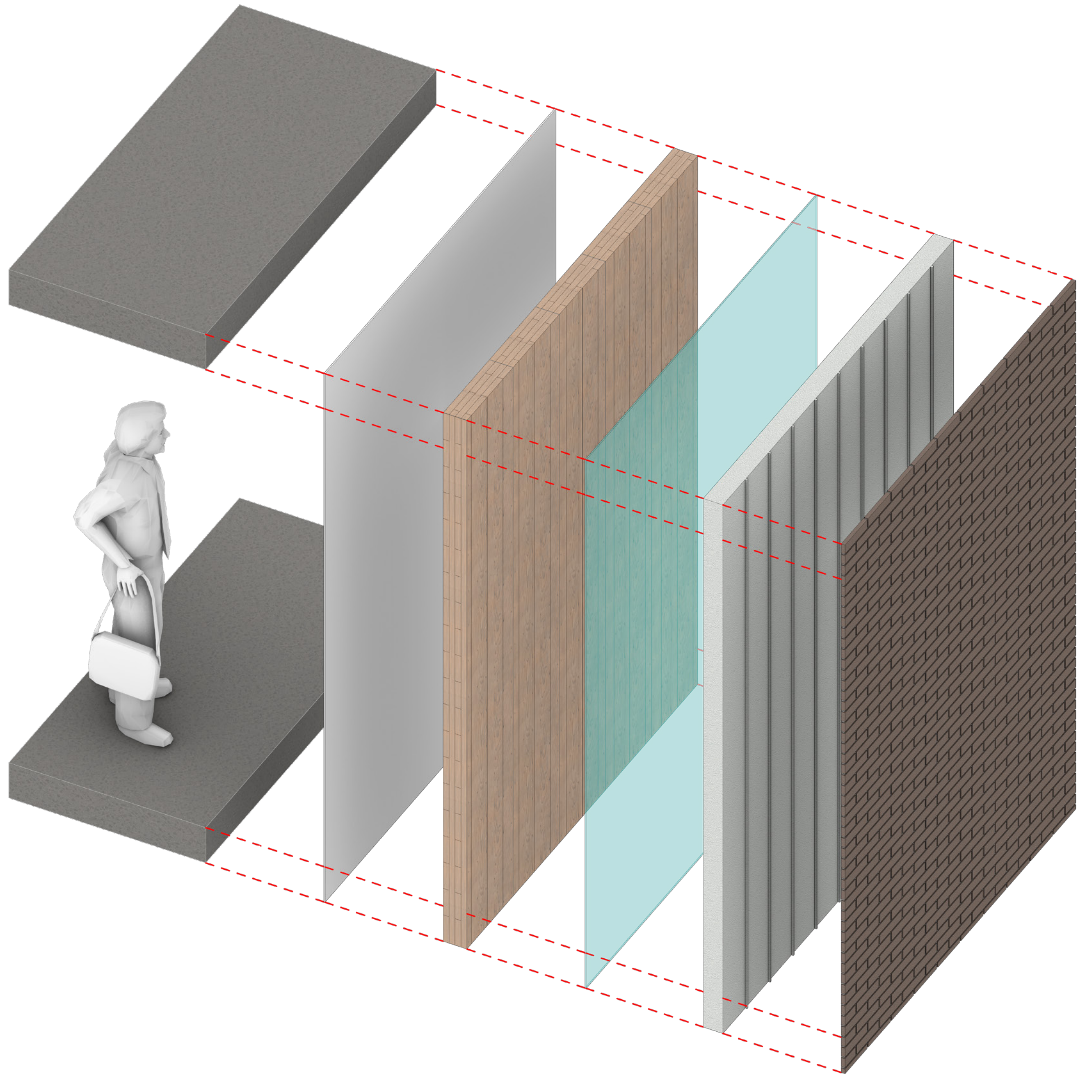


Figure 7.27 Exploded axonometric of E-board and CLT wall system.

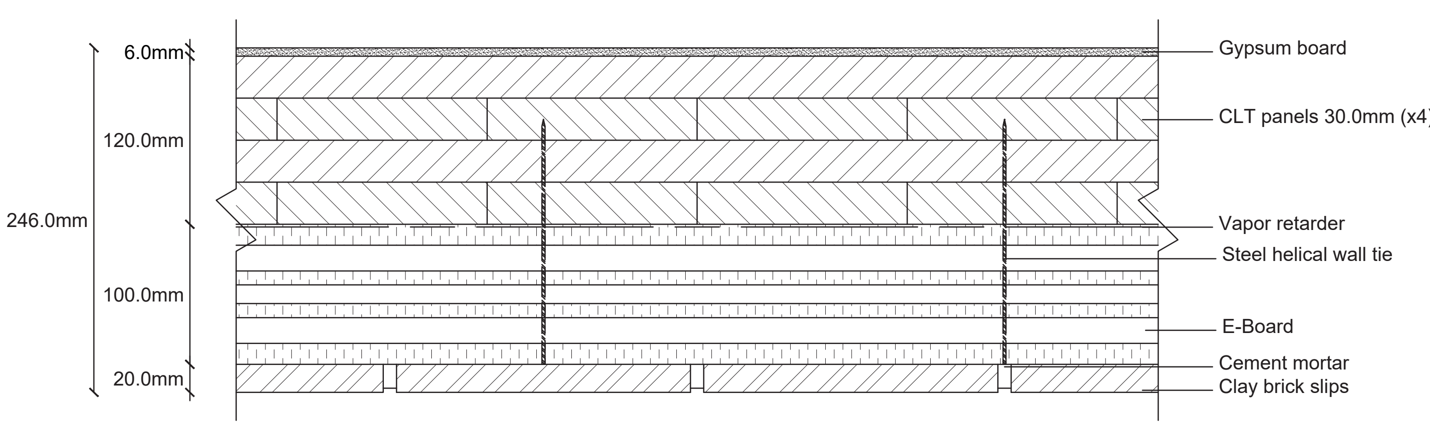


Figure 7.28 Top view Detail of E-board and CLT wall system.

4c) E-Board and Sand-Lime Block Wall: The inner layer, composed of sand-lime blocks, is connected to the E-board, which is at the same time attached with the outer layer of clay brick slips in this facade system.

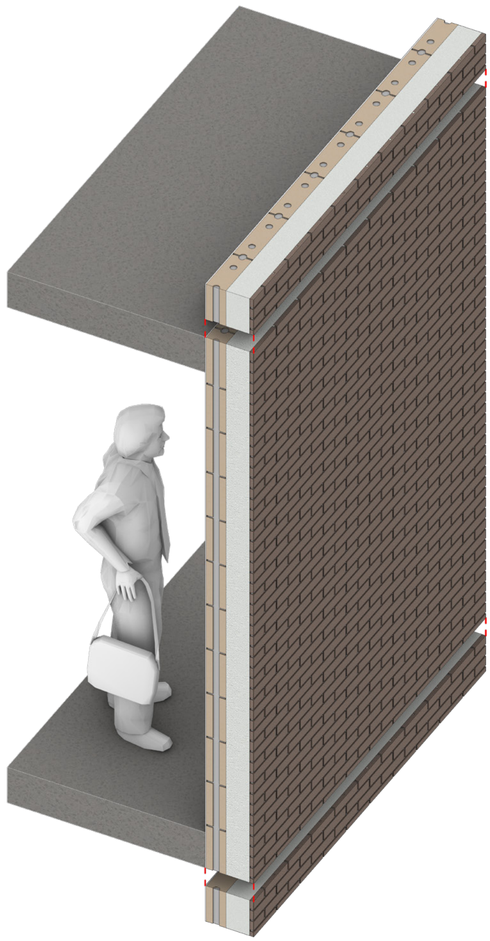


Figure 7.29 Axonometric of E-board and sand-lime block wall system.

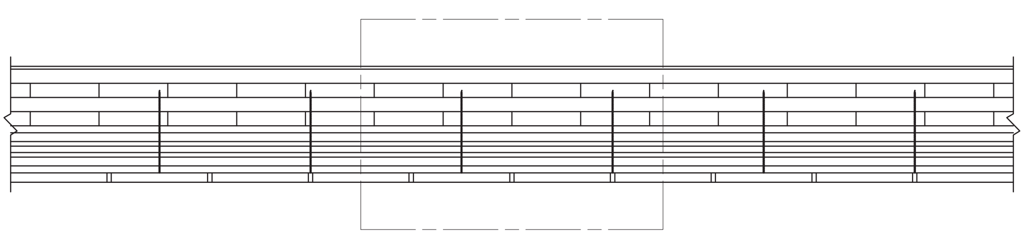


Figure 7.30 Top view of E-board and sand-lime block wall system.

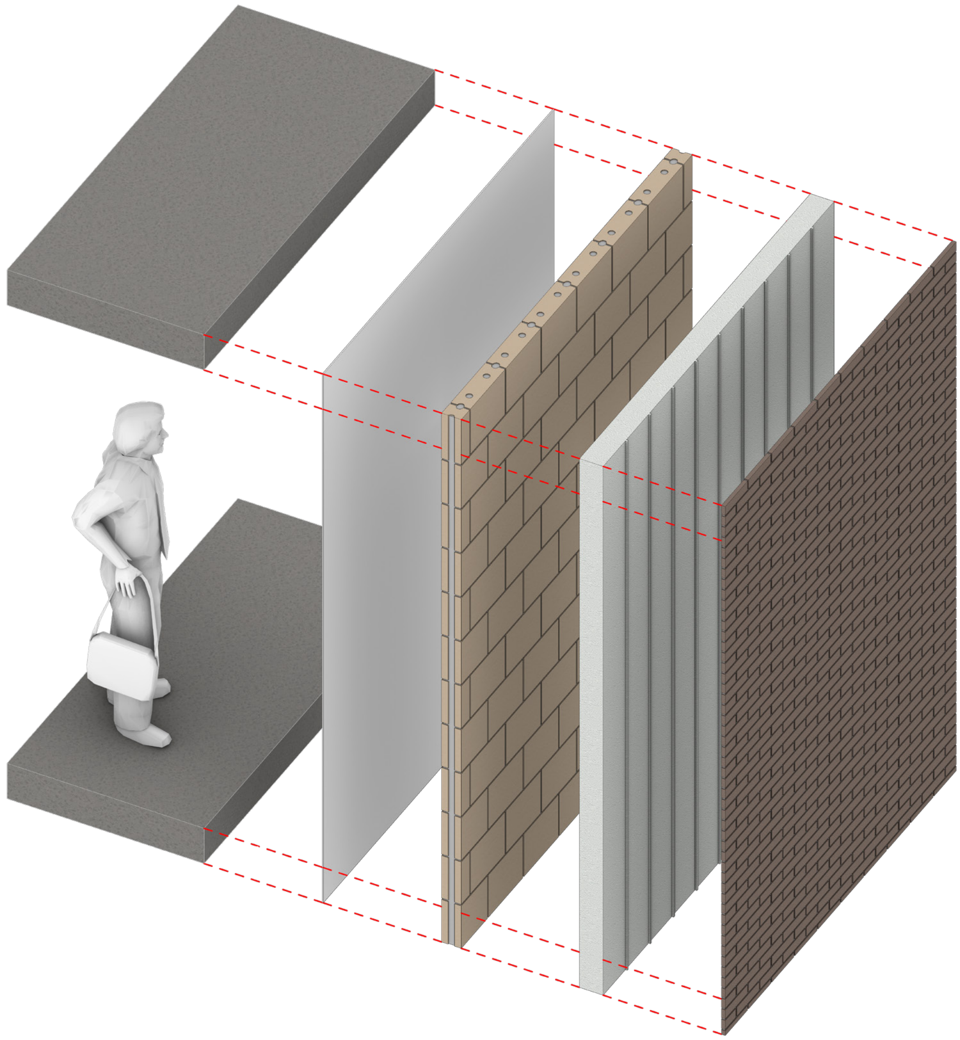


Figure 7.31 Exploded axonometric of E-board and sand-lime block wall system.

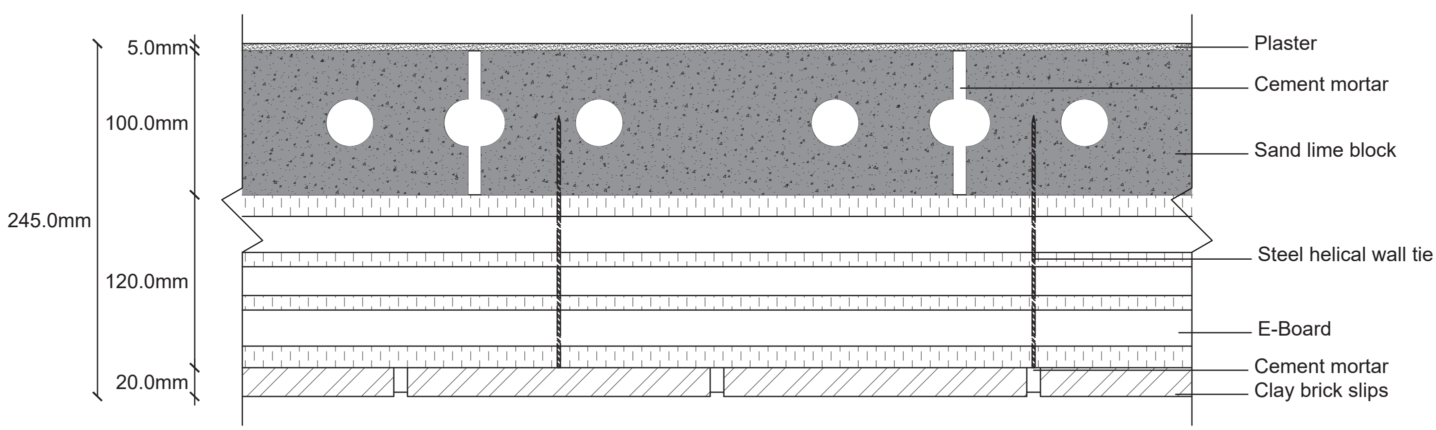


Table 7.1 Top view detail of E-board and sand-lime block wall system.

4d) E-Board and CMU Wall: The layering of this facade system consists of an outer layer of brick slips attached to e-boards, which are then followed by an inner layer composed of concrete masonry units (CMUs). These blocks are joined in the same way bricks are, by using cement or lime mortar.

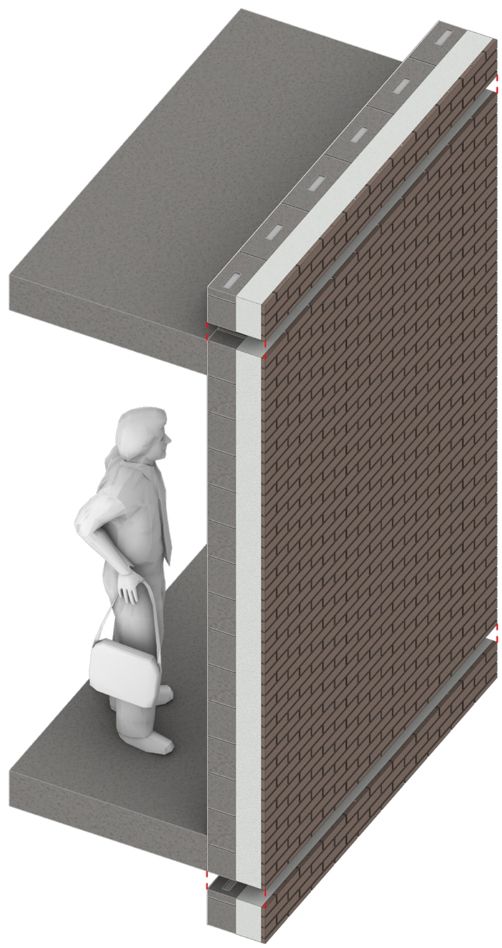


Figure 7.32 Axonometric of E-board and CMU wall system.

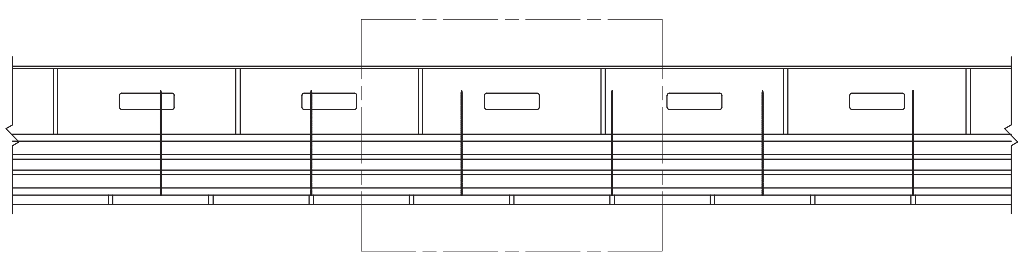


Figure 7.33 Top view of E-board and CMU wall system.

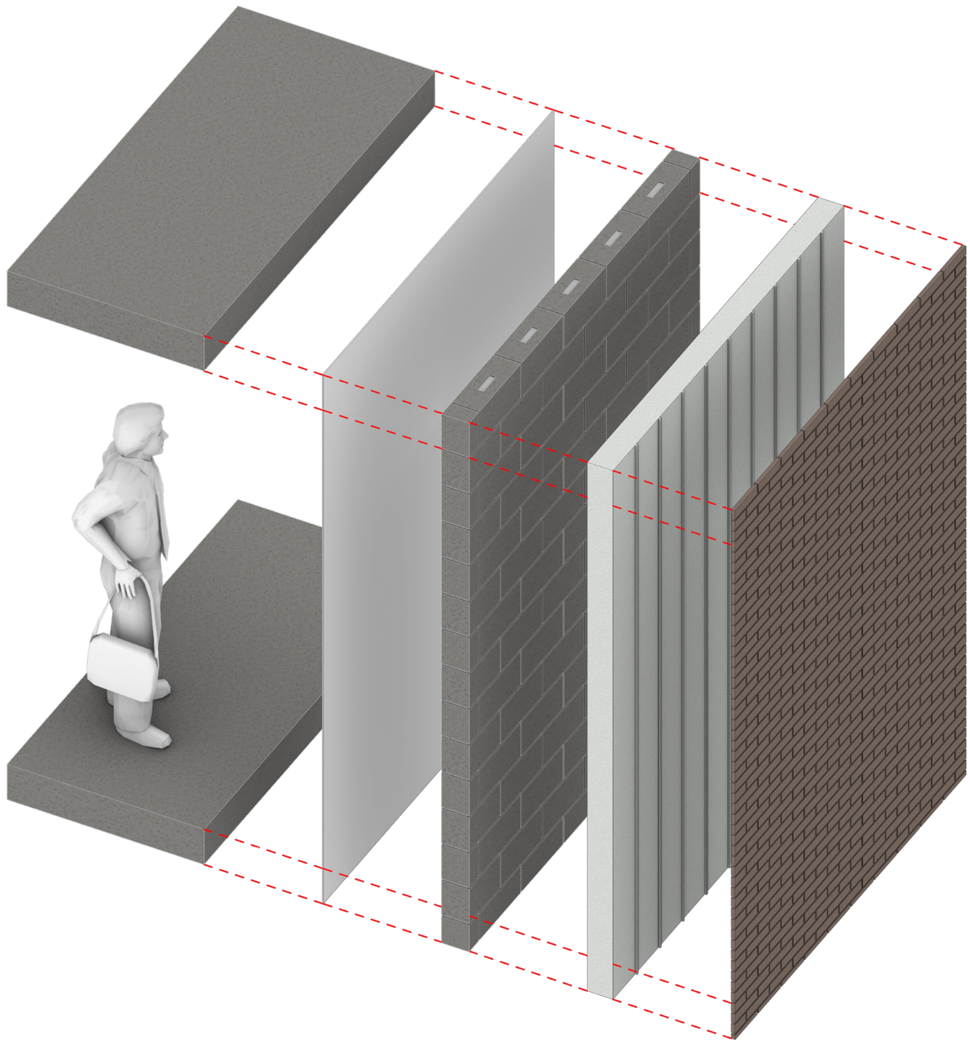


Figure 7.34 Exploded axonometric of E-board and CMU wall system.

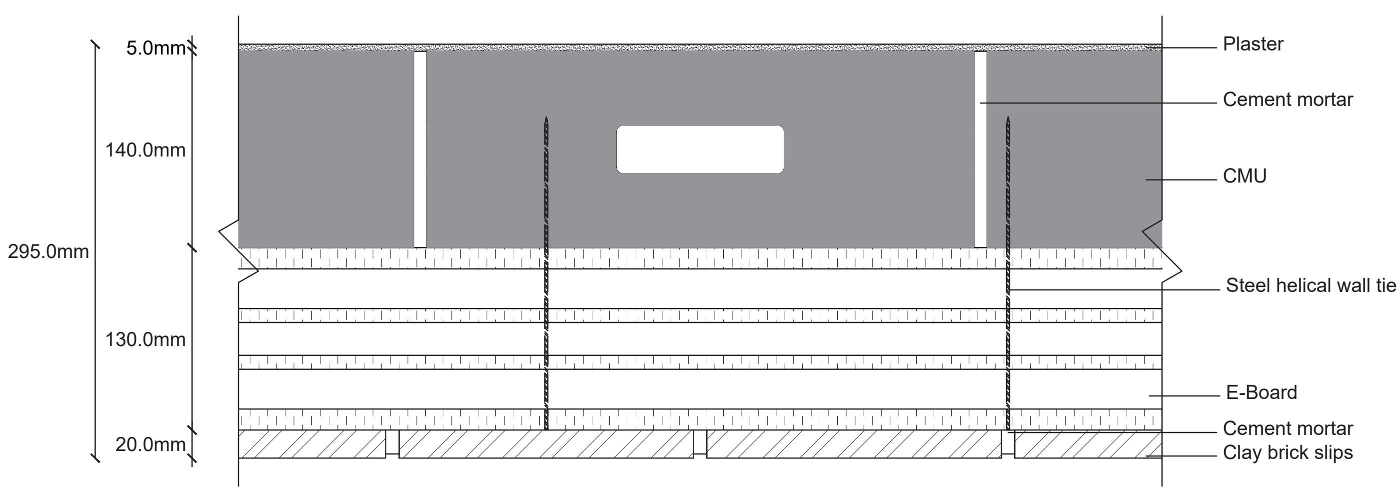


Figure 7.35 Top view detail of E-board and CMU wall system.

4e) E-Board and Timber Frames Wall: In the same way as the brick and timber frames cavity wall system (3a), the inner layer is composed of a timber panel, which consists of two external layer of OSB, separated and connected by timber studs. The empty spaces in between the studs are filled with thermal insulation. This whole timber layer is connected to the outer layer of brick slips by the e-board.

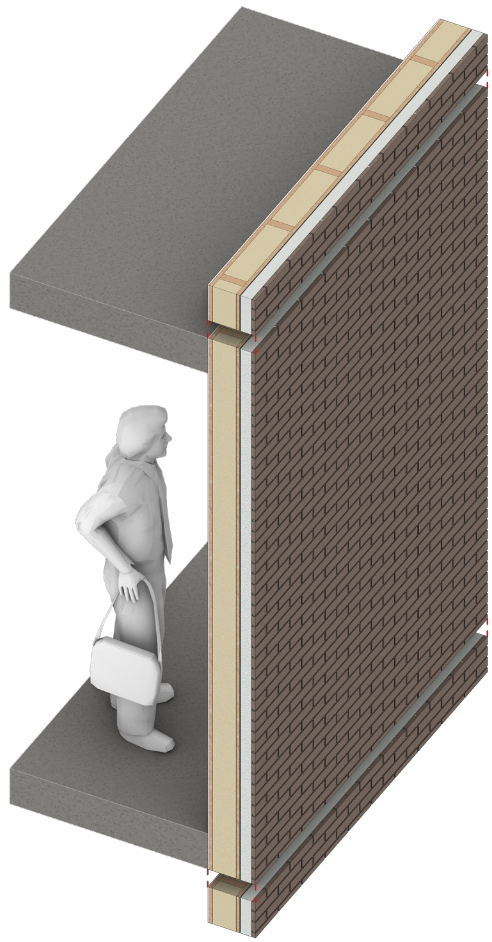


Figure 7.36 Axonometric of E-board and timber frame wall system.

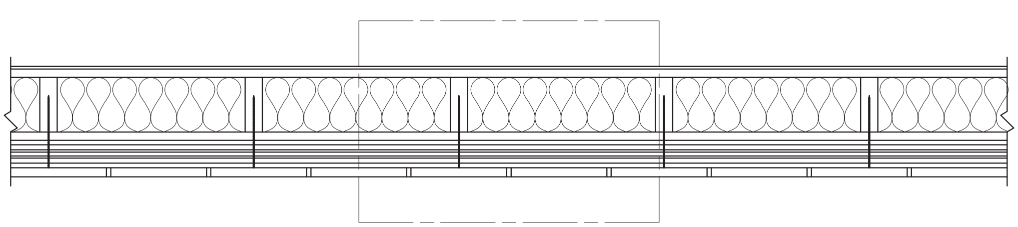


Figure 7.37 Top view of E-board and timber frame wall system.

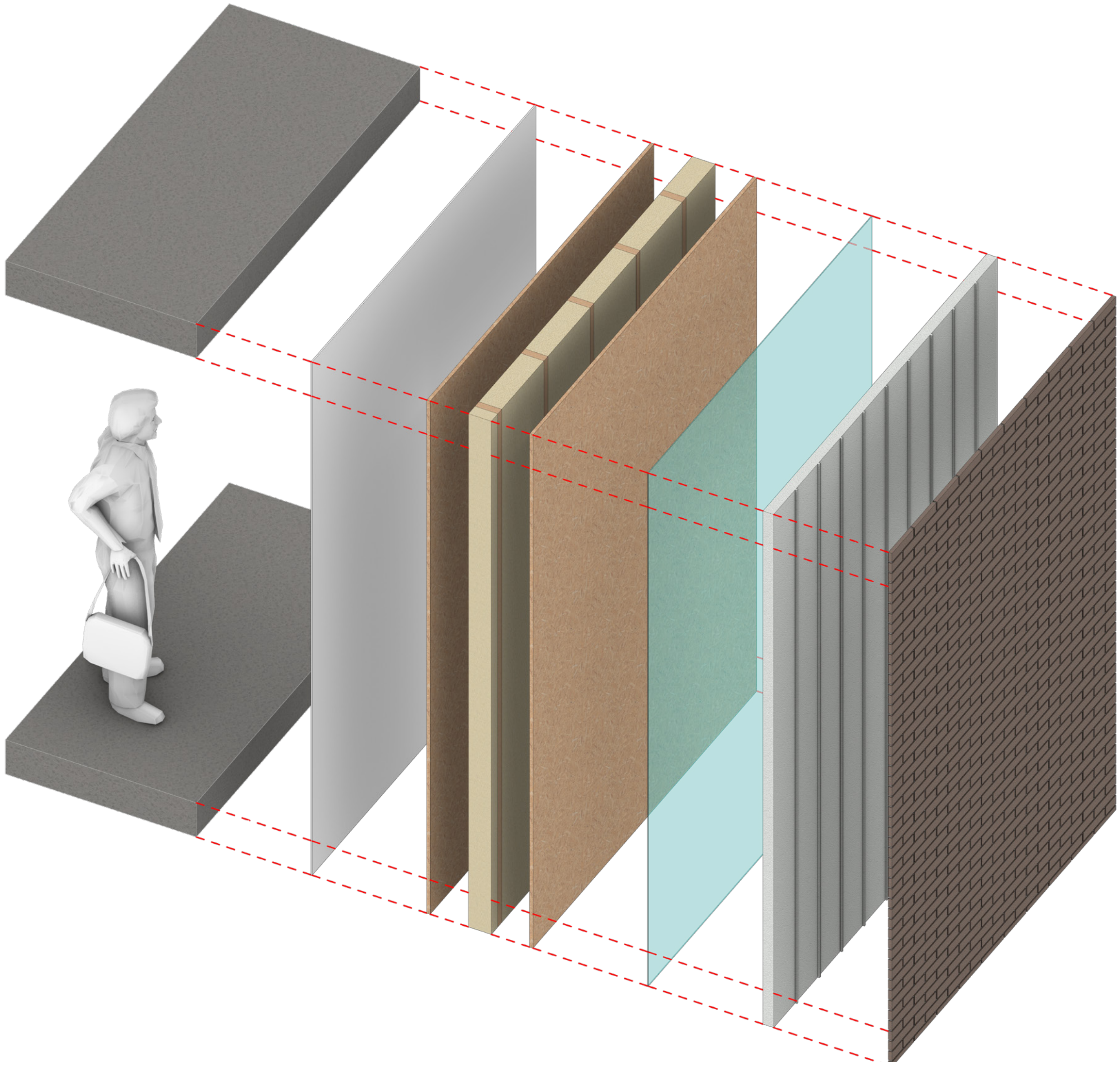


Figure 7.38 Exploded axonometric of E-board and timber frame wall system.

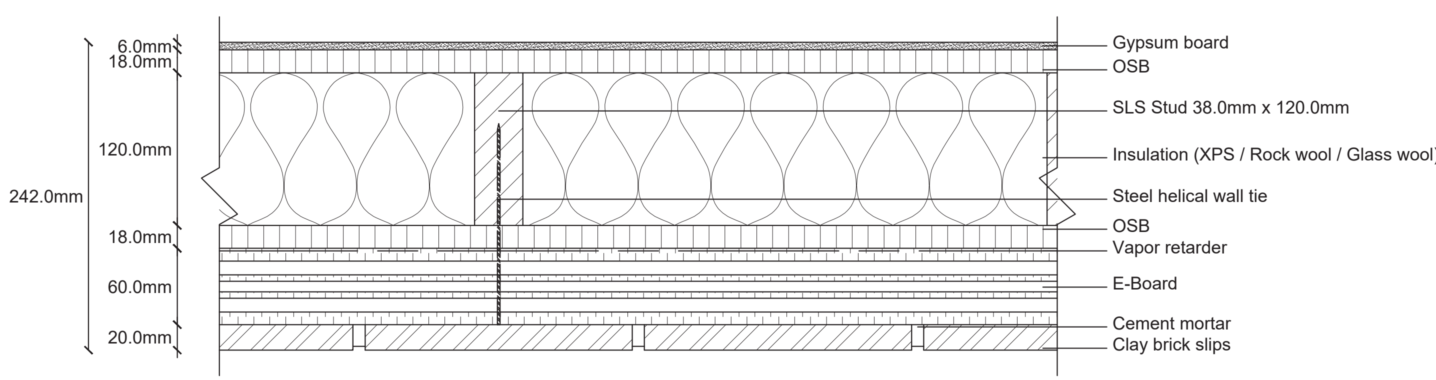


Figure 7.39 Top view detail of E-board and timber frame wall system.

7.3) Evaluating the Identified Facade Systems

After defining the traditional arrangement and composition of the previous facade systems, a formal evaluation to determine their environmental impact in terms of embodied energy and global warming potential or carbon footprint can be established. In the next chapter (6), different assessments are conducted in order to evaluate the embodied energy and the CO2 emissions of the identified facade systems related to their thermal and acoustic performance. In order to realize this evaluation, the environmental impact of the different components inside the facade systems, as shown in this chapter, are evaluated individually and summed together.

It is worth pointing out that by defining and analyzing all the different components that make up any facade system, the environmental impact can be estimated by applying the evaluation strategies presented in chapter 6. This information is useful for any engineer or designer aiming to decrease the ecological impact attributed to the act of building a facade, while at the same time looking for the best thermal and acoustic performance.

8) Facade Systems Assessment

8.1) The Assessment Strategy

After identifying the material arrangement and composition of all the previous facade systems an overall assessment in terms of embodied energy and CO_2 per m^2 of wall can be performed. However the environmental impact of any kind of construction is not the only important aspect to consider, in fact it is seldom the main or only objective when designing a building, component or product. Therefore the embodied energy and CO_2 emissions of the materials are measured against the airborne sound insulation and thermal insulation of the systems under evaluation. The objective behind the evaluations is to select the facade system which has the biggest environmental impact contribution in order to achieve a certain acoustic and thermal insulation level, as optimizing such system will have the highest contribution in environmental impact reduction.

The following sections presents the aforementioned assessments and provides the resulting data in the form of graphs, which makes the selection process easier and more efficient. By the end of this chapter the facade system responsible for the highest environmental impact is selected to be used in the development of the case studies that follow in the next chapter (7).

8.2) Environmental Impact of the Selected Facade Components

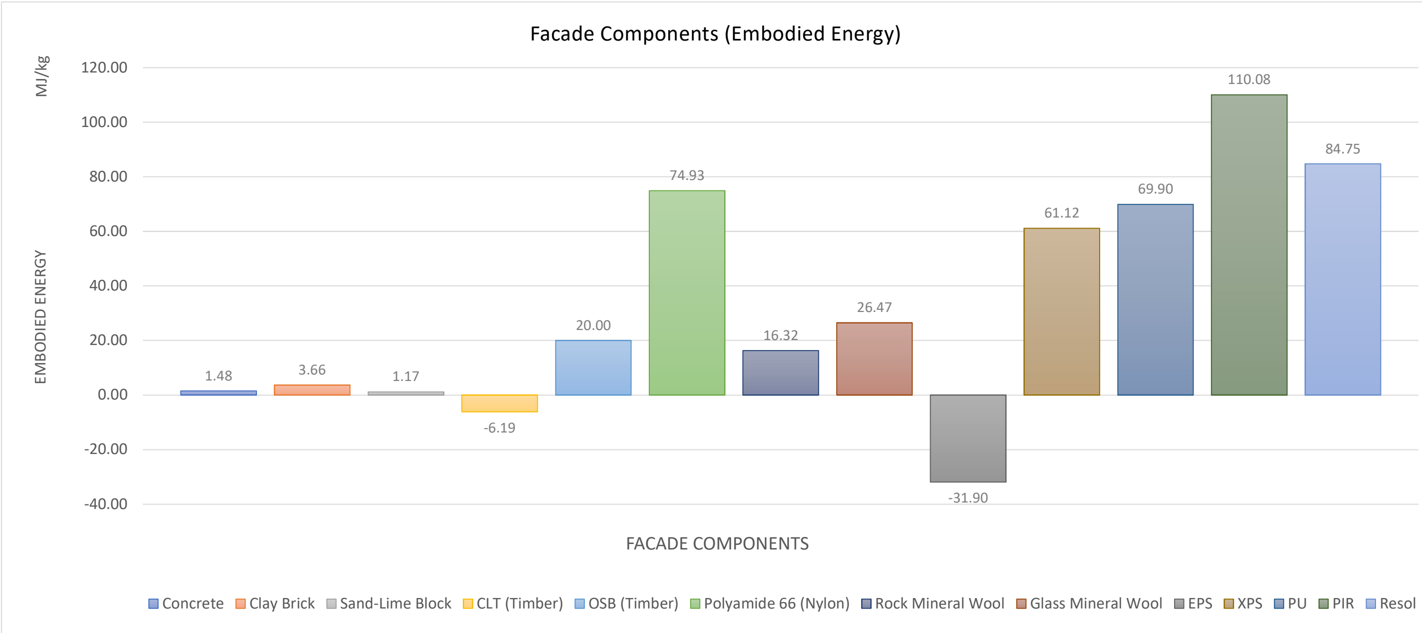
The environmental impact in terms of embodied energy and CO_2 emissions that corresponds to the materials inside the facade systems presented previously can be observed in table 8.1 below. In this table the embodied energy and the carbon footprint of the different components that make up the selected facade systems are presented in terms of weight (kg) and volume (m^3). The goal behind this comparison is to give insight into the ecological impact attributed to the different facade components or materials, before their inclusion into their respective facade systems. The idea of presenting the different measurements (kg and m^3) is to facilitate reference and comparison among the materials, since products can be sold and used by weight or by volume (Ashby, 2013).

Environmental Impact of Facade Components						
Function	**Material**	**Density [kg/m3]**	**Embodied Energy [MJ/kg]**	**Carbon Footprint [kgCO2/kg]**	**Embodied Energy [MJ/m3]**	**Carbon Footprint [kgCO2/m3]**
Facade Inner Leaf	Concrete	2,500	1.48	0.17	3,700.00	422.500
	Clay Brick	2,000	3.66	0.29	7,320.00	574.000
	Sand-Lime Block	1,900	1.17	0.14	2,226.80	258.400
	CLT (Timber)	471	-6.19	-0.63	-2,913.37	-298.412
	OSB (Timber)	650	20.00	0.93	13,000.00	606.450
Facade Vapour Retarder	Polyamide 66 (Nylon)	1,695	74.93	3.50	127,006.35	5937.585
Facade Insulation	Rock Mineral Wool	55	16.32	1.31	897.60	72.05
	Glass Mineral Wool	56	26.47	1.28	1,482.20	71.70
	EPS	20	-31.90	2.35	-637.99	46.95
	XPS	34	61.12	4.72	2,059.81	158.92
	PU	31	69.90	2.90	2,166.90	89.90
	PIR	32	110.08	5.29	3,522.50	169.38
	Resol	35	84.75	2.82	2,966.40	98.60
Facade Outer Leaf	Clay Brick	2,000	3.66	0.29	7,320.00	574.000

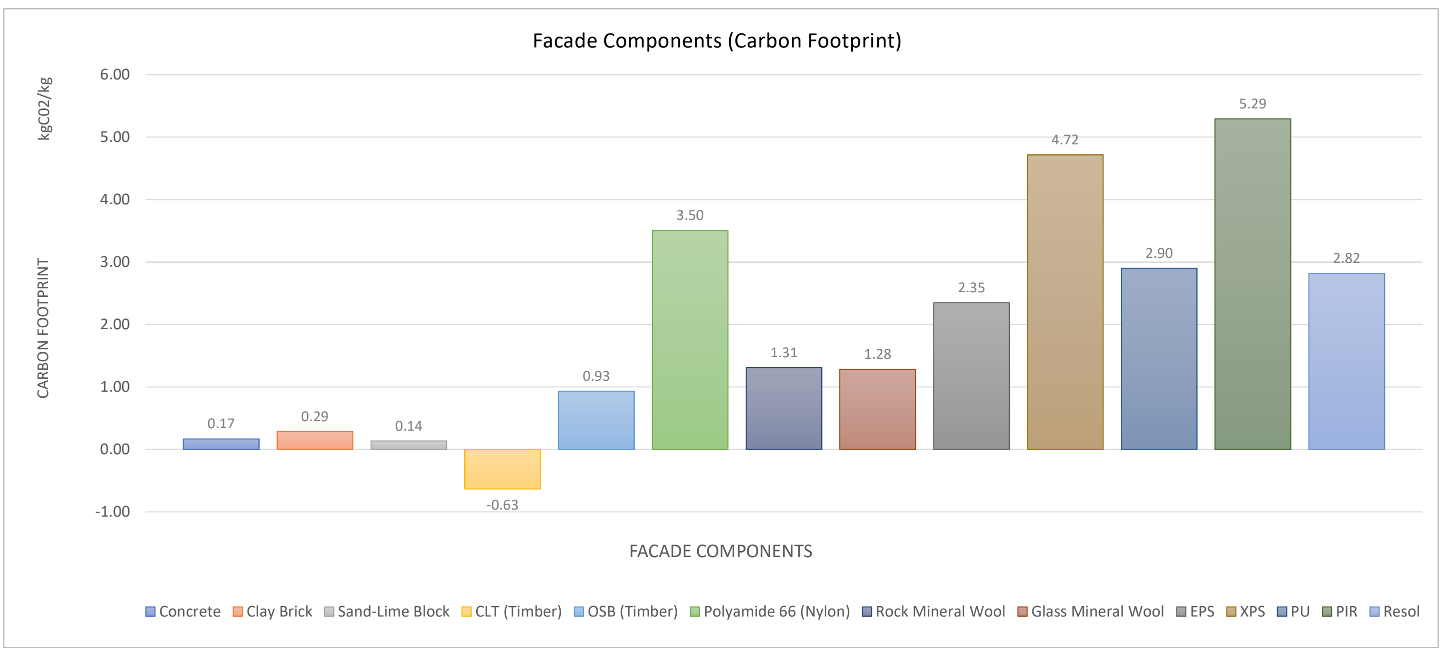
Table 8.1 Embodied energy and carbon footprint of facade components.

The embodied energy and carbon footprint values per kilogram (kg) and per cubic meter (m^3) are obtained from the Cambridge Engineering Selector Software (CES, 2019) and from environmental product declarations (EPDs). These values refer to the life-cycle stages of raw material extraction, manufacturing and processing, transportation, and waste disposal. The life-cycle stage of construction and installation, as well as the material use are not taken into account in the assessments of this thesis, since they are broad topics on their own, and their values can differ depending on the application.

The values in table 8.1 represent the total amount of energy and CO2 emissions throughout the total lifespan of the facade components. Later in this chapter the factor of time is considered by taking into account the durability of the different elements. The data from table 8.1 is represented in graphs 8.1 and 8.2 by the mass of the components (per kg), and in graphs xx and xx by volume of the components (per m^3).



Graph 8.1 Embodied energy of facade components per kilogram.

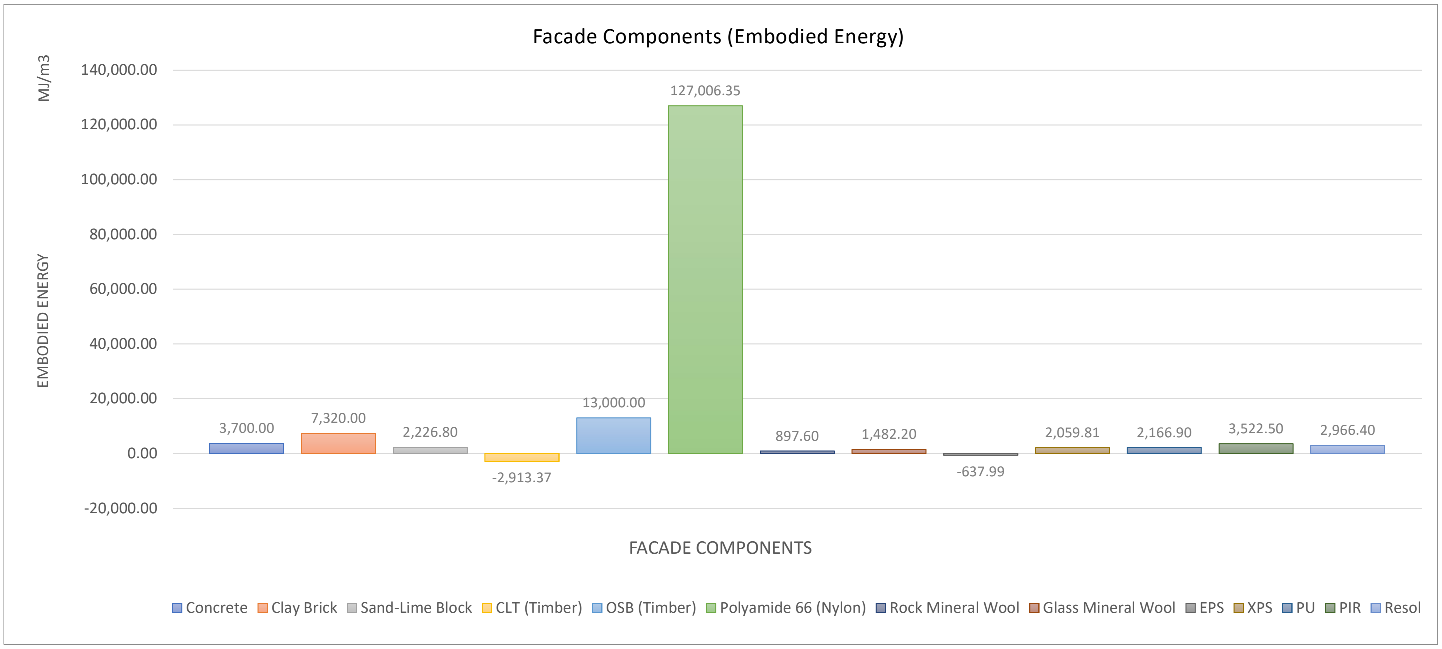


Graph 8.2 Carbon footprint of facade components per kilogram.

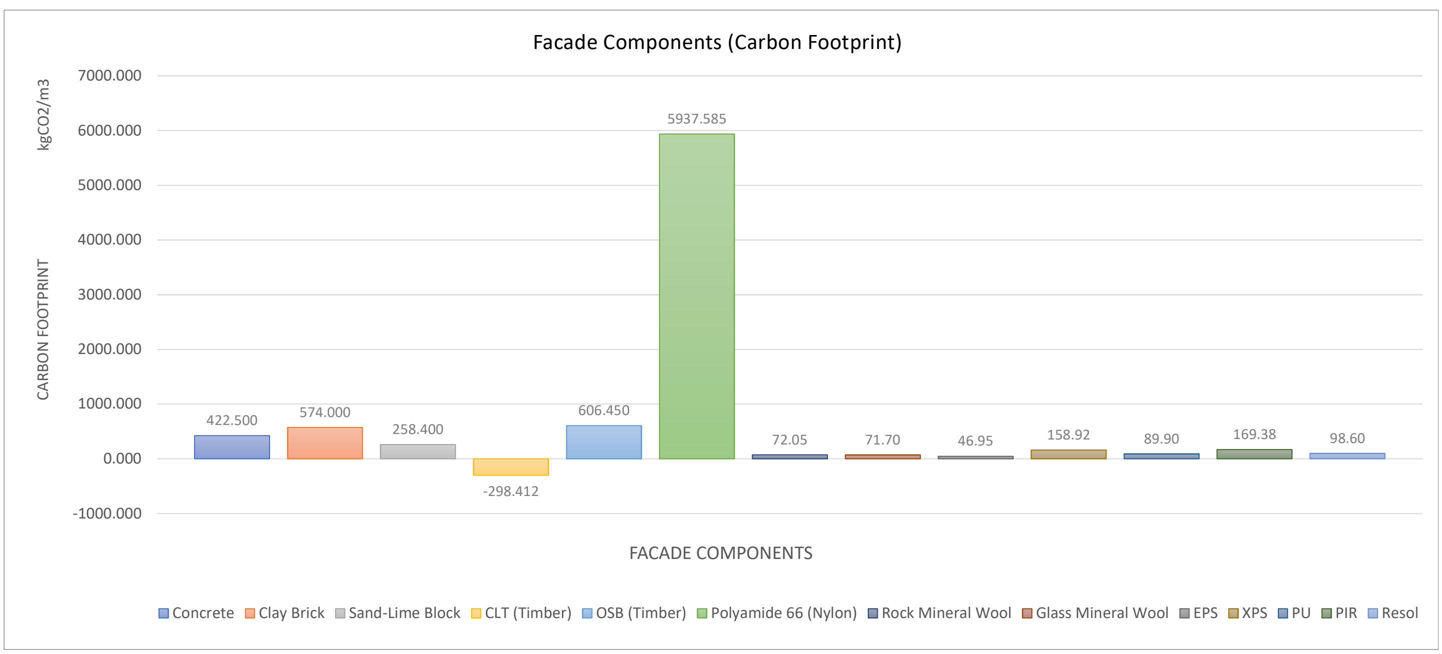
It can be observed from the graphs above (8.1 and 8.2), that when measuring per kilogram (kg), the lighter materials show higher embodied energies and CO2 emissions than the heavier ones. This occurs because larger amounts of volume are required from the lighter materials in order to reach 1 kg, in comparison to what is required from the heavier ones. This tells that the lightweight construction materials, especially the insulation, are energy intensive materials, with big carbon footprints.

Some values from the graphs above are negative, which is the case of cross laminated timber (CLT) and expanded polystyrene (EPS). In the case of CLT, the negative carbon footprint come from the fact that this component is a plant based material, therefore it absorbs carbon from the atmosphere and it stores it rather than releasing it (Ashby, 2013). Based on Ashby (2013) it can be assumed that as a consequence of sequestering carbon from the atmosphere this material contains lots of stored energy, which can be retrieved through burning. In the case of EPS, the negative embodied energy comes from the input of additional energy and material obtained from the energy recovery at the end of life (EoL) scenario (EUMEPS, 2017).

The obtained data until this point does not represents the true magnitude of environmental impact in a facade system, since amount of material or volume of the components used in the different systems varies. Additionally, any measurements related to facades are given in square meters (m2), thus the graphs presented below (8.3 and 8.4) show a closer approach by evaluating the environmental impact of the facade components by cubic meters (m³).



Graph 8.3 Embodied energy of facade components per cubic meter.



Graph 8.4 Carbon footprint of facade components per cubic meter.

The graphs above (8.3 and 8.4), measured per cubic meter, show a different picture than the graphs measure by kilogram (8.1 and 8.2). In this case, the heavier elements, which is the case for the group of ceramics (concrete, clay brick and sand-lime blocks) and timber, show higher embodied energies and carbon footprint than the lighter materials (insulation). This reveals that when taking into account the volume of construction materials, the ones with higher mass contribute to bigger impacts to the environment. This suggests that by reducing the mass of the materials, the embodied energy and carbon footprint will decrease as well.

The following section evaluates the environmental impact of the selected facade systems by analyzing the embodied energy and carbon footprint of the different materials or components that make them up. Additionally, the impact to the environment

8.3) Thermal Performance vs Environmental Impact

The environmental impact in terms of embodied energy and CO_2 emissions corresponding to different thermal insulation values are compared in this section. The thermal insulation of the different facade systems is measured by obtaining the U-value or thermal transmittance, which indicates the rate of heat flow through a product or structure. In order to obtain the U-value of the different facade systems, the analytical model provided by Bokel (2015) to calculate the total heat resistance of the construction (R_T) is applied, since the U-value is the inverse of the total heat resistance of the construction as seen in equation 6.1 (Bokel, 2015):

$$\text{e.1) } U = \frac{1}{R_T} \qquad \text{(equation 6.1)}$$

U = U-value or thermal transmittance
R_T = Total heat resistance of the construction

In a construction with different layers and without a cavity, like in the case of the board systems (e-board) presented in chapter 5, the total resistance of the construction (R_T) is obtained from the summation of all the individual layers (r_1, r_2, r_3...) forming the total heat resistance of the construction parts (R_C) (Bokel, 2015), as shown in equation 6.2, and each individual layer is calculated by dividing the thickness (d) of the part with its thermal conductivity (λ), as in equation 6.3 (Bokel, 2015):

$$\text{e.2) } R_C = r_1 + r_2 + r_3 + \ldots \qquad \text{(equation 6.2)}$$

$$\text{e.3) } r = \frac{d}{\lambda} \qquad \text{(equation 6.3)}$$

R_C = Total heat resistance of the construction parts
r = Heat resistance of the individual parts
d = Thickness of the individual parts
λ = Thermal conductivity of the individual parts

In the case of cavity constructions, like all the rest of the facade systems presented in chapter 5, the equations to calculate the total resistance of the construction (R_T) is obtained from the summation of the total heat resistance of the construction parts (r_C) with the surface resistance on the exterior (r_e), which has a value of 0.04 m²K/W in the Dutch context, and the surface resistance on the interior (r_i), which has a value of 0.13 m2K/W in the same context (Bokel, 2015), as presented in equation 6.4. In this situation the total resistance of the construction parts (r_C) takes into account the cavity present in between the different leafs (r_{cav}), which has an approximate value of 0.17 m²K/W (van der Linden & Zeegers, 2018). Once the total heat resistance of the construction (R_T) is obtained, the U-value is calculated by replacing the denominator in equation 6.1.

$$e.4)\ R_T = r_e + r_C + r_i \qquad \text{(equation 6.4)}$$

R_T = Total heat resistance of the construction
r_e = Surface resistance on the exterior
r_C = Total heat resistance of the construction parts
r_i = Surface resistance on the interior

The thermal conductivity (λ) values of the materials that compose all the selected facade systems to be evaluated are shown in table 8.2.

Thermal Conductivity (λ) of Materials		
	Materials	**Thermal Conductivity [W/mK]**
1	Clay Brick	0.55
2	Clay Brick (Slip)	0.55
3	CMU	0.8
4	Prefab Concrete Panels	0.8
5	OSB	0.13
6	Vapour Retarder	0.17
7	Gypsum Board (Drywall)	0.19
8	CLT Board	0.13
9	E-Board (EPS)	0.031
10	Gypsum Plaster	0.20
11	Sand Lime Block	0.75
12	XPS	0.0305
13	Rock Mineral Wool	0.033
14	Glass Mineral Wool	0.0315
15	EPS	0.032
16	PU	0.023
17	PIR	0.022
18	RESOL	0.021

Table 8.2 Thermal conductivity of facade components and materials.

The thermal conductivity (λ), also known as the heat conduction coefficient indicates how much heat flows through a layer of material. The highest this coefficient is, the easier it is for the material to conduct heat (Bokel, 2015). Normally materials that are porous are bad at conducting heat since they tend to contain air particles trapped in the porosity. Still air on its own is very bad at conducting heat, it presents a thermal conductivity of 0.025 W/mK. This principle can be observed from the thermal conductivities of the materials shown in table xx. The more porous materials like all the insulation (XPS, rock and glass mineral wool, EPS, PU PIR, and RESOL) have the lowest thermal conductivities, and the least porous materials like concrete and sand lime have the highest values. Even less porous materials than concrete or sand lime, or with no porosity at all, have significantly higher thermal conductivities, which is the case for metals. This makes them good conductors, as opposite to insulating materials. Steel, for example, has a value of 50.2 W/mK (Young & Sears, 1992), and aluminium, 205.0 W/mK (Young & Sears, 1992).

The environmental impact in terms of embodied energy and CO_2 emissions that corresponds to the materials presented previously (table 8.2) can be observed in table 8.3 below. In this table the embodied energy and the carbon footprint are given in different units in order to facilitate comparisons. The main purpose of this table is to obtain the output of the embodied energy and the carbon footprint per square meter of wall. In this way, the ecological impact can be adequately related to the different facade systems, and as a consequence easily understood.

Environmental Impact of Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
Clay Brick	85	100	1.05E-03	2,000	2.10	178.50	3.66	0.29	7,320.00	574	653.31	51.23	CES (Eco-Audit)
Clay Brick (Slip)	85	20	2.10E-04	2,000	0.42	35.70	3.66	0.29	7,320.00	574	130.66	10.25	CES (Eco-Audit)
CMU	12	140	1.08E-02	2,500	*21.00	252.00	1.48	0.17	3,700.00	422.5	478.74	54.67	CES (Eco-Audit)
Prefab Concrete Panels	1	100	1.00E-01	2,500	250.00	250.00	1.48	0.17	3,700.00	422.5	370.00	42.25	CES (Eco-Audit)
Sand Lime Block	12	100	7.85E-03	1,900	* 13.00	156.00	** 1.17	** 0.14	2,226.80	258.4	209.71	24.34	
E-Board (EPS)	1	100	1.00E-01	25	2.50	2.50	-25.52	1.88	-** 637.99	** 46.95	-63.80	4.70	
XPS	1	100	1.00E-01	34	3.37	3.37	61.12	4.72	2,059.81	158.92	**205.98	** 15.89	EXIBA, 2014
Rock Mineral Wool	1	100	1.00E-01	55	5.50	5.50	** 16.32	** 1.31	897.60	72.05	89.76	7.21	
Glass Mineral Wool	1	100	1.00E-01	56	5.60	5.60	26.47	1.28	** 1,482.20	** 71.70	148.22	7.17	
EPS	1	100	1.00E-01	20	2.00	2.00	-31.90	2.35	-** 637.99	** 46.95	-63.80	4.70	
PU	1	100	1.00E-01	31	3.10	3.10	** 69.90	** 2.90	2,166.90	89.90	216.69	8.99	
PIR	1	100	1.00E-01	32	3.20	3.20	110.08	5.29	3,522.50	169.38	** 352.25	** 16.94	
RESOL	1	100	1.00E-01	35	3.50	3.50	84.75	2.82	2,966.40	98.60	** 296.64	** 9.86	
Gypsum Plaster	1	5	5.00E-03	827	4.14	4.14	** 2.91	** 0.18	2,405.58	146.88	12.03	0.73	
Gypsum Board	1	6	6.00E-03	1,000	6.00	6.00	7.48	0.31	7,478.40	306.08	** 44.87	** 1.84	USG, 2019
OSB	1	18	1.80E-02	650	11.70	11.70	20.00	0.933	13,000.00	606.45	234.00	10.92	CES (Eco-Audit)
Vapour Retarder	1	2	2.00E-03	1,695	3.39	3.39	74.93	3.50	127,006.35	5,937.59	254.01	11.88	CES (Eco-Audit)
CLT Board	1	30	3.00E-02	471	14.13	14.13	-6.19	-0.63	-** 2,913.37	-** 298.41	-87.40	-8.95	

* The mass of some materials are directly obtained from the producer, therefore small variations are possible. These variations occur because some materials might have some irregularities in their shape and might not be completely solid.

** All these values are obtained from the producer´s Environmental Product Declaration (EPD) since they are products composed of many different materials, which composition is not always clearly specified.

Table 8.3 Environmental Impact of facade components database.

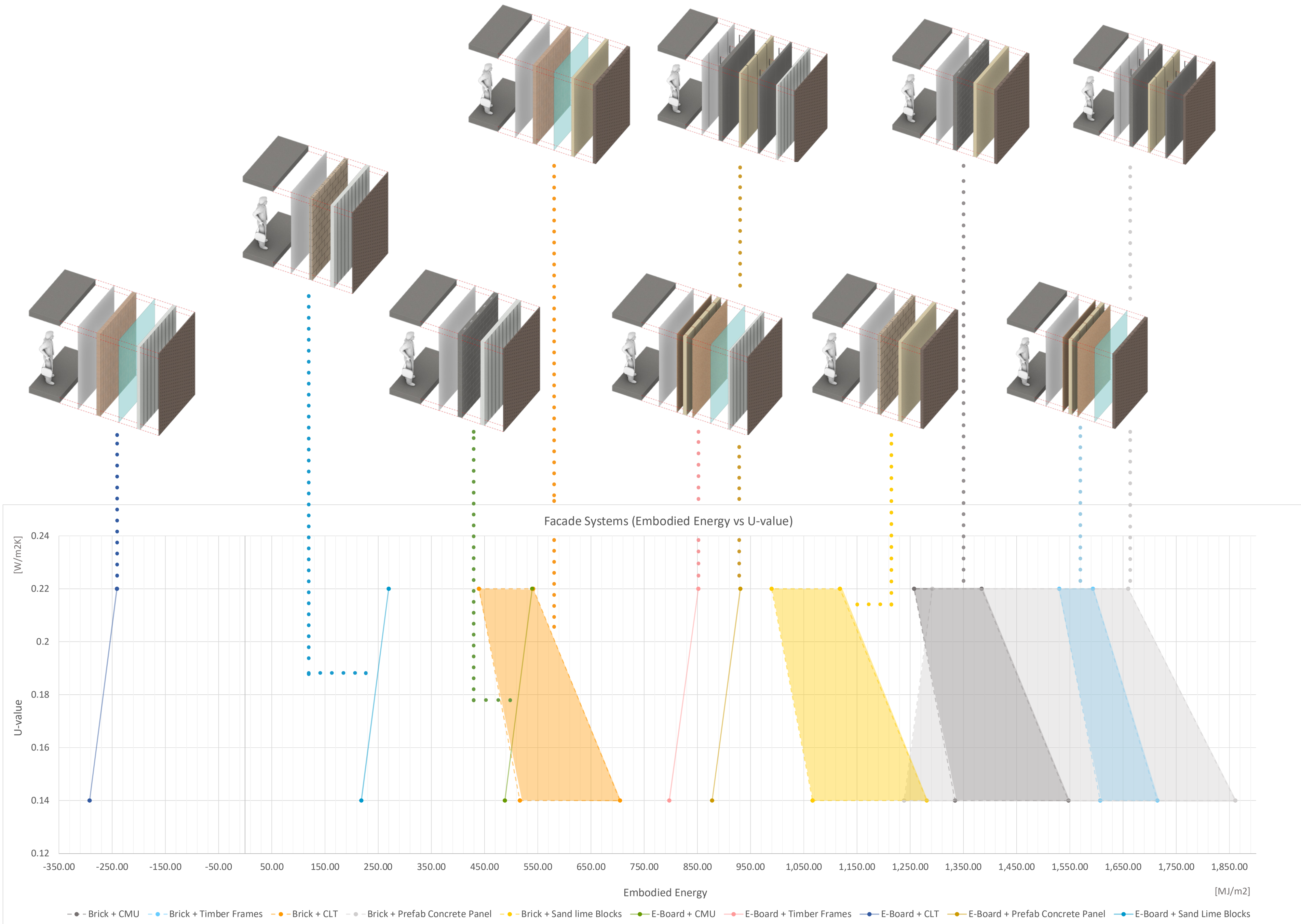
Graph 8.5 compares the Embodied energy, per m^2 of wall, of all the previously selected facade systems against different U-values, ranging from 0.22 W/M^{2}k, which comes from the minimum thermal insulation allowed in the Netherlands for new buildings (NEN 1068) to a value of 0.14 W/m^{2}K. Graph 8.6 compares the CO2, per m^2 of wall, to the same range in U-value.

From the previous graphs it is noticeable that the systems based on the traditional cavity concept are more energy intensive and release more CO_2 into the atmosphere than the ones based on E-Board. The reason for this is mainly the reduction of materials. Clay bricks are the most energy intensive material per m^3 in all of the systems after the vapor retarder (table 8.3), which is always used in very small dimensions, and OSB which is considerable thinner than the regular facing clay bricks. The reasons behind the large numbers in brick have to do with all the process involved in their manufacturing. Bricks need to be molded, normally dried in autoclaves and fired in kilns at very high temperatures. Thus by reducing the volume of brick in a m^2 of wall, the mass is reduced, and the embodied energy and CO_2 emissions per m^2 decrease as well. This is achieved with the E-Board technology, since the facing bricks are reduced to strips of only 20mm thick. With this being considered, the systems with the higher environmental impacts per m^2 of wall are the ones containing concrete, in this case, the concrete masonry wall and the prefab concrete panels.

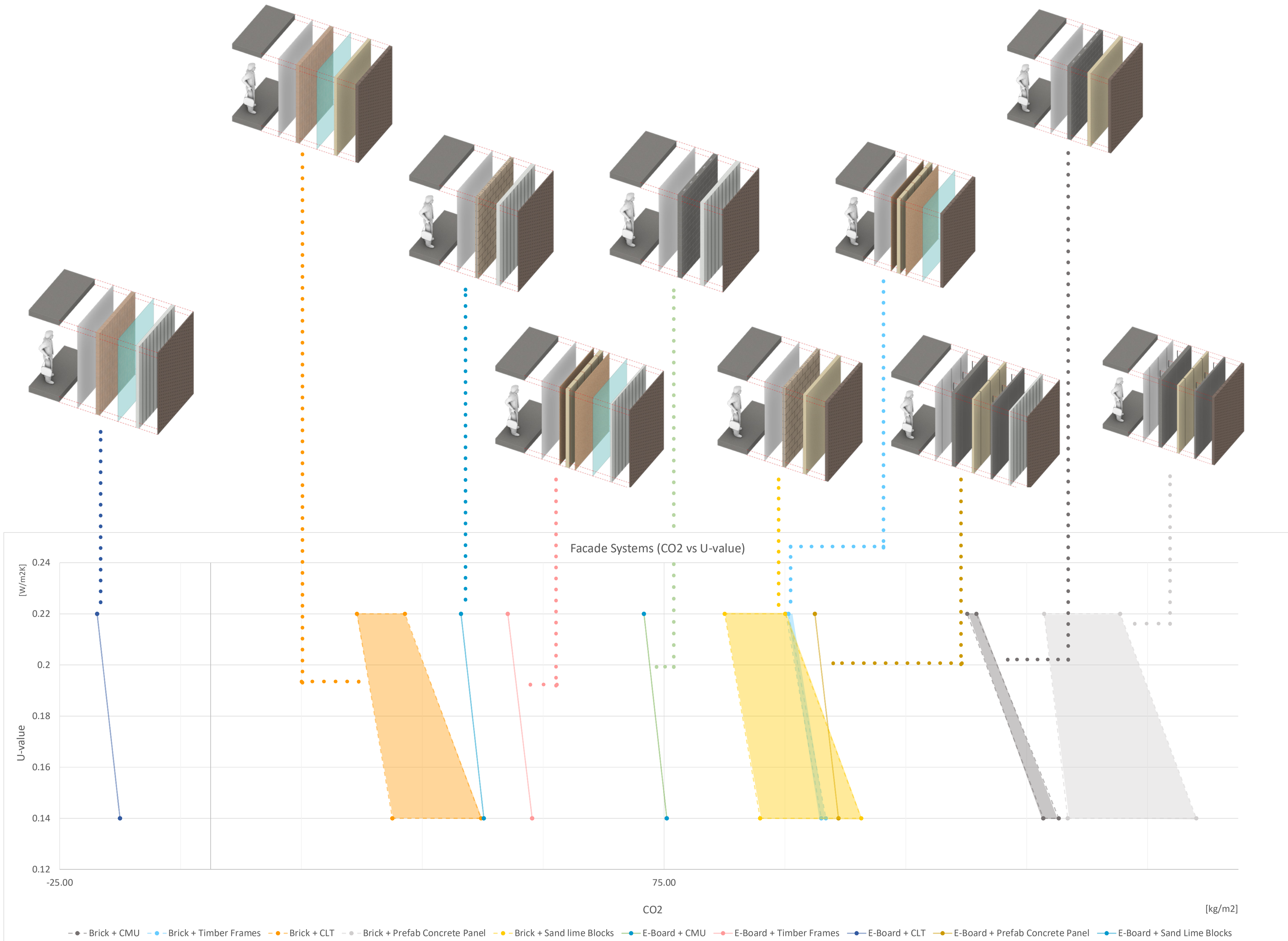
It is important to mention that the range observed in the numbers obtained in terms of the embodied energy and CO_2 emissions are mainly dictated by the variation in type of insulation and the required thickness in order to reach the different U-values presented in the graphs (from 0.22 to 0.14). The individual systems presented with the different insulations are illustrated in graph 8.7 and 8.8. From these a clearer picture is obtained on how the different insulations contribute to the environmental impact in a facade system. The environmental impact per m^2 of wall of the different facade systems in many of the cases is relatively big, with an increment of 200 MJ/m^2 and 20 kg/m^2 in many of the cases.

In all the graphs it is noticeable that the tendency of most of the facade systems is to have an increment in embodied energy or CO_2 when a better thermal insulation (lower U-value) is required, this is represented by the negative slopes in the graphs (\ ), however some systems like the board systems (e-board) end up resulting in negative embodied energies and CO_2 emissions when lower U-values are required, which represented by positive slopes in the graphs (/). The CO_2 emissions of the materials is negative when it can sequester CO_2 particles from the air. Plant based materials like timber absorb CO_2 emission from the atmosphere during their lifetime.

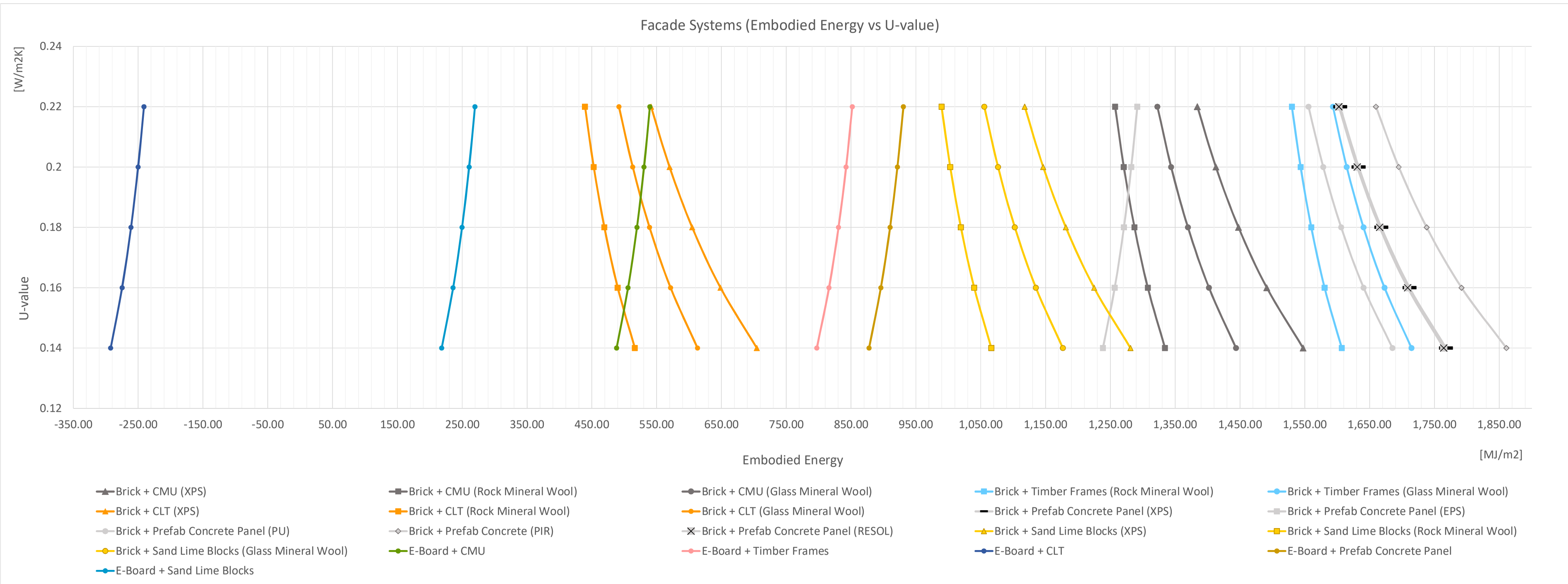
In this part of the assessment it can be concluded the system to be optimized is the prefab concrete panel system to be used in the cavity wall with bricks. Concrete similarly to brick is an energy intensive material with lots of CO_2 emissions, by redesigning the facade systems in which this material is present a big contribution to the environment can be achieved.



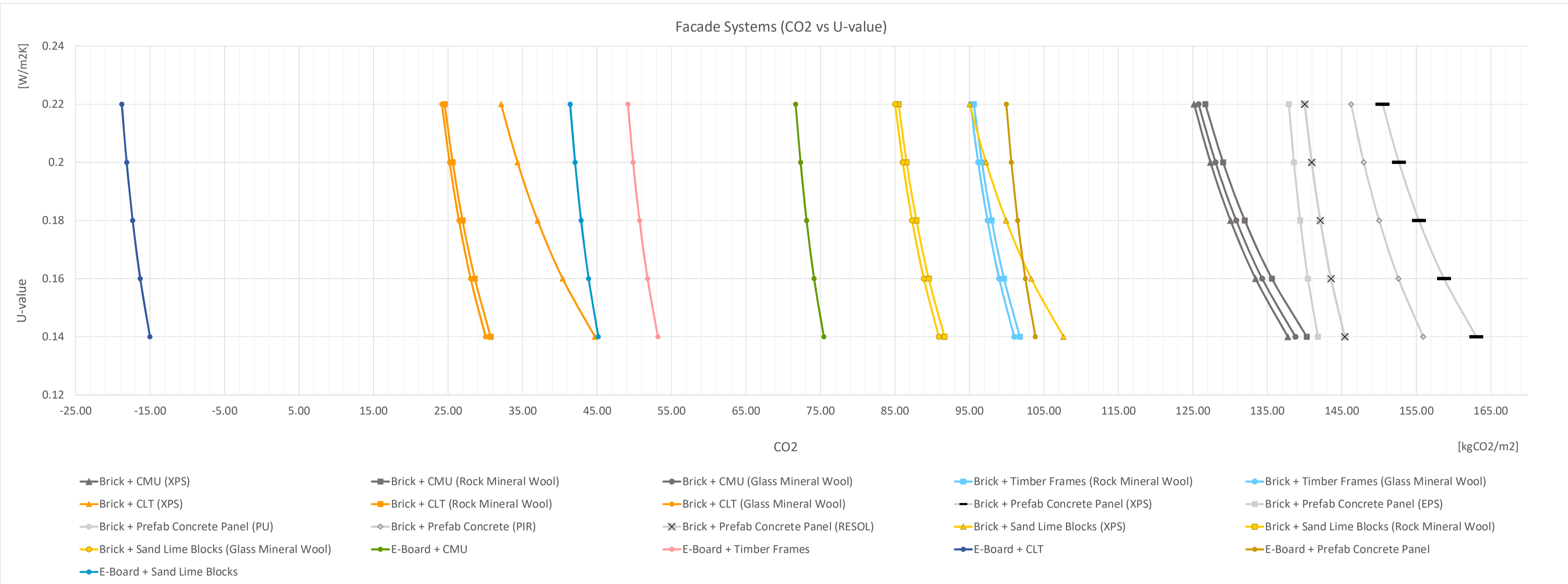
Graph 8.5 Facade Systems (embodied energy vs U-value)



Graph 8.6 Facade Systems (CO_2 vs U-value)



Facade Systems (Embodied Energy vs U-value)
U-value
[W/m2K]
0.24
0.22
0.2
0.18
0.16
0.14
0.12
-350.00
-250.00
-150.00
-50.00
50.00
150.00
250.00
350.00
450.00
550.00
650.00
750.00
850.00
950.00
1,050.00
1,150.00
1,250.00
1,350.00
1,450.00
1,550.00
1,650.00
1,750.00
1,850.00
Embodied Energy
[MJ/m2]
Brick + CMU (XPS)
Brick + CMU (Rock Mineral Wool)
Brick + CMU (Glass Mineral Wool)
Brick + Timber Frames (Rock Mineral Wool)
Brick + Timber Frames (Glass Mineral Wool)
Brick + CLT (XPS)
Brick + CLT (Rock Mineral Wool)
Brick + CLT (Glass Mineral Wool)
Brick + Prefab Concrete Panel (XPS)
Brick + Prefab Concrete Panel (EPS)
Brick + Prefab Concrete Panel (PU)
Brick + Prefab Concrete (PIR)
Brick + Prefab Concrete Panel (RESOL)
Brick + Sand Lime Blocks (XPS)
Brick + Sand Lime Blocks (Rock Mineral Wool)
Brick + Sand Lime Blocks (Glass Mineral Wool)
E-Board + CMU
E-Board + Timber Frames
E-Board + CLT
E-Board + Prefab Concrete Panel
E-Board + Sand Lime Blocks



Graph 8.7 Facade Systems (Embodied Energy vs U-value)

Graph 8.8 Facade Systems (CO2 vs U-value)

8.4) Acoustic Performance vs Environmental Impact

This section compares the embodied energy and the CO2 emissions of the selected facade systems with different airborne sound insulation values. Since these systems have different thicknesses and densities, some have significantly more mass tan others, this results in different airborne sound insulation for the different facade systems. This occurs because the sound waves (energy) impacting on a wall cause it to vibrate, as a result the air on the other side of the wall is also caused to vibrate, and the mass of the wall plays an important role, as the larger the mass the better the sound insulation, since the acceleration imparted on the wall caused by the force generated by the sound waves will decrease with mass (van der Linden & Zeegers, 2018). This principle is explained by Newton's second law of motion (equation 6.5):

$$\text{e.5)}\; F = m \cdot a \qquad \text{(Equation 6.5)}$$

F = Force
m= Mass
a = Acceleration

Since a heavier wall receives less acceleration due to its mass it is harder for it to vibrate. The small vibrations in the wall cause smaller sound pressures on the other side of the wall (receiving side), increasing the sound insulation (van der Linden & Zeegers, 2018). This is expressed in equation 6.6, as it can be seen by increasing the denominator (mass) the acceleration is reduced.

$$\text{e.6)}\; a = \frac{F}{m} \qquad \text{(Equation 6.6)}$$

Similarly to the mass, the sound insulation of a wall can also increase or decrease depending on the frequency. The higher the frequency, meaning more smaller vibrations per second, the less vibrations that are taken up by the wall, resulting in smaller sound pressure levels on the receiving side of the wall (van der Linden & Zeegers, 2018). For this reason it is important to calculate the airborne sound insulation of the wall for different frequencies, specifically the band of frequencies relevant for architectural acoustics, which range from 63 Hz to 4000 Hz (Nederlof et al., 2018).

Table 8.4 shows the airborne sound insulation of the facade systems under analysis, and it can be seen that nearly all of the systems have lower insulation at 63 Hz. For this reason this frequency will be taken for the calculations of the airborne sound insulations of all the systems, to be measured against the embodied energy and the CO_2 emissions. All of the systems with the minimum amount of material are above 20 dB, which is the minimum airborne sound insulation permitted by the Dutch Building Decree in new residences (Bouwbesluit Online, 2012). This table also gives an idea of how is the acoustic performance of the different facade systems.

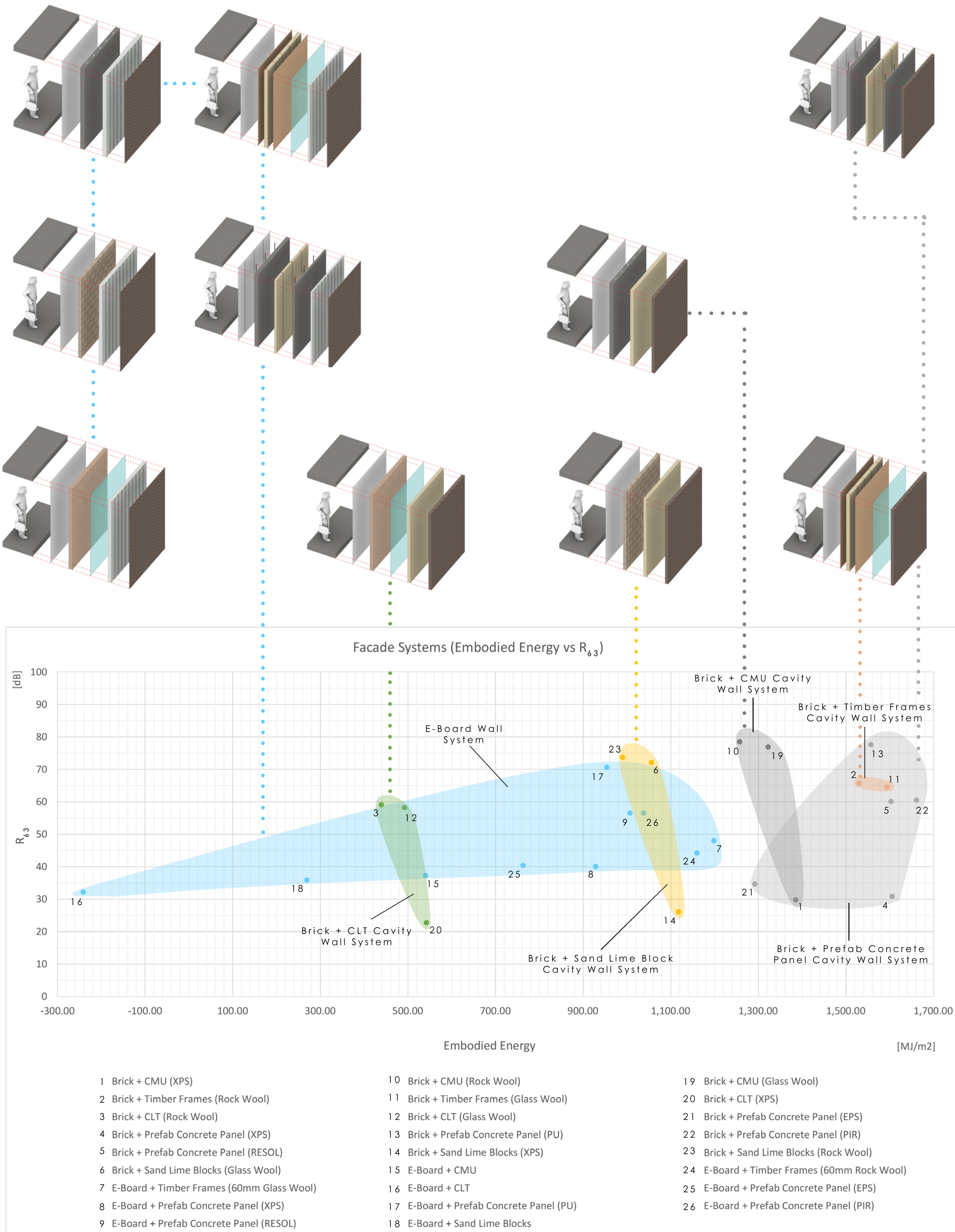
The airborne sound insulation for all of the presented systems were calculated using the Meer Lagen Model (Multi Layer Model) software (Lau Nijs, 2020). The method that this software uses to calculate the sound considers some extra parameters than the simple theoretical mass law equations for cavity walls and single leaf walls (in case of the board systems) since it considers as input additional properties like the Young's modulus, and the flow resistivity or Poisson ratio, as well as the damping (loss factor) of the different materials. This parameters make the calculations from the software more precise as the simple theoretical mass law equations neglect these effects, thus dealing mainly with the thickness, density and the mass per square meter (kg/m^2) of the different layers in the wall (M.J. Tenpierik, personal communication, April 16, 2020). Random incidence (60°) is taken into account for the calculations instead of normal or oblique incidence, since the sound fields around buildings are diffuse, meaning that the waves hitting the construction come from different directions (Nederlof et al., 2018).

Facade Systems [dB]		Frequency [Hz]						
		63	125	250	500	1k	2k	4k
Panel Systems	Brick + Prefab Concrete Panel Cavity Wall (EPS)	34.7	41.2	54.5	81.1	132.0	164.5	111.6
	Brick + Prefab Concrete Panel Cavity Wall (XPS)	30.9	38.8	50.8	74.5	127.8	164.4	101.8
	Brick + Prefab Concrete Panel Cavity Wall (PU)	77.6	106.0	130.0	188.7	197.0	197.0	197.0
	Brick + Prefab Concrete Panel Cavity Wall (PIR)	60.5	80.9	97.6	144.5	196.8	197.0	197.0
	Brick + Prefab Concrete Panel Cavity Wall (RESOL)	60.1	80.5	97.2	143.9	196.7	197.0	197.0
	Brick + CLT Cavity Wall (XPS)	22.8	36.6	45.5	59.9	95.5	83.4	105.0
	Brick + CLT Cavity Wall (Rock Wool)	59.1	84.6	123.6	167.0	196.9	197.0	197.0
	Brick + CLT Cavity Wall (Glass Wool)	58.2	83.2	121.7	164.3	196.9	197.0	197.0
Masonry Systems	Brick + Sand Lime Block Cavity Wall (XPS)	26.1	35.4	44.8	57.3	94.9	84.1	103.0
	Brick + Sand Lime Block Cavity Wall (Rock Wool)	73.7	107.4	136.4	187.7	197.0	197.0	197.0
	Brick + Sand Lime Block Cavity Wall (Glass Wool)	72.1	105.2	133.3	183.8	197.0	197.0	197.0
	Brick + CMU (XPS)	29.8	38.4	49.3	66.5	103.0	89.0	106.8
	Brick + CMU (Rock Wool)	78.5	110.7	141.1	193.2	197.0	197.0	197.0
	Brick + CMU (Glass Wool)	76.9	108.5	138.1	190.1	197.0	197.0	197.0
Frame Systems	Brick + Timber Frames Cavity Wall (Rock Wool)	65.7	89.6	122.2	149.8	196.3	197.0	197.0
	Brick + Timber Frames Cavity Wall (Glass Wool)	64.5	87.9	119.8	150.2	195.3	197.0	197.0
Board Systems	E-Board + Prefab Concrete Panel Wall (EPS)	40.4	42.1	44.9	58.6	88.5	116.8	135.7
	E-Board + Prefab Concrete Panel Wall (XPS)	40.1	42.0	41.8	51.9	80.4	114.0	130.0
	E-Board + Prefab Concrete Panel Wall (PU)	70.6	94.6	113.4	150.2	183.9	197.0	197.0
	E-Board + Prefab Concrete Panel Wall (PIR)	56.5	75.8	90.2	119	143.6	188.5	197.0
	E-Board + Prefab Concrete Panel Wall (RESOL)	56.5	76.4	91.2	120.9	144.3	189.4	197.0
	E-Board + CLT Wall	32.2	32.9	36.3	45.3	64.7	79.1	72.2
	E-Board + Sand Lime Block Wall	35.9	35.7	39.2	52.7	71.8	87.1	99.4
	E-Board + CMU Wall	37.3	37.0	42.8	57.0	76.0	91.5	102.9
	E-Board + Timber Frames Wall (Rock Wool)	44.2	54.2	75.6	103.7	127.3	167.0	197.0
	E-Board + Timber Frames Wall (Glass Wool)	48.0	62	84.4	104.9	139.7	179.4	197.0

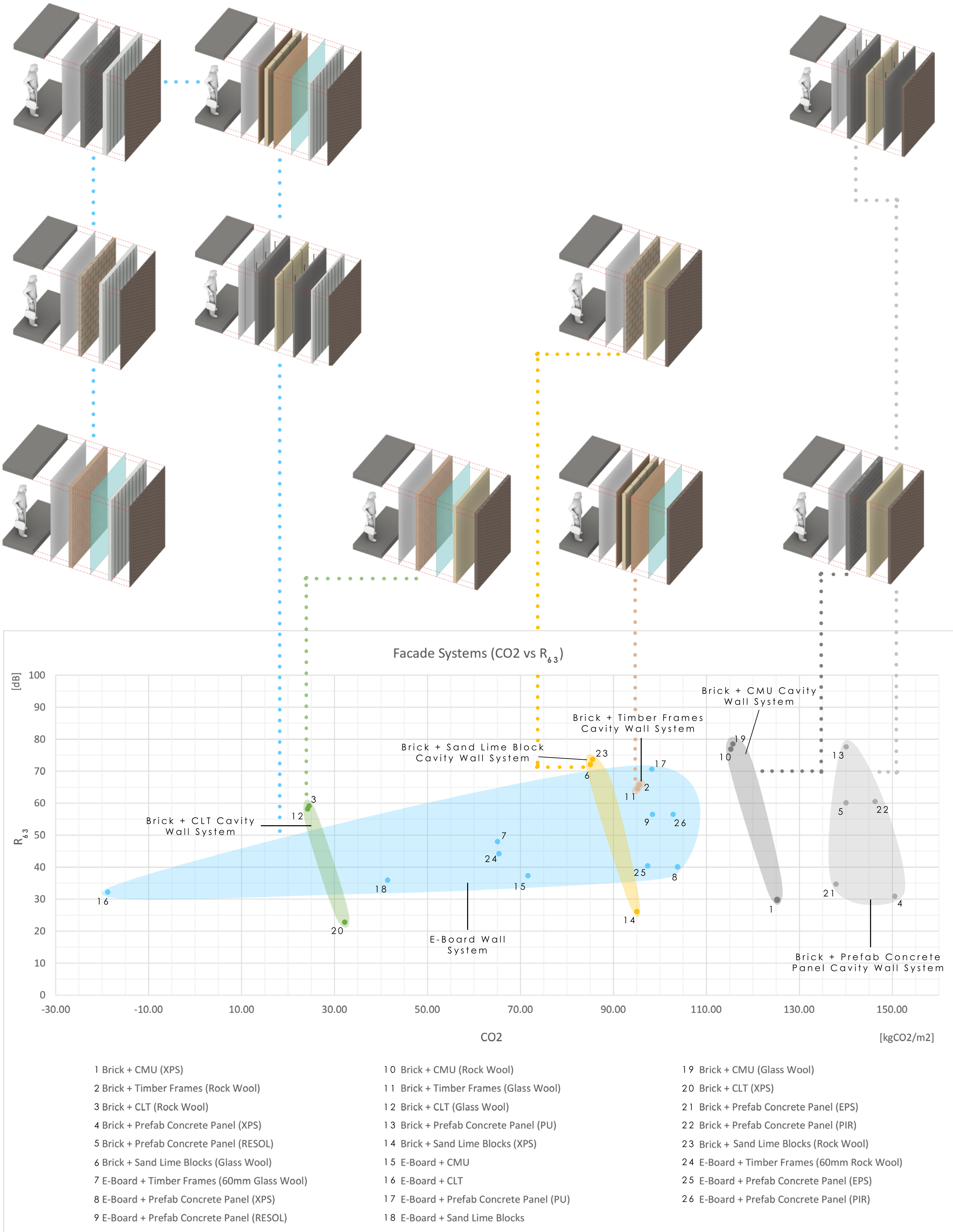
Table 8.4 Airborne sound insulation of facade systems at different frequencies.

From the overview represented in table 8.4 it is observable that the facade systems using extruded polystyrene (XPS) as insulation have lower airborne sound insulation values when compared to the other types of insulation. The reason behind this is that XPS has one of the lower densities when compared to the other insulation types and it is not as porous as the others. Sound absorption is important for good sound insulation and porous materials tend to be excellent at absorbing sound since these materials trap the air particles thus converting the incoming sound waves into heat by the effects of friction (incoming air collides with leaving air), which is absorbed by the wall (van der Linden & Zeegers, 2018).

As previously mentioned the airborne sound insulation in these facade systems decreases with the frequency, making the insulations at 63 Hz the lowest, therefore the airborne sound insulation of each system is assessed and compared with embodied energy and CO_2 emissions at this frequency, as illustrated in graphs 8.9 and 8.10. In this graphs it is noticeable that the systems with higher mass like the ones containing concrete masonry or prefab panels and sand lime blocks have higher sound insulation values than the less dense systems, like the ones that contain timber or e-board. It is also notable that the facade systems with higher mass, specially the ones incorporating concrete elements result in higher embodied energies and CO_2 emissions. Therefore, the facade system under evaluation that contributes to the largest improvement by reducing its embodied energy and CO_2 emissions while keeping a good airborne sound insulation level is brick ans the prefab concrete panel cavity wall.



Graph 8.9 Embodied energy vs airborne sound insulation of facade systems.



Graph 8.10 Carbon footprint vs airborne sound insulation of facade systems.

8.5) Assessment Results

From the assessments it can be concluded that between the thermal and airborne sound insulation of the selected facade systems, it is the former the one that establishes the minimum material requirement in order to comply with the Dutch regulations. In other words more material is required in all selected facade systems to reach a U-value of 0.22 W/m²K, than what it is required to reach a minimum airborne sound insulation of 20 dB.

The assessments also point out that the facade component with more potential for optimization in order to reduce its embodied energy and CO_2 emissions while maintaining or improving the acoustic and thermal insulation is the prefab concrete panel used in cavity wall constructions.

8.6.1) Durability Assessment

In this section, the durability of selected facade systems, as well as their main individual components are evaluated according to their expected technical lifetime. Since the durability of the materials differs, the amount the embodied energy in megajoule per square meter (MJ/m²) and the amount of kilograms of CO_2 per square meter ($kgCO_2/m^2$) are measured per year. In this way more accurate results on the facade systems that cause more damage to the environment are obtained, as some components or products end up breaking down faster than others.

First, the environmental impact of the individual facade components are analyzed, giving some insight into the impact attributed to certain materials. Then, the obtained data is used to dictate the environmental impact of the entire facade systems, which points out at the facade systems with the highest embodied energy and carbon footprint.

8.6.2) Durability of the Facade Components

In this section, the durability of the individual components of the facade systems analyzed previously are shown with their associated embodied energy and CO2 emissions per cubic meter in a year. Tables 8.5 and 8.6 below organize the data by relating the materials or components with their respective facade positions and functions.

Durability of Facade Components (By Mass)							
Function	Material	Expected Technical Lifetime [Years]	Density [kg/m3]	Embodied Energy per Technical Lifetime [MJ/kg]	Carbon Footprint per Technical Lifetime [kgCO2/kg]	Embodied Energy per year [MJ/kg]	Carbon Footprint per year [kgCO2/kg]
Facade Inner Leaf	Concrete	100	2,500	1.48	0.169	0.015	0.0017
	Clay Brick	100	2,000	3.66	0.287	0.037	0.0029
	Sand-Lime Block	100	1,900	1.17	0.136	0.01	0.0014
	CLT (Timber)	75	471	-6.19	-0.634	-0.08	-0.0084
	OSB (Timber)	75	650	20.00	0.933	0.27	0.012
Facade Vapour Retarder	Polyamide 66 (Nylon)	75	1,695	74.93	3.503	1.00	0.047
Facade Insulation	Rock Mineral Wool	75	55	16.32	1.31	0.22	0.017
	Glass Mineral Wool	75	56	26.47	1.28	0.35	0.017
	EPS	75	20	-31.90	2.35	-0.43	0.031
	XPS	75	34	61.12	4.72	0.81	0.063
	PU	75	31	69.90	2.90	0.93	0.039
	PIR	75	32	110.08	5.29	1.47	0.071
	Resol	75	35	84.75	2.82	1.13	0.038
Facade Outer Leaf	Clay Brick	100	2,000	3.66	0.287	0.037	0.0029

Table 8.5 Durability of facade components per kg per year

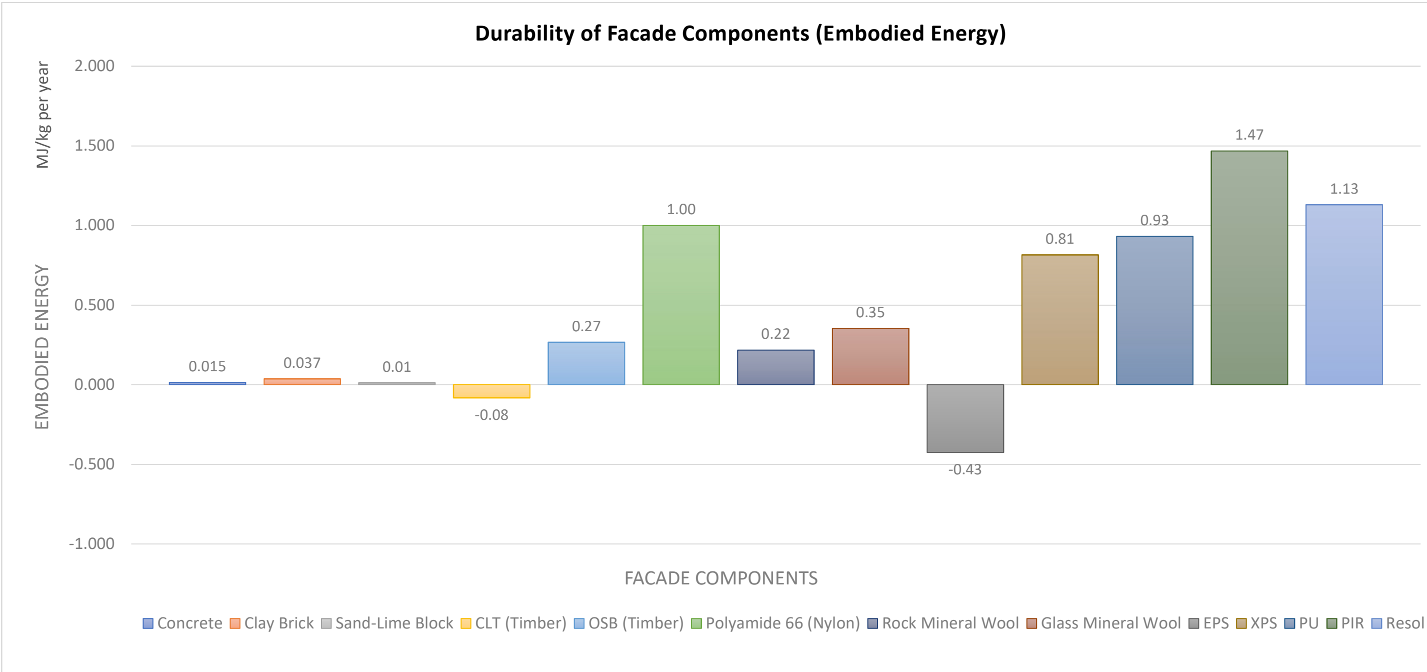
Durability of Facade Components (By Volume)							
Function	Material	Expected Technical Lifetime [Years]	Density [kg/m3]	Embodied Energy per Technical Lifetime [MJ/m3]	Carbon Footprint per Technical Lifetime [kgCO2/m3]	Embodied Energy per year [MJ/m3]	Carbon Footprint per year [kgCO2/m3]
Facade Inner Leaf	Concrete	100	2,500	3,700.00	4.225	37	0.042
	Clay Brick	100	2,000	7,320.00	5.740	73.2	0.057
	Sand-Lime Block	100	1,900	2,226.80	2.584	22.27	0.026
	CLT (Timber)	75	471	-2,913.37	-3.979	-38.84	-0.053
	OSB (Timber)	75	650	13,000.00	8.086	173.33	0.108
Facade Vapour Retarder	Polyamide 66 (Nylon)	75	1,695	127,006.35	79.168	1,693.42	1.056
Facade Insulation	Rock Mineral Wool	75	55	897.60	0.96	11.97	0.013
	Glass Mineral Wool	75	56	1,482.20	0.96	19.76	0.013
	EPS	75	20	-637.99	0.63	-8.51	0.0083
	XPS	75	34	2,059.81	2.12	27.46	0.028
	PU	75	31	2,166.90	1.20	28.89	0.016
	PIR	75	32	3,522.50	2.26	46.97	0.030
	Resol	75	35	2,966.40	1.31	39.55	0.018
Facade Outer Leaf	Clay Brick	100	2,000	7,320.00	5.740	73.2	0.057

Table 8.6 Durability of facade components per m^2 per year

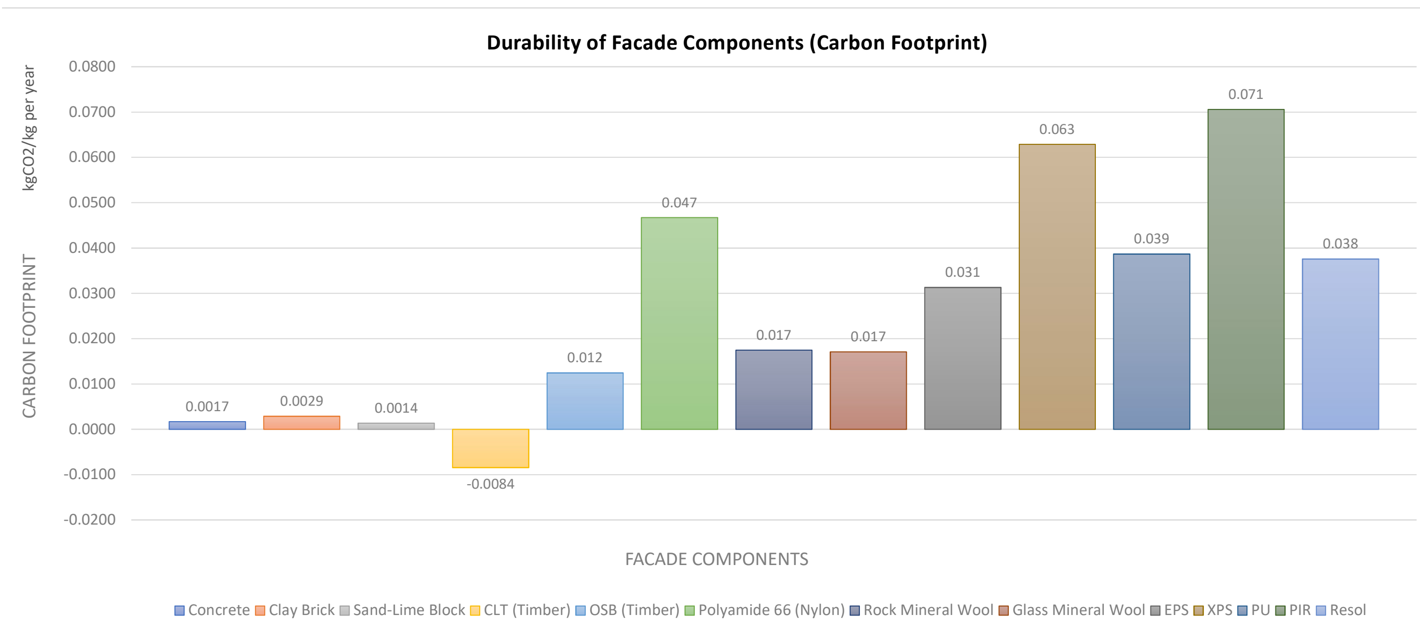
Tables 8.5 and 8.6 above, show the embodied energy and the carbon footprint per technical lifetime of the different components that form part of the selected facade systems, which are obtained from table 8.3 presented earlier in this chapter. This numbers reflect the life-cycle stages of raw material extraction, manufacturing and processing, transportation, and waste disposal. These values are then multiplied by the total amount of expected technical lifetime in years in order to obtain the environmental impact per year in terms of mass and volume. Therefore, table 8.5 presents the output values in megajoule per kilograms (MJ/kg) and kilograms of CO_2 per kilograms ($kgCO_2/kg$), and table 8.6 presents the results in megajoule per cubic meters (MJ/m^3) and kilograms of CO_2 per cubic meters ($kgCO_2/m^3$). Both measurements are important when referring to individual components or materials, as the products can be sold and used by weight or by volume (Ashby, 2013).

The following graphs illustrate the embodied energy and the carbon footprint per year of the different facade components shown in the tables above. The data provided gives insight into the environmental impact of the different product or materials in comparison to each other, but all of these components are used in different quantities in a facade system, therefore the amount of product required in each facade system, and the environmental impact as consequence is presented later in this chapter.

Graphs 8.11 and 8.12 below show the environmental impact per kilograms per year of the different components inside the facade systems. The embodied energy results are given in megajoule per kilogram per year (MJ/kg) and the carbon footprint in kilogram of CO_2 per kilogram per year (kgCO2/kg).



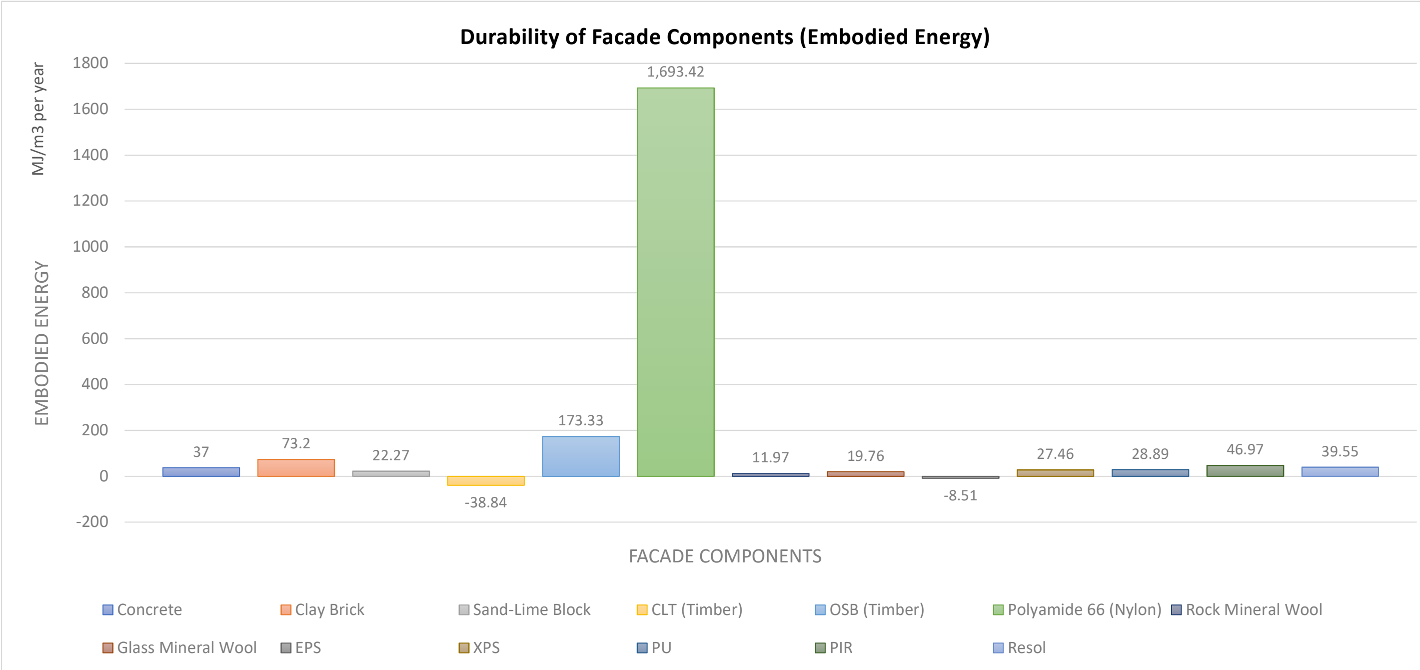
Graph 8.11 Embodied energy of the facade components per kilogram per year.



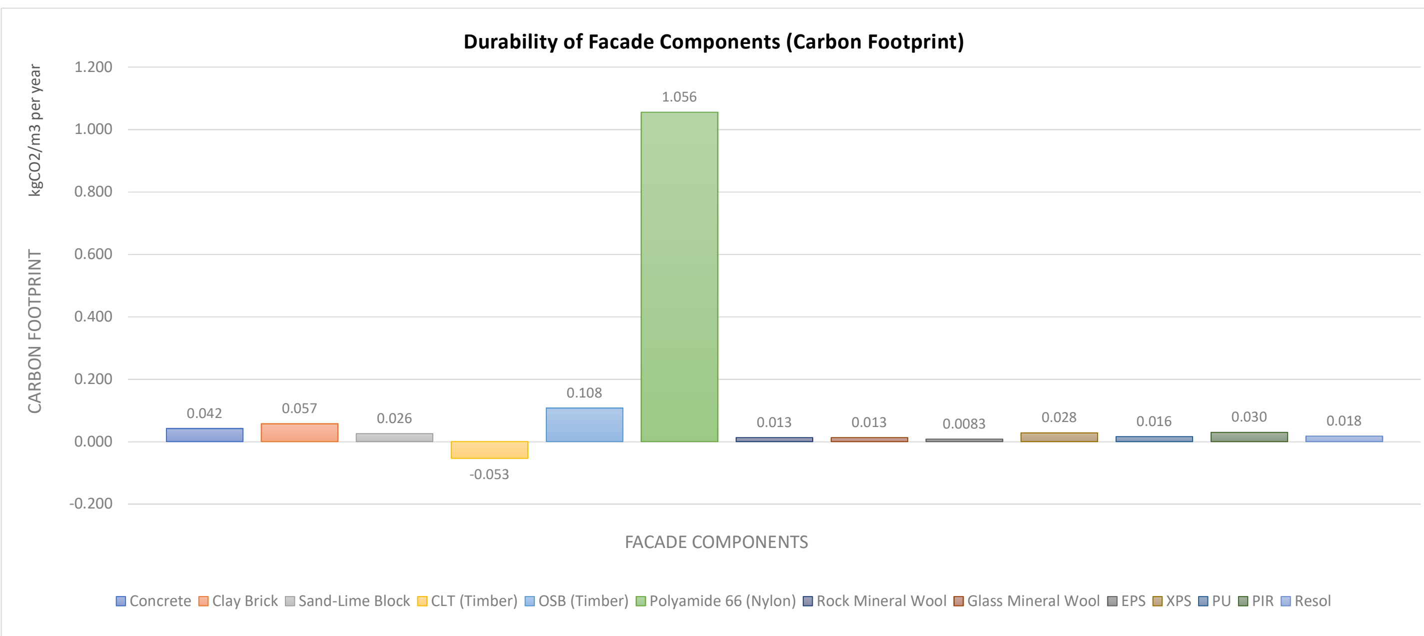
Graph 8.12 Carbon footprint of the facade components per kilogram per year.

It can be observed from the graphs above (8.11 and 8.12) that when measuring the environmental impact per kilogram and taking into account durability, the lighter components like the insulation products, present higher embodied energies and CO_2 emissions. The main reason for this is that the lighter materials tend to be less durable than the heavy ones (ceramics). Additionally, when measuring by weight, the volume of product required to reach 1 kg is more for the lightweight materials than for the heavy ones.

As mentioned earlier in this chapter the negative values of CLT are due to the capability to sequester CO2 from the environment, which as consequence stores energy through its lifetime. In the case of EPS, the negative embodied energy comes from the input of additional energy and material obtained from the energy recovery at the end of life (EoL) scenario (EUMEPS,



Graph 8.13 Embodied energy of the facade components per cubic meter per year.



Graph 8.14 Carbon footprint of the facade components per cubic meter per year.

The graphs above (8.13 and 8.14) show that although the heavier components based on brick, concrete and sand-lime blocks have higher mass per unit volume than the rest, they show similar numbers in comparison to the other lighter components, especially to the lightweight insulating materials. This results are based on the fact that the aforementioned heavy materials are all ceramics, thus they are more durable, as it can be seen in the expected technical lifetime in table 8.3. As stated by Ashby (2013), the ceramics are the most durable of all materials due to their hardness and their property to tolerate high temperatures (even more than metals). In short, these graphs show that durability plays an important role in the environmental impact of components and materials.

The vapor retarder material (nylon) and OSB show to be the materials with the highest environmental impact in terms of embodied energy and CO_2 emissions per cubic meter per year. This reflects how energy intensive these materials are, in fact the manufacturing of both materials involve arduous processes. In the case of OSB, the process involves shaving, slicing into very thin pieces, binding with resin and drying at high temperatures, all which rise the Embodied energy of the product (Hildebrand, 2014). Polyamide 66 or Nylon as it is more commonly known, represents big concerns for the environments mainly due to two main reasons. First, because of its base source petroleum, which releases high concentrations of CO_2 to the environment when extracted an processed. Second, due to its manufacturing which is very energy intensive, and which also contributes to the global warming (Evans, 2019). But the numbers of the components alone don't reflect the reality of the environmental impact caused by a facade system, since their volume differs significantly among the different systems.

8.6.3) Durability of the Facade Systems

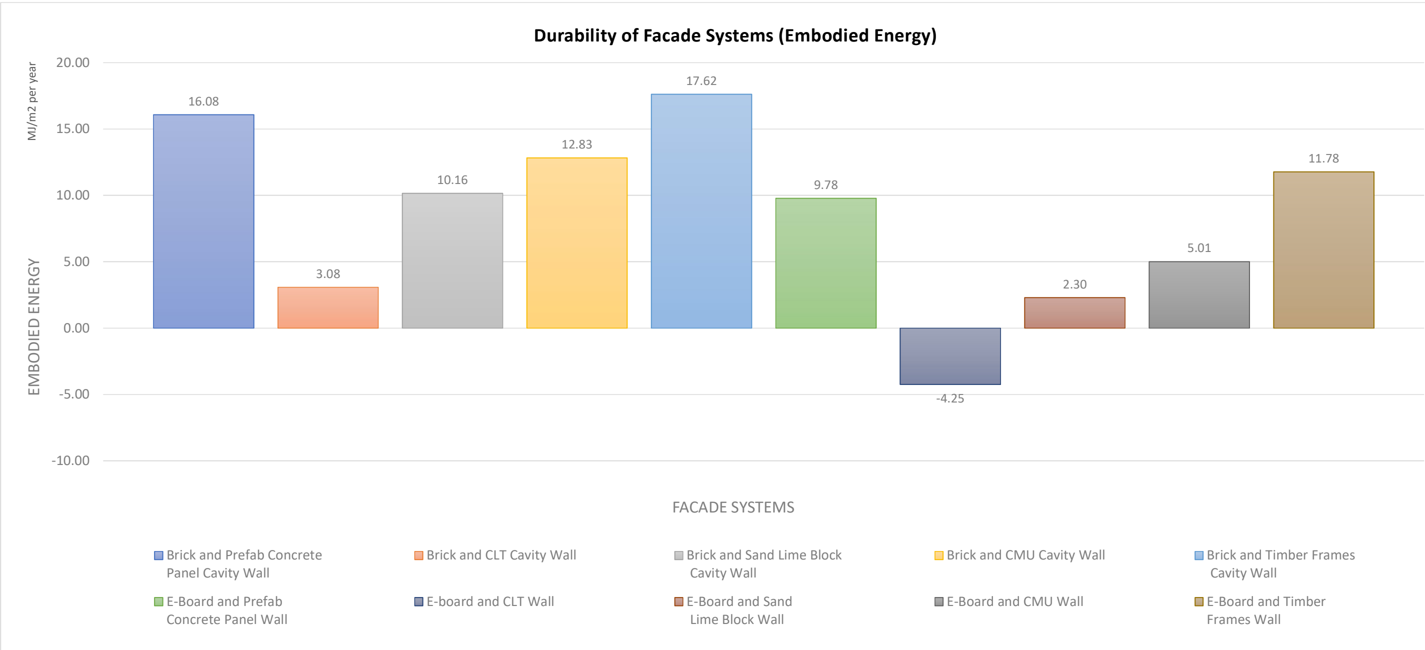
When measuring the environmental impact of a facade system while taking into consideration the durability of its components, the relevant numbers are given by their total volume in a square meter of wall. This gives the data for embodied energy per year in megajoule per square meter (MJ/m^2) and for the carbon footprint per year in kilogram of CO_2 per square meter ($kgCO_2/m^2$), as seen in table 8.7 below.

Durability of Facade Systems							
Group	**Facade System**	**Material**	**Embodied Energy per year [MJ/m3]**	**Carbon Footprint per year [kgCO2/m3]**	**Volume [m3/m2]**	**Embodied Energy per year [MJ/m2]**	**Carbon Footprint per year [kgCO2/m2]**
Panel Systems	Brick and Prefab Concrete Panel Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Concrete Panel Layers	37	0.042	1.90E-01	7.03	0.0080
		PU	28.89	0.016	8.70E-02	2.51	0.0014
						16.08	**0.015**
	Brick and CLT Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.013	1.01E-01	1.21	0.0013
		CLT Board (x4)	-155.38	-0.053	3.00E-02	-4.66	-0.0016
						3.08	**0.0048**
Masonry Systems	Brick and Sand Lime Block Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.01	1.28E-01	1.53	0.0016
		Sand lime blocks	22.27	0.03	9.42E-02	2.10	0.0024
						10.16	**0.0092**
	Brick and CMU Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.01	1.26E-01	1.51	0.0016
		CMU	37	0.042	1.29E-01	4.79	0.0055
						12.83	**0.012**
Timber Frames System	Brick and Timber Frames Cavity Wall	Clay Bricks	73.2	0.057	8.93E-02	6.53	0.0051
		OSB (x2)	173.33	0.11	3.60E-02	6.24	0.0039
		Rock Mineral Wool	11.97	0.01	1.22E-01	1.46	0.0016
		Vapor Barrier	1,693.42	1.06	2.00E-03	3.39	0.0021
						17.62	**0.013**
Board Systems	E-Board and Prefab Concrete Panel Wall	Clay Bricks (Strips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	3.40E-02	-0.29	0.00028
		Concrete Panel Layers	37	0.042	1.90E-01	7.03	0.0080
		PU	28.89	0.02	6.00E-02	1.73	0.0010
						9.78	**0.0103**
	E-board and CLT Wall	Clay Bricks (Slips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.01	1.05E-01	-0.89	0.00088
		CLT Board (x4)	-155.38	-0.05	3.00E-02	-4.66	-0.0016
						-4.25	**0.00031**
	E-Board and Sand Lime Block Wall	Clay Bricks (Strips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.01	1.30E-01	-1.11	0.0011
		Sand lime blocks	22.27	0.03	9.42E-02	2.10	0.0024
						2.30	**0.0045**
	E-Board and CMU Wall	Clay Bricks (Strips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	1.27E-01	-1.08	0.0011
		CMU	37	0.042	1.29E-01	4.79	0.0055
						5.01	**0.0076**
	E-Board and Timber Frames Wall	Clay Bricks (Slips)	73.2	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	7.20E-02	-0.61	0.0006
		OSB (x2)	173.33	0.11	3.60E-02	6.24	0.0039
		Glass Mineral Wool	11.97	0.013	1.22E-01	1.46	0.0016
		Vapor Barrier	1,693.42	1.06	2.00E-03	3.39	0.0021
						11.78	**0.0092**

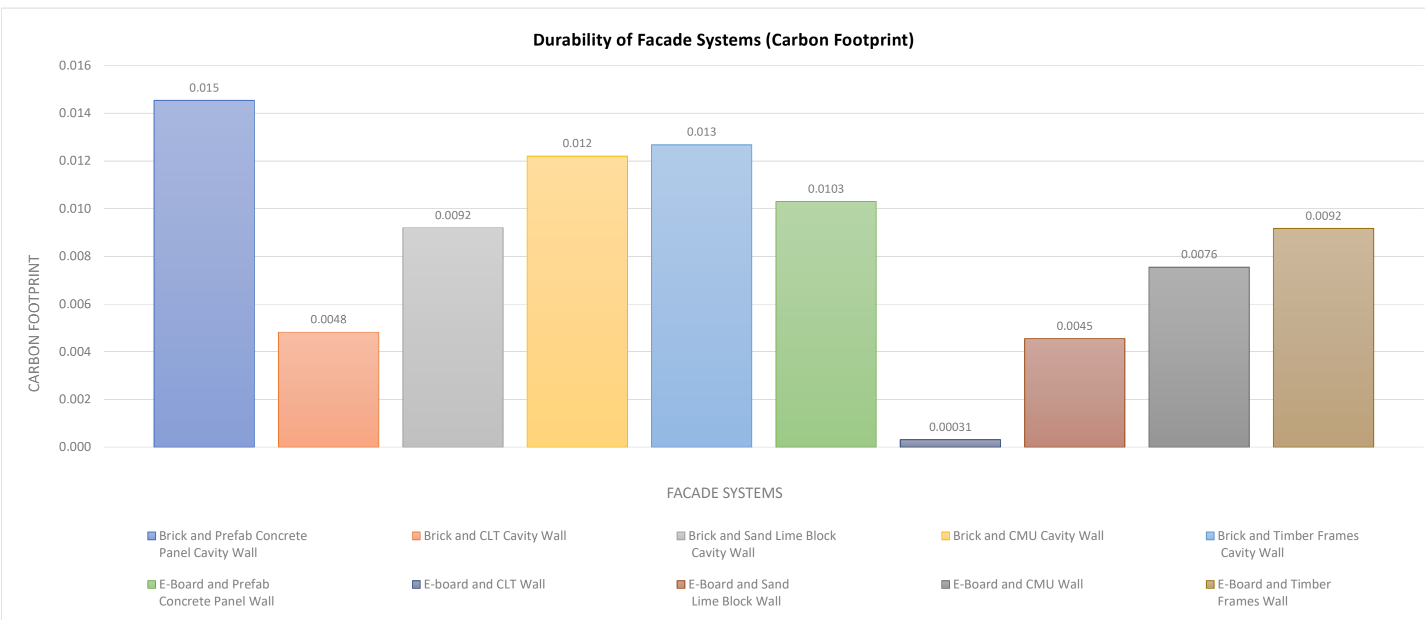
Table 8.7 Durability of the identified facade systems.

The table above organizes all the facade systems inside their respective groups defined in chapter 5, and this facade systems show the summation of all their main components in order to give as an output the total embodied energy and carbon footprint per year. The gypsum plasters and boards, which are located on the innermost layer of all the systems, are neglected in this evaluation since they do not present a significant contribution to the environmental impact of the systems, and the objective of this assessment is to compare the systems among each other. Therefore since the gypsum layer is repeated among all the systems it can be left out of the evaluation.

Graphs 8.15 and 8.16 respectively, represent the embodied energy and the carbon footprint per year of the different selected facade systems. This data is given in megajoule per square meter per year (MJ/m^2) and kilograms of CO_2 per square meter per year ($kgCO_2/m^2$), which is obtained from the previous table 8.7.



Graph 8.15 Embodied energy of the facade systems per square meter per year.



Graph 8.16 Carbon footprint of the facade systems per square meter per year.

It now evident that some systems containing components that on their own represented small contributions to the environmental impact, are now significantly increasing it. This is especially true for the heavier facade systems containing components from the material family of ceramics on their inner layer, like the prefab concrete panels, the concrete masonry units

(CMU), and the sand-lime blocks.

From this durability analysis it can be observed that the brick and timber frames cavity wall system has the highest environmental impact per year. This is because of the combination of OSB and the vapor retarder. The OSB on its own has an impact almost as high as bricks and the prefab concrete panels, as seen in table xx. However, the prefab concrete panels alone are responsible for the highest environmental impact in comparison to the other materials or components in the different systems.

It is apparent from table 8.4 that the prefab concrete panels components have the biggest volume among all the compared, which is translated to larger amounts of mass. For this reason the brick and prefab concrete panel cavity wall system is the most suitable system to optimize, since more mass can be reduced. This system is followed by the cavity wall system composed of brick and timber frames, which most critical component is OSB, as mentioned previously. Since OSB components already have small dimensions, it is convenient to replace this material for a more durable or less energy intensive one.

The durability presented in this research refers to the technical lifespan of the materials inside a facade system, which as a sum gives the value for the environmental impact of any facade system as a whole. However, it is worth to mention that the durability of a facade system can also be increased by planing and designing its components in a circular way, which facilitates disassembly. By doing so, the components with shorter lifespan inside a facade system can be easily replaced, in order to extend the technical life of the facade system. As mentioned before, this topic is out of the scope of this thesis, but it can provide valuable data in further research.

8.7) Conclusion of the Assessment Results

The previous sections show that it is possible to conduct an evaluation of the environmental impact in terms of embodied energy and carbon footprint in a fast way, which is suitable for engineers and designers seeking for this data in order to take environmentally informed decisions. By applying the methodology of the eco-audit, which only adopts the easier metrics of environmental stress, embodied energy and CO_2 emissions, the data can be easily obtained, and comparison among different materials, products or systems is easily understood by designers.

The two groups of evaluations conducted, performance versus environmental impact, and durability of the facade systems, are important in order to obtain a clear picture of the contribution of a facade system to the degradation of the environment. The first assessment gives the values for the embodied energy and carbon footprint in relation to the performance of a the facade systems, without taking into account time. This last parameter is important, because it determines how many times a certain component or product needs replacement, which again signifies some stress and strain to the environment. In this regard, the second assessment involves the technical lifetime of the different facade components, which input values are obtained from the first evaluation, and the results express more accurately the environmental impact of the facade systems.

From the assessments conducted, it can be concluded that the facade systems responsible for the highest environmental impact are the cavity wall system of brick and prefab concrete panel, and the cavity wall system of brick and timber frames. Both of these systems ended up having similar values for their embodied energy per square meter and the CO_2 emissions per square meter. In the first assessment the brick and prefab concrete panel cavity wall system scored the highest in environmental impact. But when taking into account durability, in the second assessment, the cavity wall system with brick and timber frames scored slightly higher than brick and prefab concrete panel cavity wall system, since OSB, the most commonly used material in the timber frames assembly, has a shorter technical service life than the prefab panels made out of concrete. The inclusion of the vapor retarder in the brick and timber frames cavity wall also contributes to a higher environmental impact. But by taking a closer look into the components of all the facade systems it can be observed that it is the prefab concrete panels the ones responsible for the highest environmental impact, which in turn raises significantly the total embodied energy and CO_2 emissions of the facade systems that contains it.

Since the prefab concrete panel is the component with the largest environmental impact from all the rest of the evaluated components inside the considered facade systems, it is selected to be used in the development of the case studies, that follow in the next chapter (7).

The following chapter (7) gives some insight into the application of the assessment results to reduce the environmental impact of the facade system with the highest contribution of embodied energy and carbon footprint. From the results this is the brick and prefab concrete panels cavity wall system. Therefore, the goal is to reduce the environmental impact of the aforementioned facade system, while keeping the best acoustic and thermal performance as possible by optimizing its design.

The developed evaluating tool and method is not only applied to point at the systems with larger consequences to the environment, but it is also used through many phases of the design optimization. In order to determine if the embodied energy and CO2 emissions of a facade system have decreased in comparison to the first evaluation, numbers are required. The same is true for the acoustic and thermal insulation values. Thus, constant assessment of the design optimized options is required, in terms of the acoustic and thermal performance, as well as the consequent embodied energy and carbon footprint.

9) Design Optimization

9.1) The Design Strategy

This chapter focuses on applying the data obtained from the assessment framework developed in the previous chapter (6), in order to reduce the environmental impact of the brick and prefab concrete panel cavity wall system. From the environmental impact evaluation conducted in chapter 6, this facade system is responsible for the highest embodied energy and CO_2 emissions among all the compared systems. Additionally, it was determined that its more critical components or the parts with the largest environmental burden, are the concrete prefab panels. Therefore, the objective of this chapter is to give insight into design concepts that have the potential to decrease the environmental impact of the aforementioned components, and subsequently the facade system in which they are contained.

In order to achieve the aforementioned objective, a strategy that focuses on material selection, and shape optimization is established. This strategy is illustrated in figure 9.1, which presents a flowchart that include all the proposed steps.

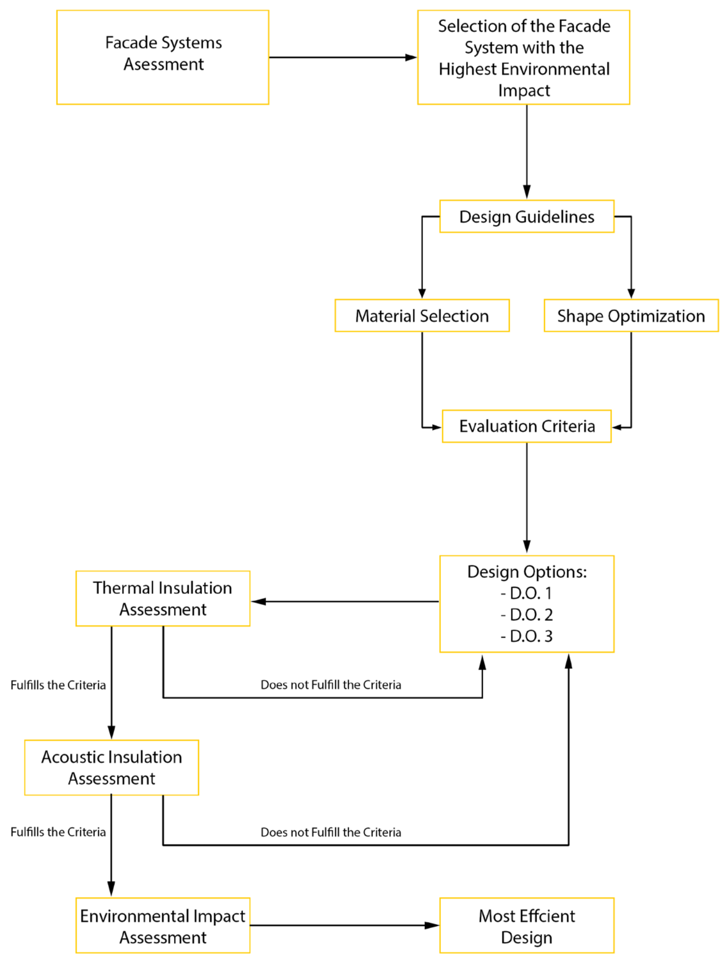


Figure 9.1 Design optimization strategy.

After the selection of the facade system with the highest environmental impact, the design guidelines based on its observations and conclusions are defined. These guidelines are based on the analysis of the material and the shape of the most critical component within the selected facade system, in order to define the evaluation criteria that are used as guides for the redesign. After establishing the evaluation criteria, three design options are proposed, focusing on the following parameters. First, the selection of a material with lower environmental impact and similar or better thermal and acoustic properties is explored. Then, the possibility of reducing the volume of the component is explored, while aiming at improving or maintaining the previous thermal and acoustic parameters. Once the design proposals are conceptualized, an assessment is conducted regarding the acoustic and thermal insulation properties. The design options that meet the evaluation criteria are compared among each other in a final assessment, which measure their environmental impact and both their acoustic and thermal performances, in order to determine the most efficient design.

As mentioned at the beginning of this section, the component that is selected to be optimized in this chapter is the prefab concrete panel, which makes part of the brick and prefab concrete panel cavity wall system. Therefore, the following section starts with the material selection phase, in order to decrease the environmental impact related to the material of the panels, which is concrete.

9.2) Material Selection: Concrete

9.2.1) The Properties

From all the 6 material families (metals, ceramics, glasses, polymers, elastomers, and hybrids), the ceramics are the most durable of all materials. Many materials belonging to this family have survived the hardships of time, ceramic pottery and ornaments dating from 5,000 B.C. have been recently uncovered, and many structures from Roman times, bonded with cement (a ceramic), still stand today. It is this quality what makes the materials belonging to this family so attractive today (Ashby, 2013). The ceramics are crystalline, inorganic solids, with the following attractive properties for the construction industry (Ashby, 2013):

a) High stiffness
b) High hardness
c) Abrasion resistance
d) High melting points
e) Low thermal expansion coefficients
f) Good electrical insulation values
g) High compressive strength
h) Low maintenance required

But as with any other family, the ceramics have their weak points too:

a) High brittleness
b) Low tensile strength
c) Low impact resistance
d) Low fracture toughness
f) Easy propagation of cracks

From this family one material sticks out due to its potential in the construction industry, and is in fact the most used, this material is concrete.

Concrete is a widely known material, commonly used in construction in almost every part of the world, either for structural elements, facades, furniture and decorations. It is a complex composite (figure 9.2), which matrix is cement and the reinforcements are a mixture of sand and gravel (Ashby, 2013).

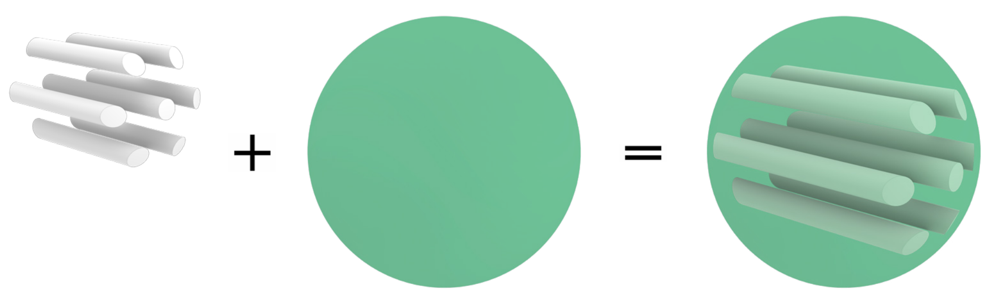


Figure 9.2 Depiction of the basic composition of a composite: The reinforcements and the matrix.

More specifically, concrete is a mixture of cement, aggregates and water (figure 9.3), sometimes with the addition of admixtures, which may be added to modify its physical properties, curing process or placing when required (Lyons, 2014).

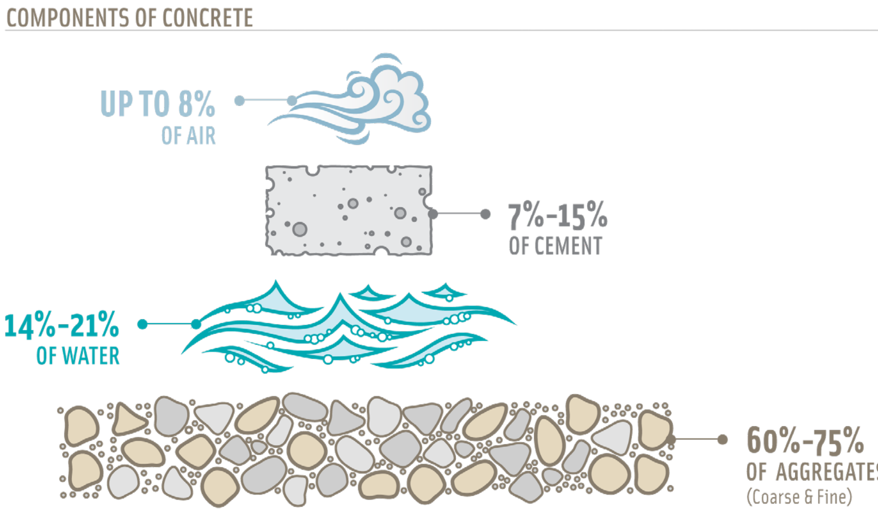


Figure 9.3 Composition of concrete

When the mixture of concrete is recently made it is a soft and plastic material, that can be shaped into almost any desired geometry, commonly the concrete is placed into molds or formwork for the production of masonry units and prefabricated or cast-in-situ floors and walls (Lyons, 2014). Since the cements used to produce concrete are hydraulic, they will set and harden due to a chemical reaction with water through hydration (Woodson, 2012). When the concrete hardens it can become a dense load-bearing material, or the opposite, a light-weight, thermally insulating material. This properties can vary, mainly depending on the type and amount of aggregates used (Lyons, 2014). The standard type of concrete is made with Portland cement, which is in fact the most commonly manufactured and used hydraulic cement in the world (Woodson, 2012), the result is a material with attractive properties for construction, as seen in table 9.1.

Normal (Portland Cement) Concrete	
Material family	Ceramic (non-technical)
Physical properties	
Density	2200 - 2600 [kg/m3]
Porosity (closed)	0 [%]
Porosity (open)	0.1 - 0.15 [%]
Mechanical properties	
Young's modulus	1.50e10 - 2.50e10 [Pa]
Specific stiffness	6.21e6 - 1.06e7 [N·m/kg]
Yield strength (elastic limit)	1.00e6 - 1.20e6 [Pa]
Tensile strength	1.10e6 - 1.30e6 [Pa]
Specific strength	406 - 517 [N.m/kg]
Elongation	0 - 1.00e-4 [-]
Compressive strength	1.33e7 - 3.00e7 [Pa]
Flexural modulus	1.50e10 - 2.50e10 [Pa]
Flexural strength (modulus of rupture)	1.70e6 - 2.40e6 [Pa]
Poisson's ratio	0.1 - 0.2 [-]
Shape factor	3 [-]
Hardness - Vickers	5.7 - 6.3 [HV]
Impact & fracture properties	
Fracture toughness	3.50e5 - 4.50e5 [Pa·m0.5]
Toughness (G)	5.83 - 11.3 [J/m2]
Thermal properties	
Melting point	930 - 1200 [°C]
Maximum service temperature	480 - 510 [°C]
Minimum service temperature	(-160) - (-150) [°C]
Thermal conductivity	0.7 - 2.6 [W/m·K]
Specific heat capacity	835 - 1050 [J/kg·°C]
Thermal expansion coefficient	5.00e-6 - 1.20e-5 [-/°C]
Thermal shock resistance	4.48 - 11.9 [°C]
Thermal distortion resistance	8.38e4 - 3.62e5 [W/m]
Latent heat of fusion	7.10e5 - 8.00e5 [J/kg]
Optical, aesthetic and acoustic properties	
Color	Gray
Transparency	Opaque
Acoustic velocity	2470 - 3280 [m/s]

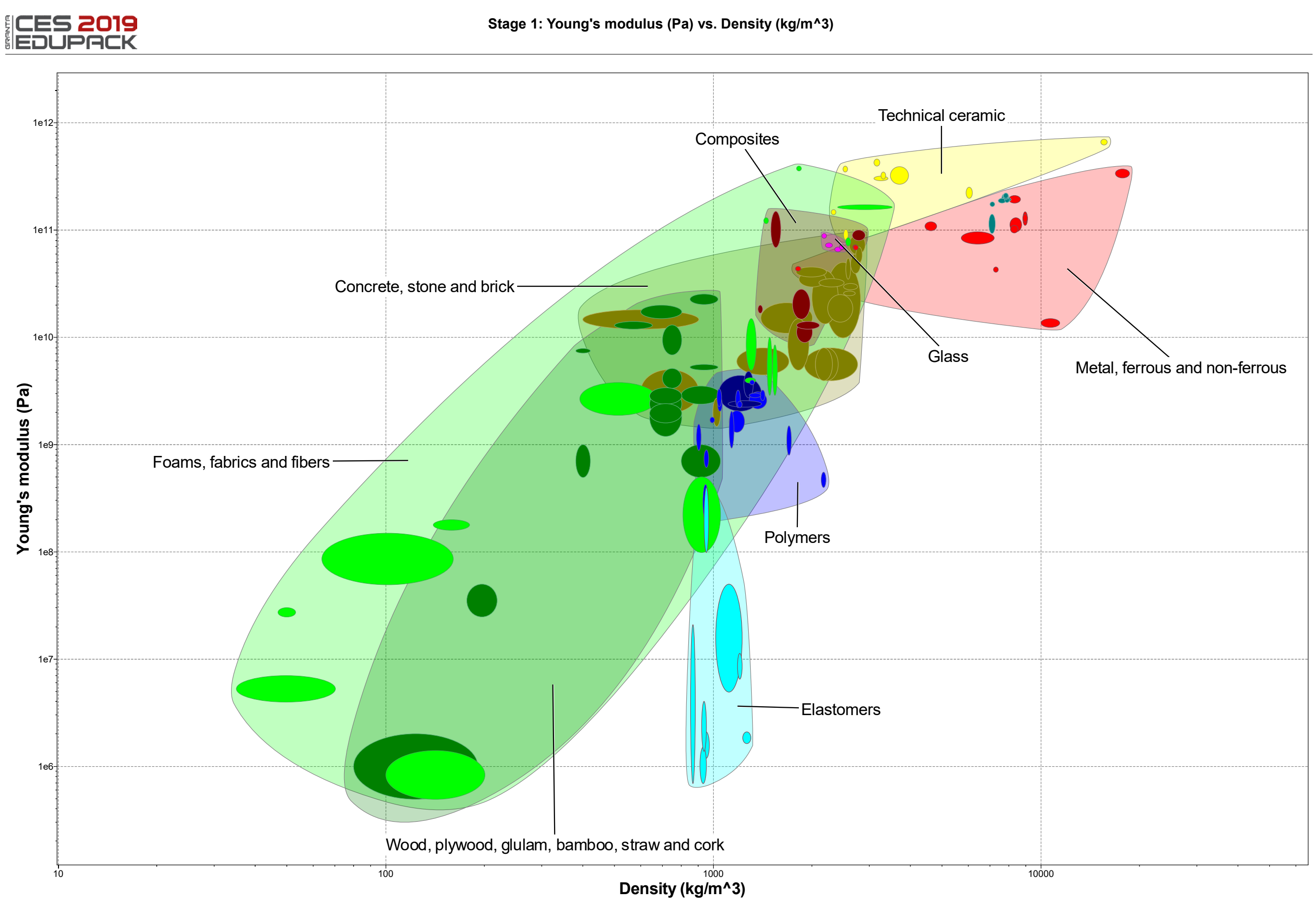
Critical materials risk	
Contains > 5wt% critical elements?	No
Durability	
Water (fresh)	Excellent
Water (salt)	Acceptable
UV radiation (sunlight)	Excellent
Flammability	Non-flammable
Primary production energy, CO2 and water	
Embodied energy, primary production	7.79e5 - 8.59e5 [J/kg]
CO2 footprint, primary production	0.116 - 0.128 [kg/kg]
Water usage	3.23e-3 - 3.57e-3 [m3/kg]
Recycling and end of life	
Recycle	Yes
Embodied energy, recycling	7.58e5 - 8.38e5 [J/kg]
CO2 footprint, recycling	0.0631 - 0.0698 [kg/kg]
Recycle fraction in current supply	13 - 14.4 [%]
Downcycle	Yes
Combust for energy recovery	No
Landfill	Yes
Biodegrade	No

Table 9.1 Material properties of concrete

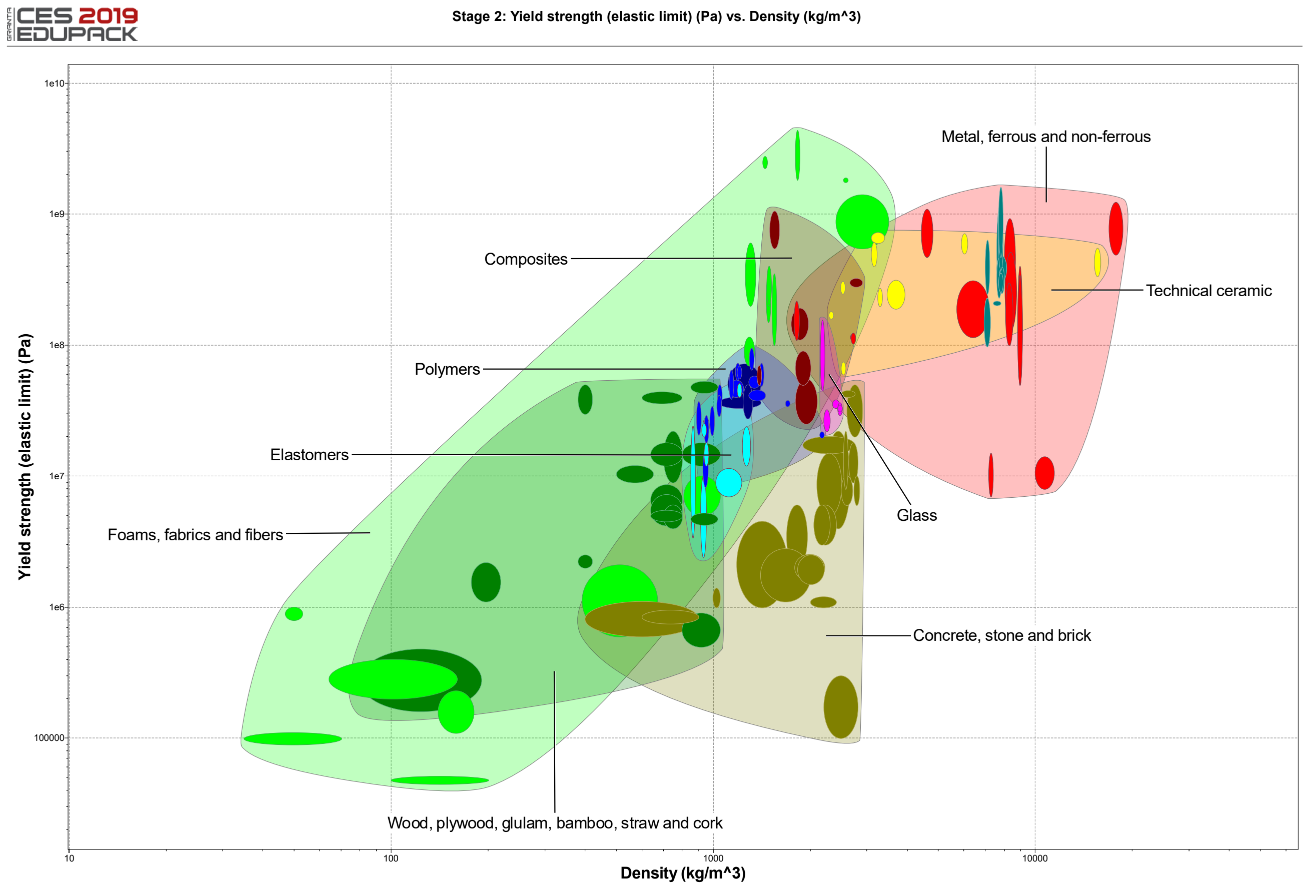
Table 9.1 shows the exceptional capabilities of concrete, as it has lower density when compared to metals used in construction, like iron (7,874 kg/m^3), steel (8,050 kg/m3) and aluminium (2,710 kg/m^3), yet with comparable stiffness (2.04e11Pa for iron, 2.00e11Pa for steel and 6.90e10 Pa for aluminium). When compared to timber used in construction, normal concrete (containing Portland cement) has nearly twice the density, but the stiffness is as high as the stiffer types of timber, as seen in figure graph 9.2. In relation to the strength or the stress at which the material first suffers permanent deformation (yield strength), normal concrete is as strong as the average timber, but is not as strong as metals, however thanks to its composite-like qualities concrete can be made stronger by modifying its composition as in high performance concrete (HPC), or with the addition of steel reinforcements or by cable tensioning.

Normal concrete is a poor insulator, but it has better thermal properties when compared to other materials used in the construction industry. Its thermal conductivity is considerably lower than that of metals by almost a factor of 10, making concrete a better thermal insulator, since it transfers less heat, as it can be observed in graph 9.3. The thermal expansion coefficient of concrete is very close to that of steel, and to that of natural materials like timber (graph 9.3), this makes them compatible in a building, specially when they have contact with the exterior, as they expand in a similar manner, reducing the internal stresses generated by the difference of the materials. Other properties like the ones corresponding to the durability of concrete make this material favorable as a construction material. This can be seen in table xx, which shows that concrete has excellent durability against water and UV radiation and it is a non-flammable material. For this reason concrete does not need fire-safety insulation. This is also the reason of why many ancient buildings, made with the first mixtures of concrete dating from Roman times have survived all this time and are still standing.

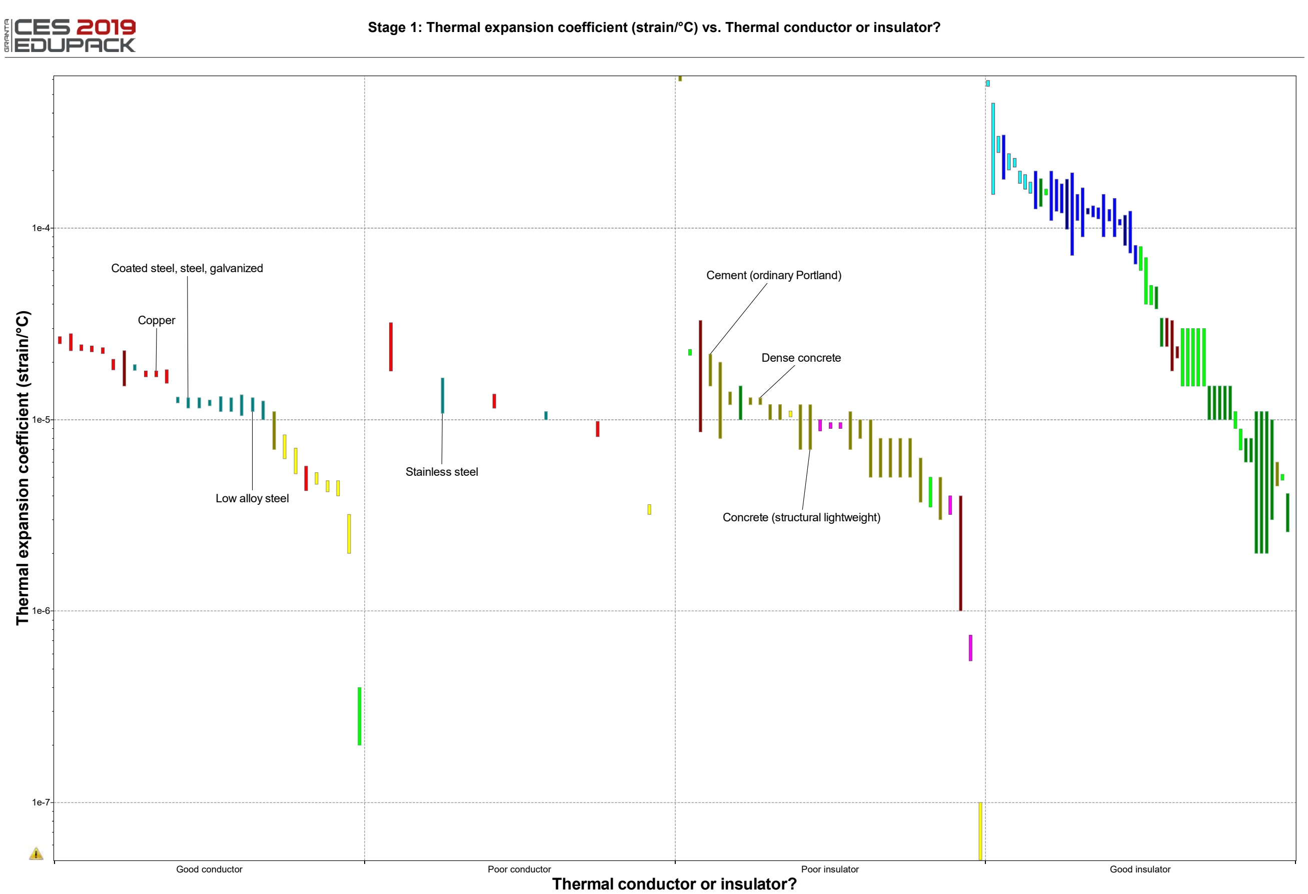
The aforementioned properties are not the only attractive of concrete, but the price makes it a desired material for many constructions, it is relatively cheap. But one of the biggest problems with concrete is its recyclability, the same characteristic that creates the superior properties in the composites (hybridization), makes them near-impossible to recycle, since the sub-components are extremely difficult to separate. For this reason concrete is mainly downcycled to be used as hard core for new constructions (Lyons, 2014).



Graph 9.1 Young's modulus vs density graph.



Graph 9.2 Density vs Yield strength graph



Graph 9.3 Thermal expansion coefficient vs Thermal conductor or insulator graph.

9.2.2) The Components

As previously mentioned, concrete is a combination of different materials, thus it involves the processing of different components. This section will present the process and qualities of all the materials that make up concrete.

1) Portland Cement

Since the English mason Joseph Aspdin created Portland cement (Setardeh & Darvas, 2017), it became the most commonly manufactured and used hydraulic cement in the world (Woodson, 2012), the term hydraulic simply means that they react with water. It is manufactured by mixing ground "clinker" with small amounts of ground gypsum and other minerals. Clinker is the name given to the grinding of limestone, which provides calcium oxide (CaO), and clays, shales, sandstone, iron ores and others, which provide silicon dioxide (SiO_2) and aluminium trioxide (Al_2O_3), which are then baked at very high temperatures of around 1,260°C (Setardeh & Darvas, 2017), as illustrated in the flow diagram of figure 9.4.

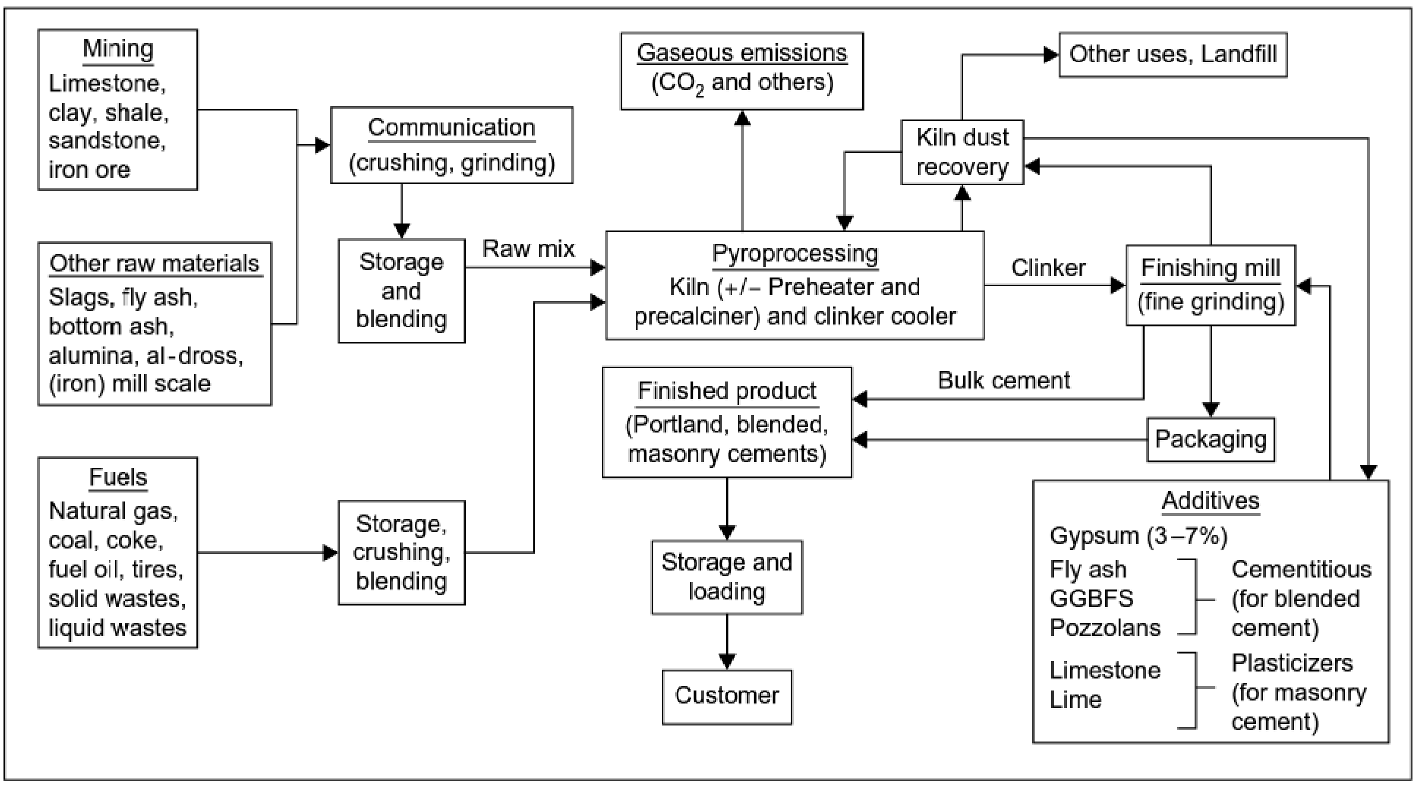


Figure 9.4 Manufacturing process of cement.

Once the clinker has cooled down it is grinded to about a size of 0.10 mm (Setardeh & Darvas, 2017), and later mixed with other additives like ground gypsum to create the finished product, which is Portland cement (Woodson, 2012). By modifying the composition of the mix or the manufacturing temperature, different properties can be achieved, which are mainly classified into 5 types (Woodson, 2012):

1) Type 1: General use Portland cement (Ordinary Portland Cement).
2) Type 2: General use Portland cement with moderate sulfate resistance and heat of hydration.
3) Type 3: High-early-strength Portland cement.
4) Type 4: Portland cement with low-heat hydration.
5) Type 5: Portland cement with high sulfate resistance.

From all these types of cement, type 1 and 3 are the most commonly used for building structures (Stardeh & Darvas, 2017).

It is worth pointing out that the basic raw materials of concrete (limestone, clay, shale, gypsum, etc.) are all relatively inexpensive. These materials are found in abundance almost everywhere around the world, so the extraction of these materials in not that much of a problem, making them cheap. But it is all the processing involved in the making of cement, specially the baking process at very high temperatures which elevates its price, and requires the biggest amount of energy, thus having the biggest CO2 emissions. This makes cement by far the most expensive and environmentally harmful component of concrete (Setardeh & Darvas, 2017).

2) Aggregates

Cement on its own is not a good material to build structures, even less facades, it is simply not strong enough for these purposes, moreover a lot of cement would be needed to build any kind of structure or building component, and as mentioned in the previous section it is the more expensive component of concrete, so on its own it is not efficient. For these matter aggregates play an important role. As stated by Lyons (2014), aggregates have significant effects on the properties of concrete. This properties include improvements in the compressive strength, size, grading, shape, appearance (Lyons, 2014), and economy (PCA, 2019). Aggregates make up the bulk of the volume of concrete, as seen in figure xx, composing 60-75 % of the total volume (Stardeh & Darvas, 2017). They are classified in 3 categories (Lyons, 2014):

1) Dense aggregates: These are the most commonly used in the production of concrete. They are classified in two classes (Stardeh & Darvas, 2017):

1.1) Coarse aggregates: These are commonly natural gravel or stone, which are larger in size than 6.35 mm. These aggregates allow the concrete to increase its compressive strength, as well as filling most of its volume.

1.2) Fine aggregates: In this class the particles are smaller than 6.35mm, for this reason sand is commonly used. The main purpose for using this fine grain is to fill the voids in between the larger particles of the coarse aggregates.

To achieve a good and consistent quality in the production of concrete a good gradation is necessary, this means that a good distribution of different sizes of aggregates is necessary to fill all the voids in the mix (Lyons, 2014).

2) Lightweight aggregates: These types of aggregates are used when a reduction in the mass of concrete is required. Where normal concrete has densities ranging from 2200-2500 kg/m^3, the densities of lightweight concrete are below 2000 kg/m^3. This generates the following properties when compared to standard or ordinary Portland cement concrete as listed below (Lyons, 2014):

a) Improvement of the thermal insulation, but reduction in the compressive strength, as the material that replaces the normally used coarse aggregates have less compressive strength.

b) Increased high-frequency sound absorption, but decreased sound insulation.

c) Reduction of self-weight of the structure since there is a reduction in the density of the concrete elements.

Lightweight concrete can be divided in 3 general categories (Lyons, 2014), as illustrated in figure 9.5:

2.1) Lightweight aggregate concrete: This aggregates are normally obtained from the manufacturing of other products or from some minerals, like pulverized fly ash, foame blast furnace slag, expanded clay and shale, expanded polyesterene (EPS) and others.

2.2) Aerated concrete: Also known as aircrete is manufactured mainly by using foams or aluminium powders. These expansion agents react with the cement, aggregates and water mixture expanding its volume, living air bubbles on the way (PCA, 2019). The result is a lightweight concrete with densities ranging from 400-1600 kg/m³ and due to the porosity of the material it can have thermal conductivities (λ) of as low as 0.1 W/m · K (Lyons, 2014).

2.3) No-fines concrete: The concrete belonging to this category can be used for load-bearing purposes. This concrete is manufactured by adding aggregates that have roughly the same size, usually between 10-20mm and cement. This process leaves void spaces in between the aggregates when the concrete hardens, which increase the thermal properties of the final material when compared to the normal dense concrete.

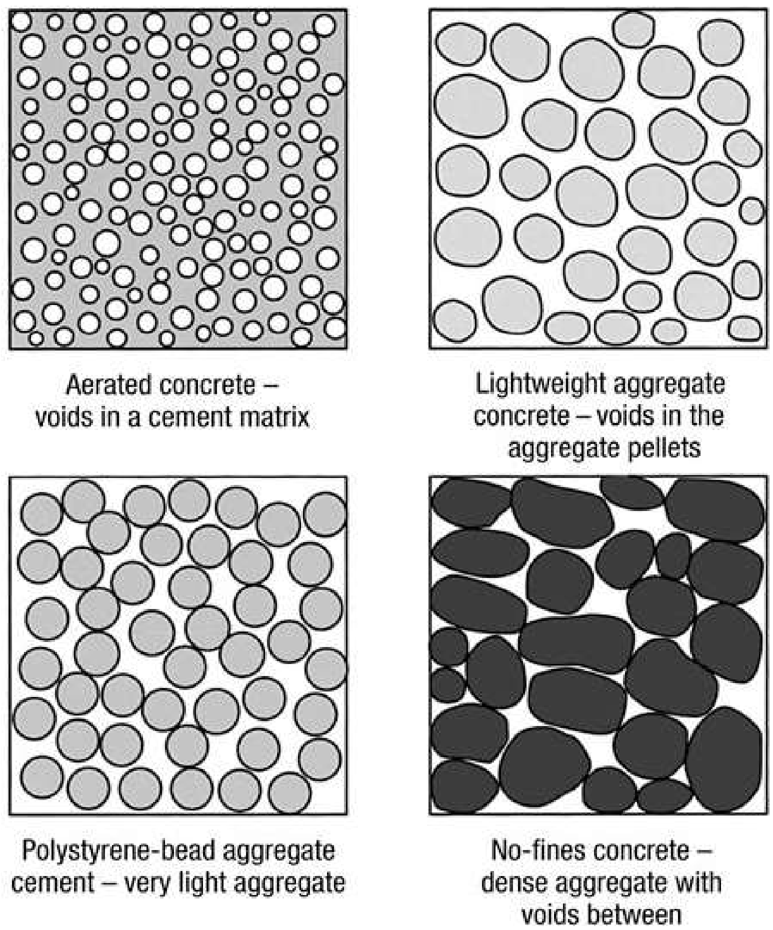


Figure 9.5 Types of lightweight concrete.

2.3) High-density aggregates: They are used to produce dense concretes of 3,000-5,000 kg/m³. They are mainly used when radiation shielding is required, so they are not relevant in this research.

3) Water

This substance is an essential component in the composition of concrete, as it is responsible for the hydration process, which is the chemical reaction between cement and water. This reaction gives the resulting paste the binding properties to adhere all the materials together in the making of concrete. The hydration process consists of three stages (Stardeh & Darvas, 2017):

Stage 1) Setting: In this stage the concrete starts solidifying slowly from its previously semi-liquid state.

Stage 2) Hardening: This stage starts taking place after 2 hours of adding water to the concrete mix, at this point the concrete is almost completely solid and it starts becoming harder, until it completely solidifies, but it still lacks strength.

Stage 3) Strength development: The strength of concrete starts developing as the days pass by, with a rapid increase in strength on the first days and then a more gradual increase afterwards.

9.2.3) Types of Concrete

Different types of concrete are obtained by modifying their composition, as a result the embodied energy and CO2 emissions can be reduced, depending on the material composition and proportions of the mixture. Some materials are just more eco-friendly than others. But the effects in the properties of concrete is limited since the mixture is only partially modified. Considering that the objective of this thesis is to optimize the acoustic and thermal insulation, as well as reduce the embodied energy and CO2 emissions of the prefab concrete panel facade system, this section evaluates some widely known types of concrete in terms of their mass per unit volume (density) and thermal conductivity. The purpose of this evaluation is to select the type of concrete with better thermal and acoustic properties to be applied in the concrete prefab panels, which will be later optimized by design, with the idea of reducing mass. This in return will reduce the embodied energy and CO2 emissions of the material due to the material reduction.

The types of concrete to be analyzed are the following, and the properties under evaluation can be observed in table 9.2:

1) Aereated Concrete: In order to obtain this type of concrete, fine aggregates and an expansion agents are mixed with cement to make the mixture expand and leave near to 80% air in the material (PCA, n.d.). The agents used are commonly foams or aluminium powders and the compressive strengths are around 20 MPa (Lyons, 2014).

2) High Performance Concrete (HPC): This type has been modified to be more durable and stronger than ordinary concrete, while maintaining almost the same density around 2,400 kg/m^3. It normally has high compressive strength above 55 MPa (ACI, n.d.).

3) Lightweight Structural Concrete: This type of concrete is produced using lightweight aggregates, which reduce the weight of concrete by around 30% (ESCSI, n.d.). A reduction in weight provides less dead load in any construction, which brings economic and environmental benefits.

4) Polymer Concrete: In this type the aggregate is bound together with a polymer matrix and it doesn't undergo through the hydration phase of ordinary concrete, the result is a concrete with fast curing times and high compressive strengths (ACI, n.d.).

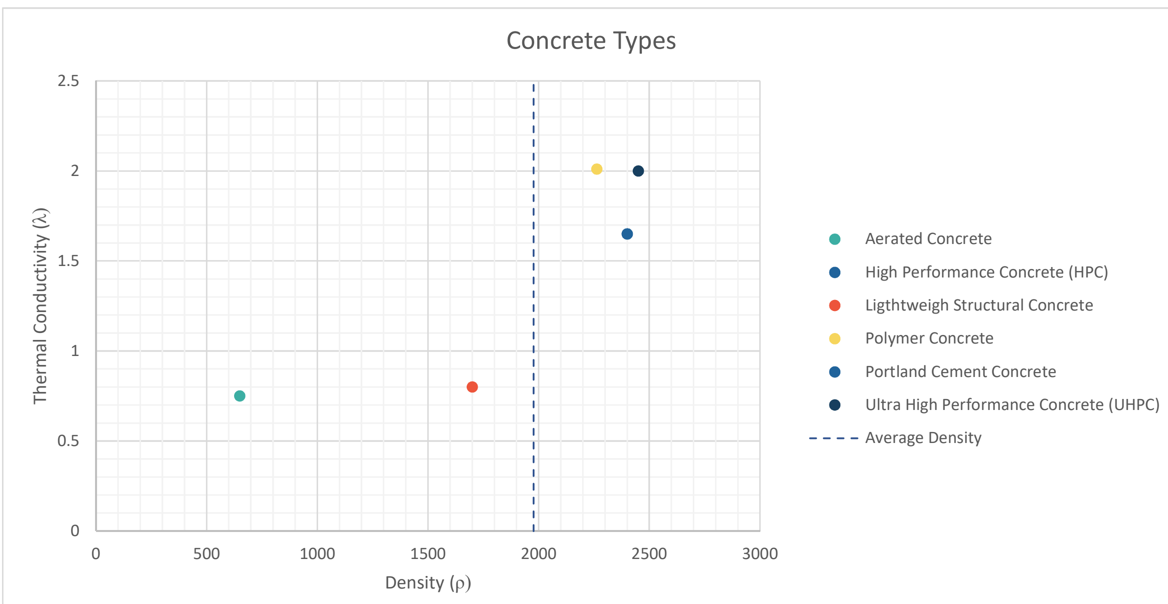
5) Portland Cement Concrete: This is commonly known as traditional or ordinary concrete, and it is the most used type of concrete around the world.

6) Ultra High Performance Concrete (UHPC): It has up to eight times the compressive strength of traditional concrete (Lyons, 2014), which is around 120 MPa (PCA, n.d.). It is made by using the same mixture of Portland cement, fibres and aggregates no larger than 1 mm. The increased compressive and flexural strengths decrease the use of material for structural purposes, as thinner sections can be used with this material.

	Concrete Types			
	Type	Density [kg/m3]	Thermal Conductivity [W/mK]	Reference
1	Aerated Concrete	650	0.75	CES (2019)
2	High Performance Concrete (HPC)	2400	1.65	CES (2019)
3	Lightweight Structural Concrete	1,700	0.8	CES (2019)
4	Polymer Concrete	2,263	2.01	Elalaoui et al. (2012)
5	Portland Cement Concrete	2,400	1.65	CES 2019
6	Ultra High Performance Concrete (UHPC)	2,450	2.0	Yang & Park (2019)

Table 9.2 The thermal conductivity of the types of concrete.

Graph 9.4 shows the density vs the thermal conductivity of all the aforementioned concrete types. Some clear differences are observable in both axes, and it can also be deducted that there is a direct relation between both properties, considering that the thermal conductivity seems to be lower if the mass per unit volume decreases as well. It seems logical that the best option is to select the type of concrete with the least density and the lowest thermal conductivity in order to save material, but reducing mass only profits the thermal insulation, and decreases the acoustic insulation, moreover the objective in the design optimization phase is to reduce material to decrease the embodied energy and CO_2 emissions, which will en up reducing more the overall mass of the material. This would reducing further the airborne sound insulation and the structural performance of the concrete panels. Therefore the best material selection is the one with the lowest thermal conductivity and average density. Lightweight structural concrete is the type of concrete that presents the best results, due to its low thermal conductivity and density closest to the average among the compared materials.



Graph 9.4 Density vs thermal conductivity of the different concrete types.9.3.1) Shape Optimization: Prefab Concrete Panels

This chapter explores the possibilities of shape optimization of the prefab concrete panel facade system based on the research results obtained, where the attributed embodied energy and CO_2 emissions are measured against the acoustic and thermal performance. Therefore, three different design scenarios are proposed and analyzed with the objective of reducing the embodied energy and CO_2 emissions, while trying to approximate the acoustic and thermal insulation values as much as possible to the ones obtained from the results of the prefab concrete panel system.

First, the shape optimization strategies are explained and established. Then, the three design options are presented and assessed in order to meet the evaluation criteria defined in this chapter. Lastly, the design optimized options are compared among the cavity wall system with brick on the exterior layer to provide an overall comparison among all the selected facade systems assessed in chapter 6. Program simulation analysis, based on the analytical models and software presented in chapter 6 are used for this study. The aforementioned steps are illustrated in figure xx, which shows the workflow adopted in this chapter.

9.3) Shape Optimization Strategy

Based on the observations of the facade system assessment in chapter 6, the best way to decrease the environmental impact is by material reduction, as the facade systems that scored the highest, meaning more embodied energy and CO2 emissions, are the bulkier ones. For this reason the design guidelines adopted in this chapter are based around reducing the material of the prefab concrete panels, while reaching the best acoustic and thermal performance as possible, in other words increasing the efficiency of the facade system. With this goal in mind, the following strategy is devised, and is better illustrated in figure 9.6:

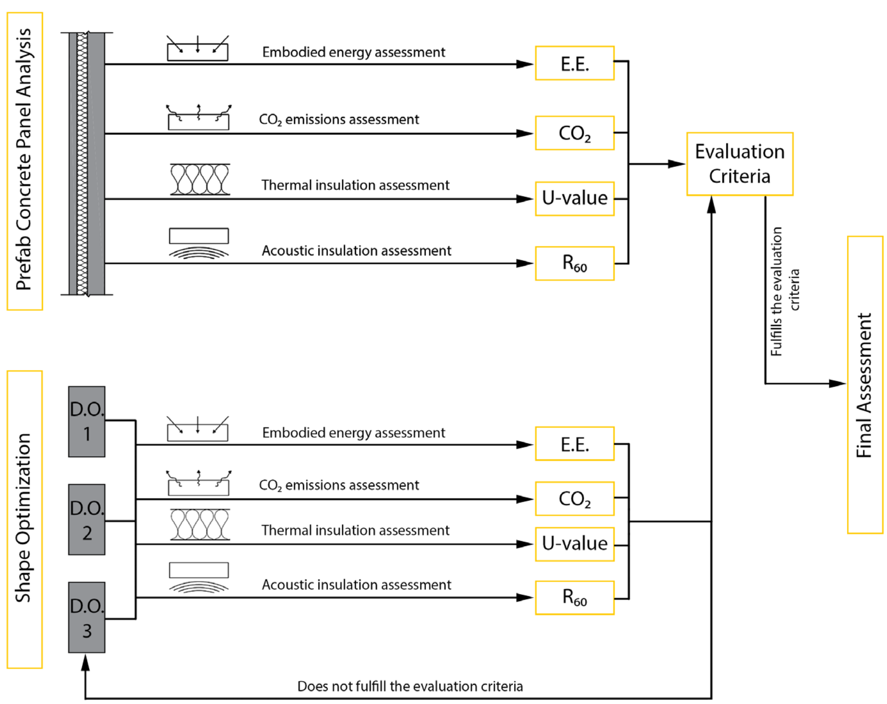


Figure 9.6 Shape optimization strategy flowchart.

1. Present an overview of the prefab concrete panel system and an assessment in which the embodied energy and CO2 emissions will be measured, as well as the U-value and the airborne sound insulation for random incidence at 63 Hz. This will provide the evaluation criteria for the optimized design options to follow.

2. Proposal of three design optimized options in order to decrease the embodied energy and CO2 emissions, while approximating the thermal and acoustic performance as much as possible to the evaluation criteria proposed earlier.

3. Combine the design optimized options in to a cavity wall system with brick on the exterior layer, to be reinserted in the graphs presented in chapter 6, in order to draw conclusions based on a final overall assessment.

9.3.1) Prefab Concrete Panels: System Overview

There are many advantages when prefabricating a construction element over building them on-site. As Allen and Iano (2019) indicate, these include the production of elements at ground level, under shelter, in climate-controlled environments, and with consistent quality. The latter point also suggests an environmental advantage as there is less material waste when there is consistency in the manufacturing of a product. Since buildings are commonly made of a repetition of many elements like walls or slabs, prefabricating these elements can reduce construction times and labor, therefore prefabricating concrete facades makes sense.

The prefab concrete panels can be either a loadbearing or non-loadbearing form of construction and they exhibit many important qualities like weather tightness, high fire resistance, high acoustic insulation and thermal mass, all which make them increasingly popular nowadays in the construction industry (Watts, 2019). One big disadvantage though is the size restriction, which is determined by the maximum permissible vehicle width of 3.7 to 4.3 meters After their manufacturing these elements are transported to the construction site, where they are erected as rigid components by cranes and installed in their respective positions (Allen and Iano, 2019). The prefab concrete panels can be divided in three main categories (Taracon Precast, n.d; WGE Group, n.d.), which will be explained in the next section.

When using the term prefab concrete panels the idea is to refer to the prefabrication of concrete wall elements which can be achieved by different processes like casting or extrusion.

9.3.2) The Types

The prefab concrete panels can come in different shapes, sizes and layering (with or without insulation), but nonetheless they are divided into 3 main types (Taracon Precast, n.d; WGE Group, n.d.), which are widely used in any kind of construction from residential to industrial (WGE Group, n.d.):

1) Solid Walls: This category refers to the prefabricated walls that are made up primarily of concrete, and without any insulation. The walls can be completely solid, in which the only additional material is steel (applied for the reinforcement), or hollow on the inside in order to reduce mass.

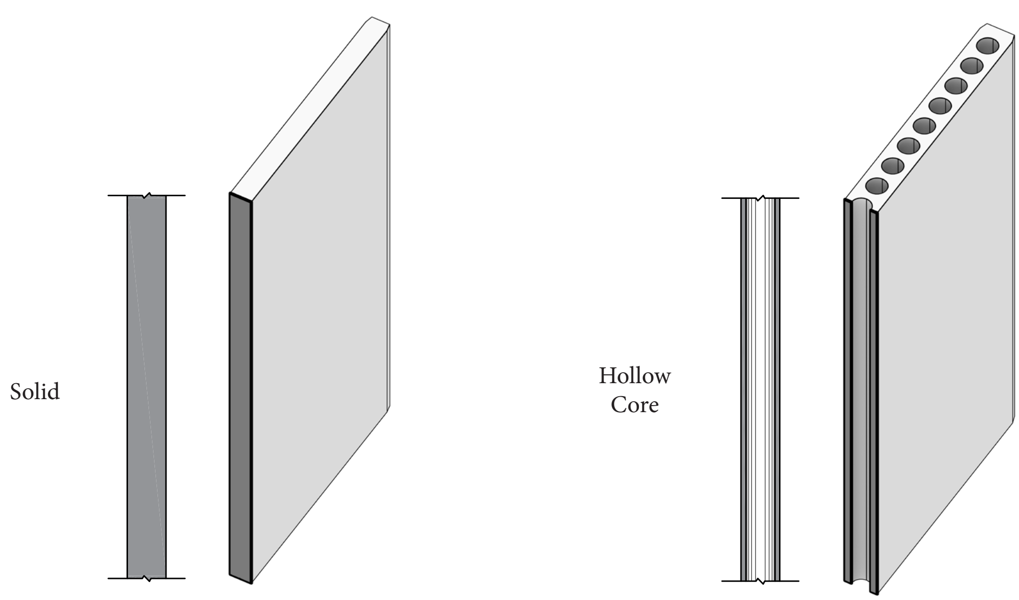


Figure 9.7 Solid prefab concrete panel types.

2) Sandwich Walls: In this category, the panels are cast with rigid insulation between two outer layers of concrete. The concrete layers or wythes can vary in thickness mainly to provide structural properties, but by doing so they can also provide better acoustic insulation. In a similar manner, the insulation in the middle of the panel can vary in thickness to provide better thermal and acoustic insulation properties.

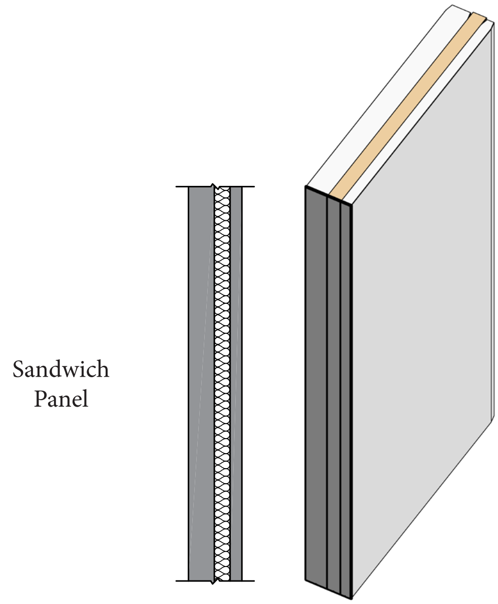


Figure 9.8 Sandwich prefab concrete panel type.

3) Thin-shell Walls: This are lightweight panels, since they are mainly composed of a thin layer of concrete on the outside, which is supported by steel profiles on the inside. This system can be loadbearing , as well as used in curtain walls, because the steel frames resist the axial and transverse loads, and the concrete layer stiffens the steel (Chusid, 2009).

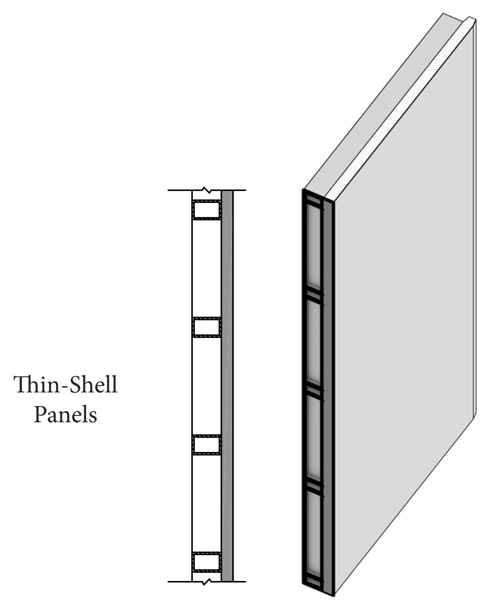


Figure 9.9 Thin-shell prefab concrete panel type.

9.3.3) The Process

The manufacturing process of concrete prefab elements has many advantages over sitecasting. First, it can be carried out completely at ground level. Second, It can be carried out under controlled conditions, protected from the adverse weather.

Lastly, high and consistent quality can be achieved due to standardized and controlled workmanship (Allen & Ino, 2019).

Traditionally, the concrete is cast by workers into forms made of different materials in order to produce panels with almost any desired surface finish. These forms can be made of steel, concrete, glass-fiber reinforced plastic or wood. The advantage of using them is that they can be used many times, before they need renewal, so their cost is kept relatively low. Additionally, these forms are designed to equip the necessary components to pretension the reinforcing steel in the prefab elements (Allen & Iano, 2019).

In addition to the traditional method of casting concrete, in which workers pour or cast concrete into molds, machines can be used instead, in order to automate the process. There are three main casting machine categories (IPHA, n.d.):

1) Extruder: It casts the panel by using a concrete mix with low content of cement. Inside the machine the concrete is compacted and vibrated, and then it is extruded into a casting bed.

2) Slipformer: It casts the panels in different stages, using vibration to form the element around moving steel cores. It can only produce continuous sections.

3) Flowformer: It casts the concrete without any mechanism or drive units. The concrete is let to flow by gravity and vibration in different ways to produce almost any desired surface finish.

9.3.4) Prefab Concrete Panel: Assessment

With the idea of providing the evaluation criteria for the shape optimized designs, an assessment of the standard prefab sandwich panels alone, which were previously evaluated in a cavity wall with brick on the outside is conducted in this section. The environmental impact in terms of embodied energy and CO_2 emissions is measured, as well as the airborne sound insulation for random incidence at 63 Hz, and the thermal insulation. The design of the panel under evaluation is illustrated in figures 9.10 and 9.11, and in order to provide a valid comparison with the different design options the defined dimensions of a single panel are of 3 meters wide by 3 meters high.

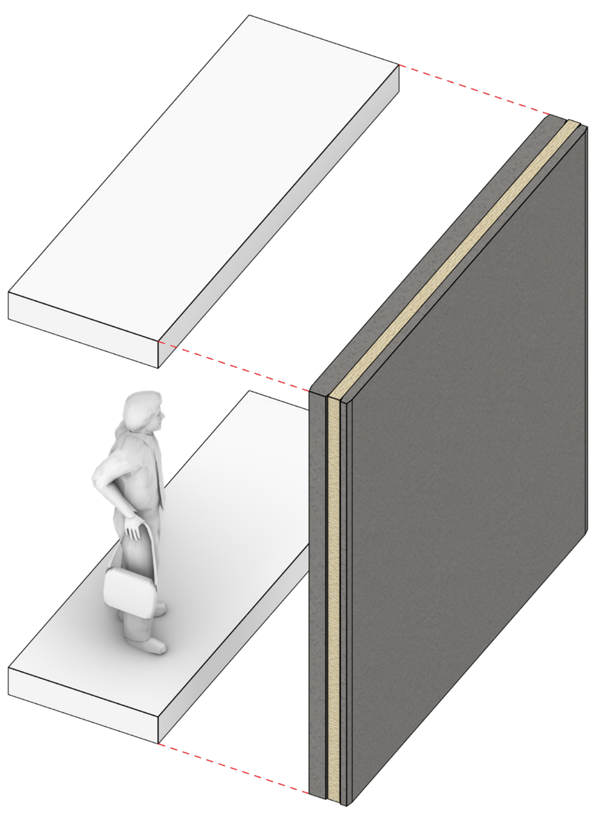


Figure 9.10 Axonometric of sandwich prefab concrete panel.

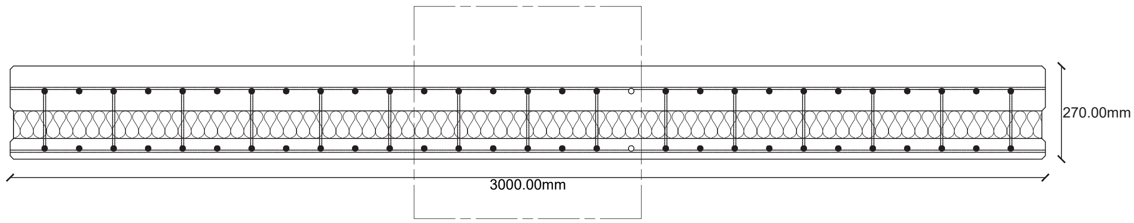


Figure 9.11 Top view of prefab sandwich panel.

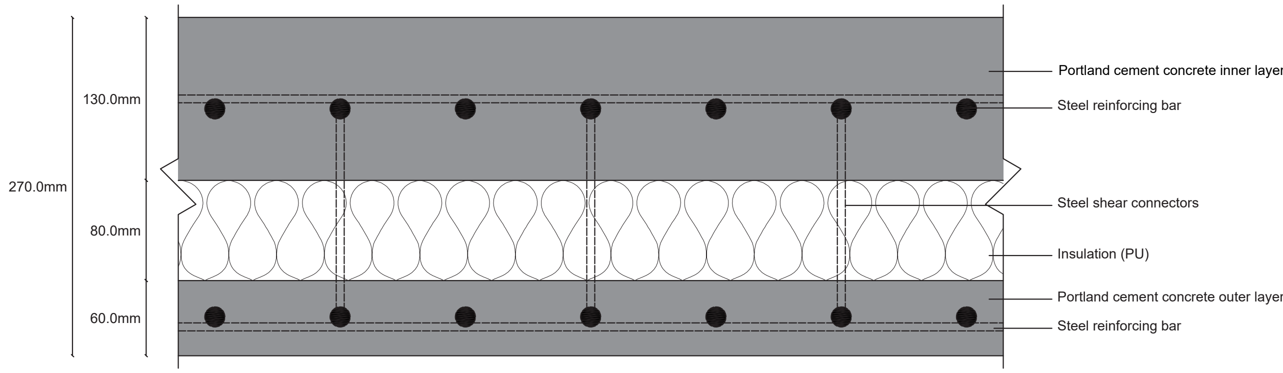


Figure 9.12 Top view detail of prefab sandwich panel.

The panel under evaluation, shown above in figure xx, is composed of an interior and an exterior layer of Portland cement concrete, with a middle layer of polyurethane (PU) insulation, which is obtained from the facade systems and insulation evaluation conducted in chapter 6. The PU insulation is chosen for the evaluation among the other types, as it is has the least environmental impact after EPS, but it needs less material in order to reach a minimum U-value of 0.22 W/m²K. Moreover, at this thermal insulation value it provides a better airborne sound insulation of more than 40 dB when compared to EPS.

9.3.5) Environmental Impact Assessment: Embodied Energy and CO_2 Emissions

The evaluation of the embodied energy and CO_2 emissions inside the prefab concrete sandwich panel under evaluation is already presented in chapter 6, inside the cavity wall with brick on the outer layer. For this reason the embodied energy of the panel can be extracted from the cavity wall systems with brick, which were previously calculated in the aforementioned chapter. Therefore the tool used for this calculation is the database created in Excel, that provides all the relevant data of the material layering and dimensions inside the prefab concrete panel facade system in order to calculate its embodied energy and CO_2 emissions, as shown in table 9.3.

Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
Portland Cement Concrete	-	-	-	2,500.00	-	-	1.48	0.17	3,700.00	422.50	-	-	CES (Eco-Audit)
PU	-	-	-	31	-	-	69.9	2.9	2166.9	89.9	-	-	PU Europe, 2014

Table 9.3 Environmental impact of sandwich prefab panel per cubic meter.

This section provides the embodied energy in megajoule per square meter of wall (MJ/m²) as well as the CO_2 emissions in kilograms of CO_2 per square meter of wall of the prefab concrete panel on its own. In order to calculate these parameters the thickness of the prefab concrete panel components is multiplied with the environmental impact per cubic meter of the product (MJ/m³ and kgCO²/m³). The total environmental impact of the prefab concrete panels under evaluation can be observed in table 9.4.

Environmental Impact of Construction Materials													
Material	**Quantity (per m2) [-]**	**d [mm]**	**Volume [m3/unit]**	**Density [kg/m3]**	**Mass [kg/unit]**	**Mass [kg/m2]**	**Energy [MJ/kg]**	**CO2 [kg/kg]**	**Energy [MJ/m3]**	**CO2 [kg/m3]**	**Energy (Wall) [MJ/m2]**	**CO2 (Wall) [kg/m2]**	**Reference**
Prefab Concrete Panels (Interior Layer)	1	130	1.30E-01	2,500.00	325.00	325.00	1.48	0.17	3,700.00	422.50	481.00	54.93	CES (Eco-Audit)
PU Insulation	1	87	8.70E-02	31	2.70	2.70	** 69.90	** 2.90	2,166.90	89.90	188.52	7.82	PU Europe, 2014
Prefab Concrete Panels (Exterior Layer)	1	60	6.00E-02	2,500.00	150.00	150.00	1.48	0.17	3,700.00	422.50	222.00	25.35	CES (Eco-Audit)
Total Environmental Impact	-	-	-	-	-	-	-	-	-	-	**891.52**	**88.10**	

Table 9.4 Environmental impact of sandwich prefab panel per square meter.

The total obtained values of 891.52 MJ/m² for the embodied energy and 88.10 $kgCO_2/m^2$ for the carbon emissions will set the evaluation criteria for the optimization phase based on the environmental impact.

9.3.6) Thermal Insulation Assessment: U-value

The evaluation of the prefab concrete sandwich panel in terms of thermal insulation are calculated by using the software THERM 7.7. This software is based on the analytical model provided by Bokel (2015) for the calculation of thermal transmittance or U-value presented in chapter 6. This software is used as the calculation tool of this system and for the optimized options, as it takes into account the thermal bridges in the models, which is neglected in the analytical approach.

Figure 9.13 shows the results of the U-value calculation for the prefab concrete panel on its own, as it was previously calculated in chapter 6 as part of a whole cavity wall system with bricks on the outer layer.

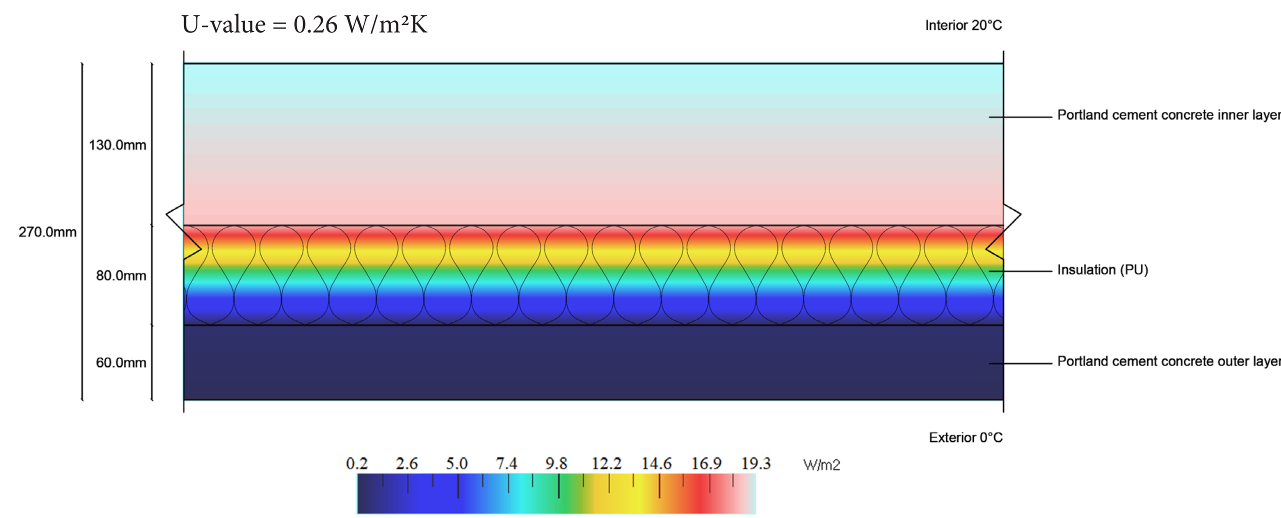


Figure 9.13 U-value of prefab sandwich panel.

The obtained U-value from the software was of 0.26 W/m²K, which is very close to the value that can be obtained from using the analytical model which gives 0.24 W/m²K. Since there are no thermal bridges in model, as the steel shear connectors are neglected for this study, the heat flow that is observed in image 9.12 is evenly distributed. The U-value of 0.26 W/m²K is used as the evaluation criteria for the thermal performance of the design phase.

9.3.7) Acoustic Insulation Assessment: R_{60}

The airborne sound insulation of the prefab concrete sandwich panel under analysis are calculated using the MLM (Meer Lagen Model) software by Lau Nijs (2020). The model calculates the sound waves as coming from all directions, therefore the sound insulation is calculated at random incidence with an angle of 60°. The output from the software gives the sound insulation values (R_{60}) in a frequency band that extends from the low 63 Hz to the high 8,000 Hz. For the purpose of this evaluation the airborne sound insulation to be compared with the other options presented in the next sections is the one at 63 Hz.

Airborne Sound Insulation of Prefab Concrete Sandwich Panel								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	Prefab concrete panel	sol	130.00	2,500.00	2.00E+10	0.00	0.05	0.27
2	PU insulation	liq	87.00	31.00	5.00E+04	0.00	0.00	20,000.00
3	Prefab concrete panel	sol	130.00	2,500.00	2.00E+10	0.00	0.05	0.27
ƒ [Hz]	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**77.3**	107.3	132.1	178.9	197.0	197.0	197.0	197.0

Table 9.5 Airborne sound insulation of prefab sandwich panel.

Table 9.5 is obtained from results of the MLM software, and it can be observed that the sound insulation of this massive facade system is reflected in the high airborne sound insulation values in all of the frequencies. Even the airborne sound insulation at the lowest frequency of 63 Hz show a high value of 77.3 dB. This number is used as reference to compare the design options presented in the next section.

9.3.8) Evaluation Criteria

As it can be observed, the prefab concrete sandwich panels analyzed in the previous section exhibits good acoustic and thermal performance, which is mainly due to the bulky layers that compose the entire system, but these come at the expense of high embodied energy and CO2 emissions. Therefore the following sections will explore the design possibilities, focusing on shape optimization in order to reduce the overall mass of the system with the goal of reducing the environmental impact. The evaluation criteria obtained from the previous analysis, which will be used in the next sections is summarized below in table 9.6.

Evaluation Criteria of Prefab Concrete Sandwich Panel	
Embodied Energy [MJ/m2]	**891.52**
CO2 Emissions [kgCO2/m2]	**88.1**
U-value [W/m2K]	**0.26**
R60 [dB]	**77.3**

Table 9.6 Evaluation criteria parameters of prefab concrete sandwich panel.

9.4) Design Options: Shape Optimization

Since reducing the mass of a material or product decreases the environmental impact caused by it, the design strategies adopted in the proposal of the three options that follow are based on optimizing the shape of the prefab sandwich panels previously analyzed in order to reduce the amount of material used, while aiming to approximate the acoustic and thermal performance as much as possible to the ones established in the evaluation criteria. In order to meet this requirements, the design concept of the three options is based around the principle of reducing material as in the prefab hollow core panels, and providing insulation as in the case of the prefab sandwich panels, as illustrated in figure 9.14.

The following sections illustrate the three different design options, as well as their respective assessment in terms of their embodied energy, CO_2 emissions, thermal and acoustic insulation.

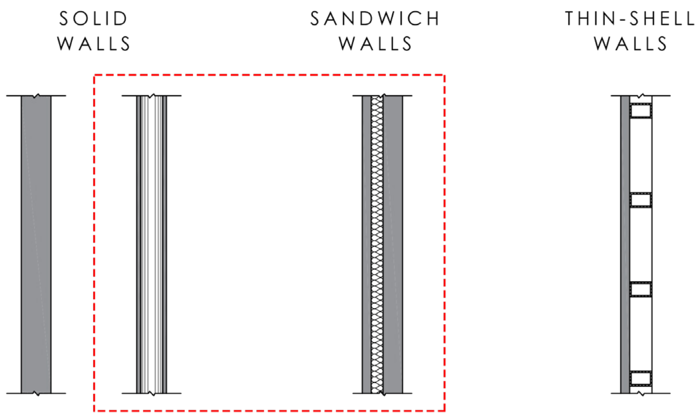


Figure 9.14 General design optimization concept.

1) Design Option 1

The first design exploration is based on generating empty spaces inside a single layer of prefab panel, in which the concrete layer is evenly distributed, leaving a waffle like pattern in the panel. The idea is to reduce the amount of concrete normally used in the traditional prefab panels.

Two different variants were designed and analyzed in order to provide the one that meets the evaluation criteria.

1.1) Variant 1: Concept

In the first variant the concept is to give a minimum layer thickness of 30 mm of concrete around the whole panel, leaving empty spaces in between of 20 mm in the direction of the heat flow (Q), since the convective flow of air inside a cavity or void is smaller when it is close to 10 mm (Piccioni, 2019). This variant can be seen below in figures 9.15 and 9.16. Additionally, the empty spaces are staggered in the direction of the heat flow in order to increase the time of heat transfer.

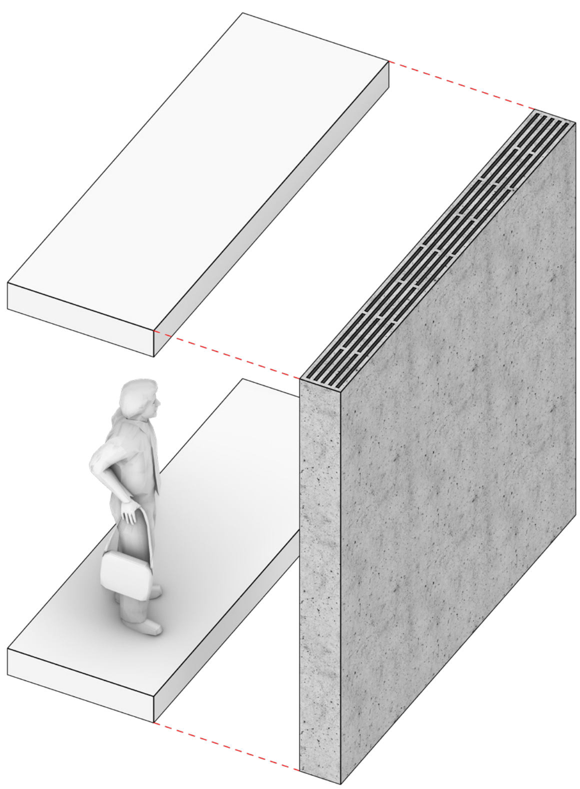


Figure 9.15 Axonometric of design option 1 (variant 1).

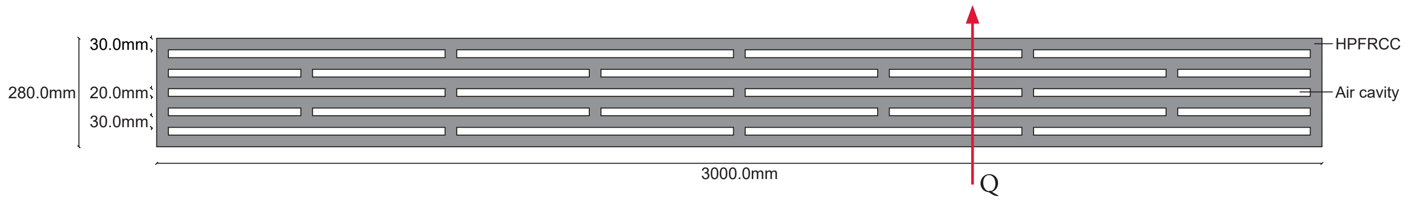


Figure 9.16 Top view of Design option 1 (variant 1).

Since this is a geometry composed of many small details it will be challenging to produce using the conventional methods of casting or extrusion used to fabricate facade panels, therefore this variant is assumed to be produced by additive manufacturing or 3d printing. Providing an insight into the production process is important in order to make decisions related to the material. As lightweight structural concrete is composed of coarse aggregates it is not a viable option as a material to 3d print. More suitable materials for the intended applications are the High Performance Fiber Reinforced Cementitious Composites (HPFRCCs), which are fiber reinforced mortars optimized in order to increase their structural behavior (Wangler e. al., 2019).

1.2) Variant 1: Embodied Energy and CO_2 Emissions

Due to the lack of data in terms of embodied energy and CO2 emissions exhibited in the extraction, manufacturing, transport and end of life potential of HPFRCCs, the same values as Portland cement concrete are considered for the calculation of the environmental impact of this variant, with the exception of the density. This property has a value of 1,850 kg/m³ at a heat treatment of 22°C (Li et al., 2017), as presented below in table 9.7.

Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
HPFRCCs	-	-	-	1,850.00	-	-	1.48	0.17	2,738.00	312.65	-	-	CES (Eco-Audit)

Table 9.7 Environmental impact of design option 1 (variant 1) per cubic meter.

As this design variant is composed of a single material with some empty spaces in between, the overall volume in a square meter of wall is calculated to obtain the embodied energy per square meter of wall (MJ/m²) and the CO_2 emissions per square meter of wall ($kgCO_2/m^2$), as seen underneath in table 9.8.

Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
Design Option 1: Variant 1	-	-	1.87E-01	1,850.00	345.21	345.21	1.48	0.17	2,738.00	312.65	510.91	58.34	CES (Eco-Audit)

Table 9.8 Environmental impact of design option 1 (variant 1) per square meter.

The results obtained from the calculations show a total embodied energy of 497.10 MJ/m2 and CO2 emissions of 56.76 kgCO2/m2, representing an environmental impact reduction of 44.4% and 35.6% respectively.

1.3) Variant 1: U-value

In order to calculate the U-value of this variant, the thermal conductivity (λ) of the HPFRCCs of 1.35 W/mK at a heat treatment of 22°C (Li et al., 2017) is provided as a material input for the calculations in the software THERM 7.7. The results can be observed below in figure 9.17.

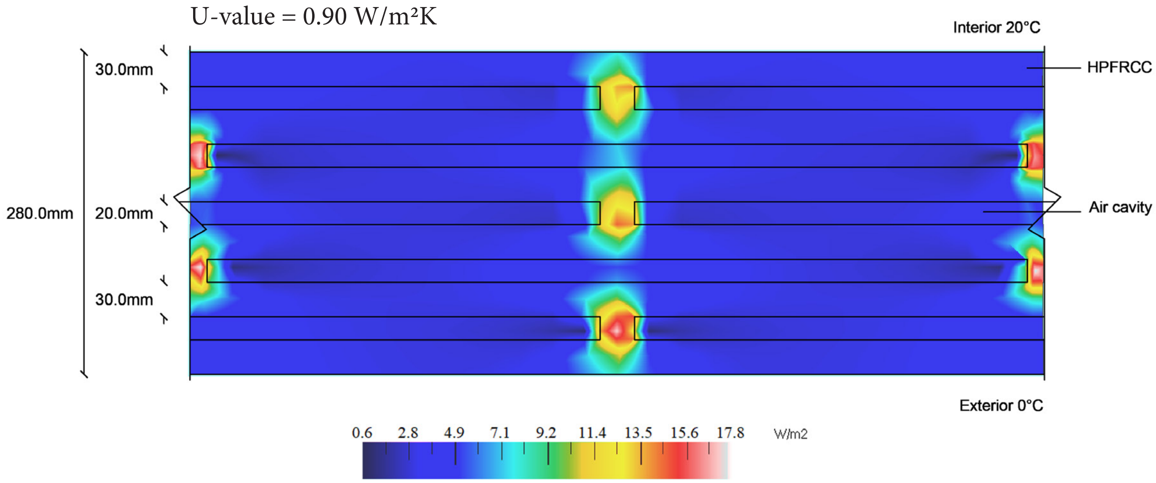


Figure 9.17 U-value of design option 1 (variant 1).

The result obtained from the calculations is very high, with a U-value of 0.90 W/m2K, which is more than 3 times the number in the prefab sandwich panel. This shows that even if still air is trapped inside the empty holes, the overall thermal performance is not very good. The thermal bridges inside the panel also have a big contribution the low insulation values, as seen above in figure 9.17.

1.4) Variant 1: R60

The internal composition of the panel resembles a cavity wall or a multi layered window, where there are many layers of solid material divided by a thin layer of air. Therefore the panel is calculated in a similar manner. In this particular case the weakest points in the panel are the ones in which direction there is less cementitious material, as this material is denser than air, thus providing more insulation against sound. For this motive, the layers taken into account for acoustic calculation are illustrated inside the red rectangle in figure 9.18.

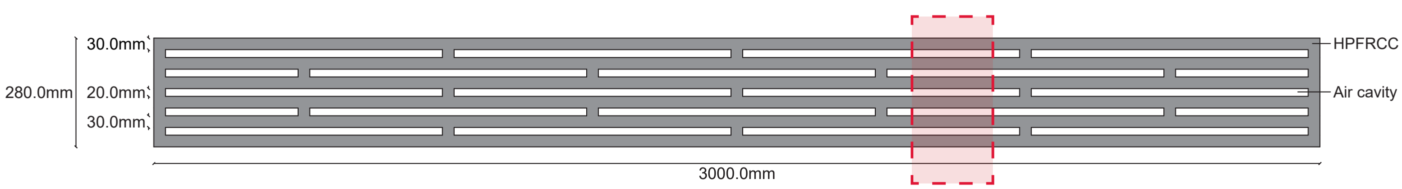


Figure 9.18 Section considered for airborne sound insulation calculation.

In order to obtain the sound insulation results, the Young's modulus of HPFRCC, which is around 24.5 MPa or 2.45 x 10^{10} N/m² (Hermes, 2011), is inserted in the software.

It is worth pointing out that due to limitations, the MLM software can only take a maximum input of 10 layers, and 11 are present in this variant. Consequently, 9 layers will be inserted into the program in order to provide an enclosed model with 2 layers of HPFRCC on the outer layers. The result obtained from the 9 layers is taken as the airborne sound insulation since the true outcome must be near the obtained result due to the thin layers of HPFRCC and air that are missing. Table 9.9 below shows the layer arrangement and the results of the calculation.

Airborne Sound Insulation of Design Option 1: Variation 1								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
2	Air	liq	20	1.21	1.42E+05	0.00	0.00	0.00
3	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
4	Air	liq	20	1.21	1.42E+05	0.00	0.00	0.00
5	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
6	Air	liq	20	1.21	1.42E+05	0.00	0.00	0.00
7	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
8	Air	liq	20	1.21	1.42E+05	0.00	0.00	0.00
9	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
f [Hz]	**63**	125	250	500	1,000	2,000	4,000	8,000
R_{60} [dB]	**15.2**	19.1	27.8	32.3	61.5	116.5	151.8	52.5

Table 9.9 Airborne sound insulation of design option 1 (variant 1).

From the results it can observed that the sound insulation values in the lower frequency band are small in comparison to the prefab sandwich panel, especially the one at 63 Hz with a value of 15.2 dB.

1.5) Variant 1: Outcome

Even though the variant 1 showed promising results in reducing material and decreasing both the embodied energy and CO_2 emissions in comparison to the prefab concrete panel, the thermal and acoustic performance do not meet the evaluation criteria. Therefore, the next variant explores the possibilities of improving the weakest points found in this evaluation.

2) Variant 2: Concept

With the idea of improving the thermal and acoustic performance of variant 1, this option explores the possibilities of improving the weakest points found in the previous evaluation. The alternative of adding insulation in the empty spaces inside the panel is examined. As previously mentioned in section 9.3.6, the polyurethane (PU) insulation is the most efficient from the all the compared for the prefab concrete sandwich panels, thus it is explored in this variant. The PU insulation can be applied in the form of spray, therefore there is a possibility for this material to be extruded by a 3d printer. Since the polyurethane provides better thermal and acoustic insulation than air on its own, the empty spaces in the previous variant are made larger and they are filled with PU while keeping the total thickness of the panel close to the previous one, as seen in the axonometric and top views below (figures 9.19 and 9.20).

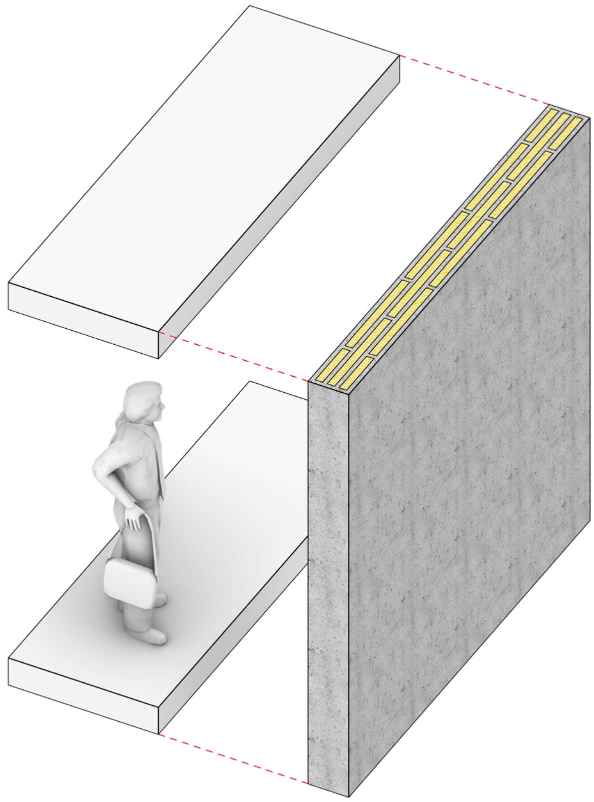


Figure 9.19 Axonometric of design option 1 (variant 2).

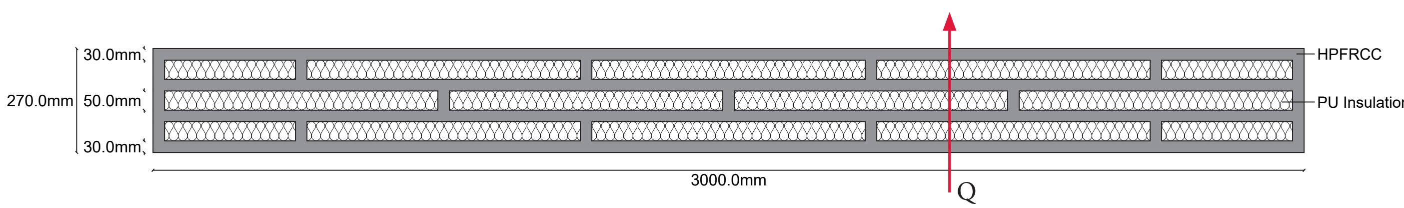


Figure 9.20 Top view of design option 1 (variant 2).

2.1) Variant 2: Embodied Energy and CO_2 Emissions

The same values used for the environmental impact calculations of the HPRFCC in the previous variant are used in this design, as well from the ones coming from the PU insulation used in the prefab sandwich panels, and presented below in tables 9.10 and 9.11.

Environmental Impact of Construction Materials													
Material	**Quantity (per m2) [-]**	**d [mm]**	**Volume [m3/unit]**	**Density [kg/m3]**	**Mass [kg/unit]**	**Mass [kg/m2]**	**Energy [MJ/kg]**	**CO2 [kg/kg]**	**Energy [MJ/m3]**	**CO2 [kg/m3]**	**Energy (Wall) [MJ/m2]**	**CO2 (Wall) [kg/m2]**	**Reference**
HPFRCCs	-	-	-	1,850	-	-	1.48	0.17	2,738.00	312.65	-	-	CES (Eco-Audit)
PU	-	-	-	31	-	-	69.9	2.9	2,166.90	89.9	-	-	PU Europe, 2014

Table 9.10 Environmental impact of design option 1 (variant 2) per cubic meter.

Environmental Impact of Construction Materials													
Material	**Quantity (per m2) [-]**	**d [mm]**	**Volume [m3/unit]**	**Density [kg/m3]**	**Mass [kg/unit]**	**Mass [kg/m2]**	**Energy [MJ/kg]**	**CO2 [kg/kg]**	**Energy [MJ/m3]**	**CO2 [kg/m3]**	**Energy (Wall) [MJ/m2]**	**CO2 (Wall) [kg/m2]**	**Reference**
HPFRCC Layer	-	-	1.29E-01	1,850	237.73	237.73	1.48	0.17	2,738.00	312.65	351.83	40.18	CES (Eco-Audit)
PU Insulation	-	-	1.42E-01	31	4.40	4.40	69.9	2.9	2,166.90	89.9	307.70	12.766	PU Europe, 2014
Total Environmental Impact	-	-	-	-	-	-	-	-	-	-	**659.53**	**52.94**	

Table 9.11 Environmental impact of design option 1 (variant 2) per square meter.

The total embodied energy of this design is 659.53 MJ/m², which is higher than in variant 1, and the CO_2 emissions 52.94 $kgCO_2/m^2$, giving a slightly lower result than the previous variant. However, both these properties are lower to the ones from the prefab sandwich panels by 26% and 40% respectively.

2.2) Variant 2: U-value

The same material properties used in the previous examples are used as input in THERM 7.7 in order to calculate the U-value of this design variant, and can be observed below in image 9.21.

The U-value calculated for this variant is of 0.26 W/m²K, which is the same as the number resulting from the prefab sandwich panel. In this manner it can be deducted that expanding the holes inside the panel and filling them with insulation is more effective than providing many smaller cavities inside filled with air inside the panel, as was the case with the variant 1.

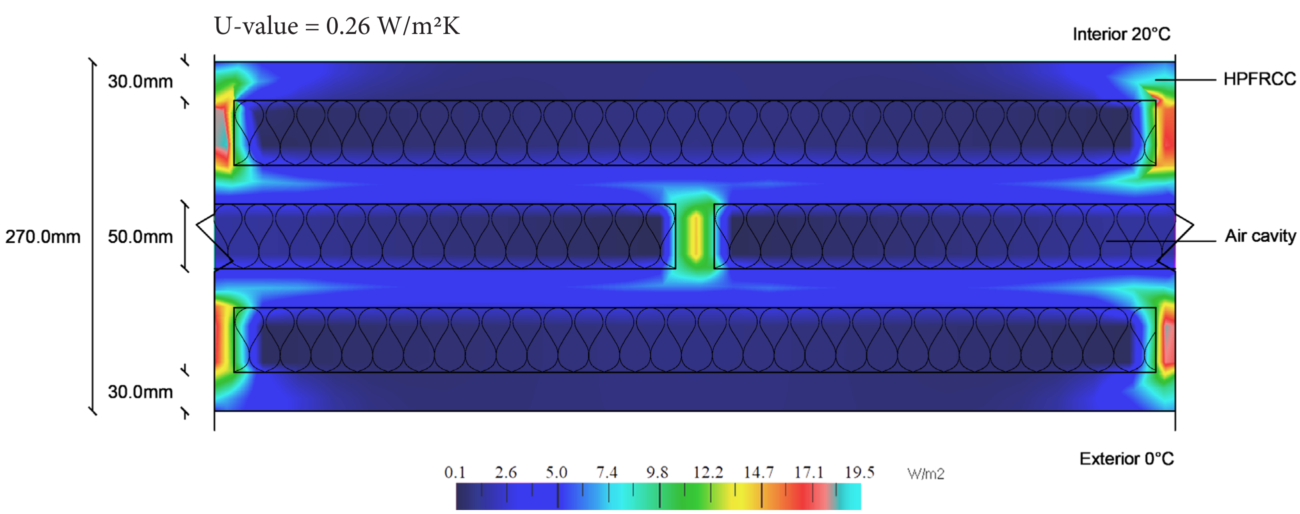


Figure 9.21 U-value of design option 1 (variant 2).

2.3) Variant 2: R60

The acoustic calculation of this design variant is done in a similar manner as in variant 1, but without the layer limitation. Another difference are the layers taken into account for the calculation. Since polyurethane has a higher airborne sound insulation than HPFRCC or concrete when compare in the same dimensions, as observed in table 9.12, the weakest points in the panel are in the direction where there is more cementitious material. Therefore, the layers taken into account for the acoustic calculation are highlighted red, in figure 9.22.

Airborne Sound Insulation: HPFRCC vs PU								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
***f* [Hz]**	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**22.2**	27.8	32.6	27.8	32.7	40.7	46.7	53.3
2	PU Insulation	liq	30	31	5.00E+04	0.00	0.00	20000.00
***f* [Hz]**	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**24.1**	26.9	32.6	40.6	49.2	60.5	75.1	93.6

Table 9.12 Airborne sound insulation of HPFRCC vs PU.

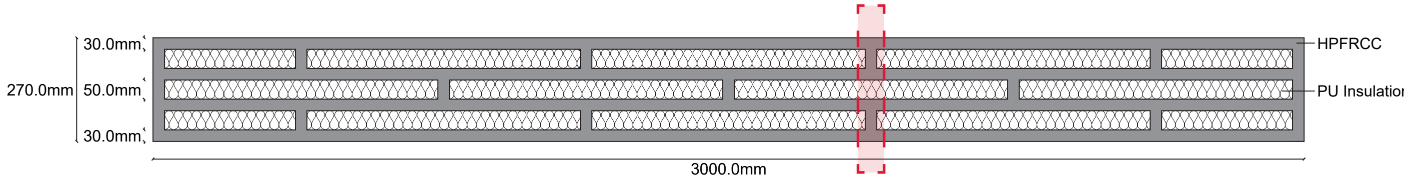


Figure 9.22 Section considered for airborne sound insulation.

Airborne Sound Insulation of Design Option 1: Variation 2								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
2	PU Insulation	liq	30	31	5.00E+04	0.00	0.00	20000.00
3	HPFRCC	sol	30	1,850.00	2.45E+10	0.00	0.05	0.27
ƒ [Hz]	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**61.2**	79	92.5	121.7	146.4	175.5	196.1	197.0

Table 9.13 Airborne sound insulation of design option 1 (variant 2).

The results of the calculation show that the airborne sound insulation of variant 2 is 61.2 dB, which is higher than the value obtained in variant 1, but slightly lower than the sound insulation of the prefab sandwich panels by 16.1 dB.

2.4) Variant 2: Outcome

Although the thickness of the panel in this design variant is the same as in the prefab sandwich panel, this option has a reduction of 49% of the mass, due to the lower density and volume of the HPFRCC in comparison to the Portland cement concrete that is used in the sandwich panels. Consequently, the mass reduction has environmental benefits when compared to the prefab sandwich panel, since a considerable contraction in the embodied energy and CO_2 emissions is obtained.

In terms of thermal performance, this design variant does a good work in reaching to the same U-value as the prefab sandwich panel. The only parameter that scored lower than the prefab sandwich panels in this option is the airborne sound insulation, but due to the fact that this value is still high and it can get even higher when used in a cavity wall in combination with brick on the outside, this design option is a good alternative to the traditional prefab concrete sandwich panel.

3) Design Option 2

3.1) Concept

The design exploration in this option is oriented towards reducing the overall thickness of the concrete that is found in the typical prefab sandwich panels, and provide more material only where is needed to avoid unwanted deflection and stresses. Since the design of this panel is very similar to the traditional ones used in construction for walls and slabs, it can be manufactured using similar production methods, like casting or extrusion. For this reason the material used in this option is lightweight structural concrete, as it was concluded in chapter 7 from the types of concrete analyzed, that it was the best type of concrete to decrease the environmental impact and keep a good thermal and acoustic performance at the same time. The axonometric and top views of the design can be observed below in figures 9.23 and 9.24.

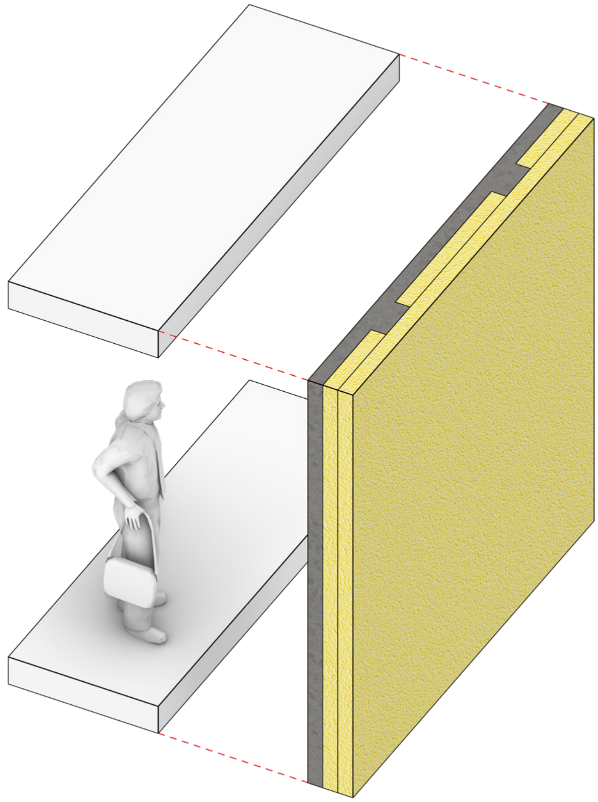


Figure 9.23 Axonometric of design option 2.

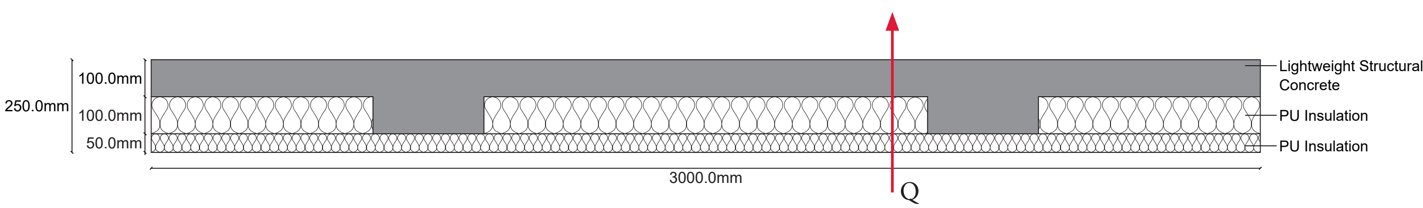


Figure 9.24 Top view of design option 2.

3.2) Embodied Energy and CO_2 Emissions

Similarly to the variant 2 of the first design option, this panel is mainly composed of 2 materials, lightweight structural concrete and PU insulation. Due to the lack of data in regards to the environmental impact caused by the different types of concrete, the embodied energy and CO_2 emissions per kilogram (MJ/kg and kgCO2/kg) are assumed to be the same. Table 9.14 presented below shows the environmental impact properties of the materials in this panel.

Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
Ligthweight Structural Concrete	-	-	-	1,700	-	-	1.48	0.17	2,516.00	287.3	-	-	CES (Eco-Audit)
PU	-	-	-	31	-	-	69.9	2.9	2,166.90	89.9	-	-	PU Europe, 2014

Table 9.14 Environmental impact of design option 2 per cubic meter.

Table 9.14 above already shows significantly lower numbers on the environmental impact per cubic meter than the prefab sandwich panels, due to the use of concrete with lower density. The total environmental impact of this design per square meter is show underneath in table 9.15.

Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
Ligthweight Structural Concrete Panel	-	-	1.20E-01	1,700	204.00	204.00	1.48	0.17	2,516.00	287.3	301.92	34.48	CES (Eco-Audit)
PU Insulation	-	-	0.13	31	4.03	4.03	69.9	2.9	2,166.90	89.9	281.697	11.687	PU Europe, 2014
Total Environmental Impact	-	-	-	-	-	-	-	-	-	-	**583.62**	**46.16**	

Table 9.15 Environmental impact of design option 2 per square meter.

This design presents an environmental impact of 538.62 MJ/m2 and 46.16 kgCO2/m2, which shows a reduction of 39.6% and 47.6% respectively, in comparison to the prefab sandwich panel.

3.3) U-value

The average thermal conductivity of lightweight structural concrete is 0.8 W/mK, which is used as input to calculate the total thermal transmittance of this design, as seen below in figure 9.25.

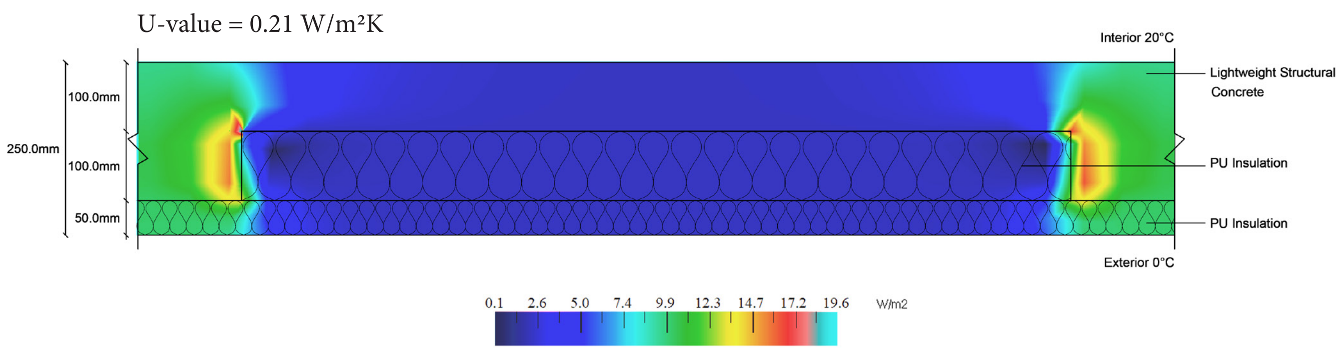


Figure 9.25 U-value of design option 2.

The result of the calculation shows a U-value of 0.21 W/m2K, which is in fact better than the one exhibited by the prefab sandwich panels. It is evident that by decreasing the amount of concrete, and increasing the amount of polyurethane insulation, a better outcome is obtained in terms of thermal performance.

3.4) R60

As it can be observed in table 9.16, the lightweight structural concrete has lower sound insulation when compared to Polyurethane, therefore the layers in the section that will be taken for analysis in the MLM software are in the direction where there is more concrete present, as shown in figure 9.26. The density and the Young's modulus of lightweight structural concrete, as retrieved from CES (2019) are 1,700 kg/m³ and 16 MPa or 1.6 x 10^{10} N/m² respectively.

The total airborne sound insulation for this panel at 63 Hz is a value of 51.7 dB as it can be observed in table 9.17. Although lower than the sound insulation of the prefab sandwich panel, this level of insulation is reasonably high.

Airborne Sound Insulation: Lightweight Structural Concrete vs PU								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	Ligthweight Concrete	sol	30	1,700.00	1.60E+10	0.00	0.05	0.27
ƒ [Hz]	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**21.5**	27.2	32.3	30.9	29.5	38.6	45.2	50.3
2	PU Insulation	liq	30	31	5.00E+04	0.00	0.00	20000.00
ƒ [Hz]	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**24.1**	26.9	32.6	40.6	49.2	60.5	75.1	93.6

Table 9.16 Airborne sound insulation of Lightweight concrete vs PU insulation.

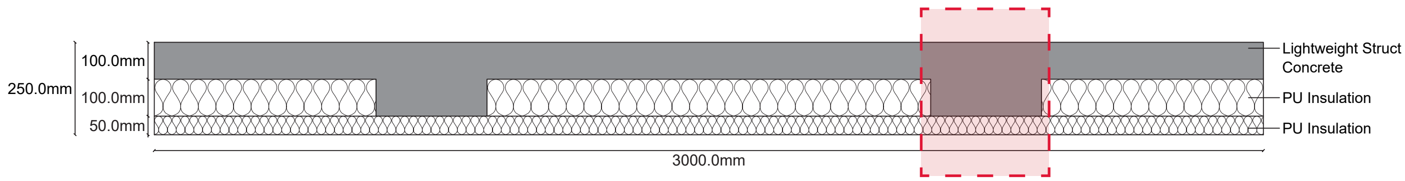


Figure 9.26 Section considered for airborne sound insulation calculation.

Airborne Sound Insulation of Design Option 2								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	Ligthweight Concrete	sol	200	1,700.00	1.60E+10	0.00	0.05	0.27
2	PU Insulation	liq	50	31	5.00E+04	0.00	0.00	20000.00
ƒ [Hz]	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**51.7**	62.0	81.6	105.3	128.0	153.4	187.2	196.9

Table 9.17 Airborne sound insulation of design option 2.

3.5) Outcome

This design option shows promising results as an alternative to the traditional prefab sandwich panels. When comparing these two, the design option 2 not only has a smaller thickness, but it also presents 56.5% of reduction in mass. As consequence, the environmental impact is significantly reduced.

A downside to this design, when compared to the sandwich panel is the sound insulation, which as a consequence of reducing the mass it exhibits a decrease in decibels. However, the sound insulation value can be easily improved by increasing the amount of polyurethane insulation, which will not alter the mass in an important quantity.

4) Design Option 3

4.1) Concept

Since the two previous design options showed promising results when trying to reduce the environmental impact and keeping as much as possible the acoustic and thermal performance established by the evaluation criteria, design option 3 evolves around the concept of merging both ideas. In general the aim is to incorporate the insulation inside the panel as in option 1, but by simplifying the shape and increasing slightly the thickness of the concrete layer and the holes as in option 2. The intention is for this design option to be manufactured by using the conventional production methods of casting or extrusion. The design is illustrated in figures 9.27 and 9.28.

9.19).

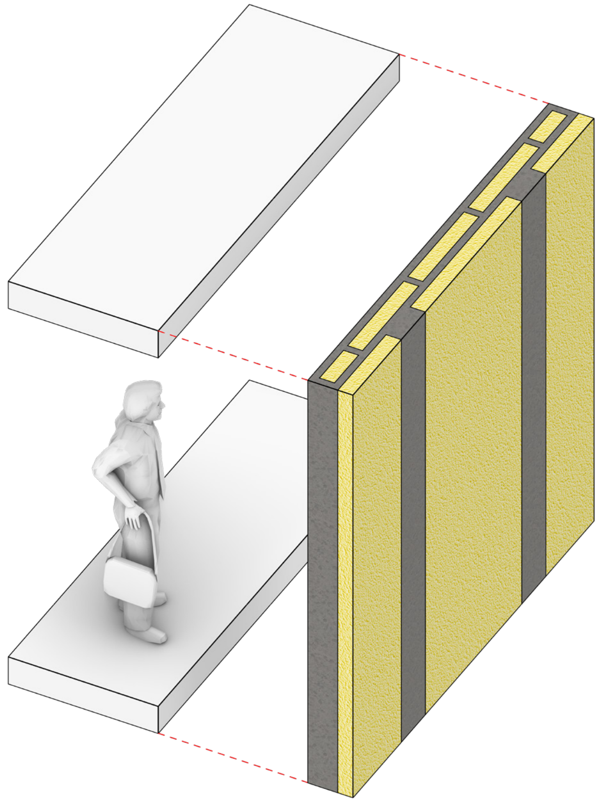


Figure 9.27 Axonometric of design option 3.

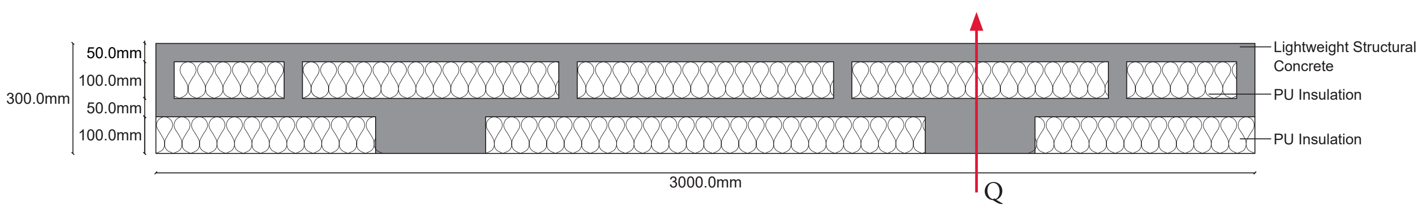


Figure 9.28 Top view of design option 3.

4.2) Embodied Energy and CO_2 Emissions

The materials used in this option are lightweight structural concrete and PU insulation. The embodied energy and CO_2 emissions per cubic meter of the materials in this option are the same as in option 2, as can be observed below in table 9.18.

Environmental Impact of Construction Materials													
Material	**Quantity (per m2) [-]**	**d [mm]**	**Volume [m3/unit]**	**Density [kg/m3]**	**Mass [kg/unit]**	**Mass [kg/m2]**	**Energy [MJ/kg]**	**CO2 [kg/kg]**	**Energy [MJ/m3]**	**CO2 [kg/m3]**	**Energy (Wall) [MJ/m2]**	**CO2 (Wall) [kg/m2]**	**Reference**
Ligthweight Structural Concrete	-	-	-	1,700	-	-	1.48	0.17	2,516.00	287.3	-	-	CES (Eco-Audit)
PU	-	-	-	31	-	-	69.9	2.9	2,166.90	89.9	-	-	PU Europe, 2014

Table 9.18 Environmental impact of design option 3 per cubic meter.

The total embodied energy and CO_2 Emissions of the panel per square meter are given in the table below (Table 9.19).

Environmental Impact of Construction Materials													
Material	Quantity (per m2) [-]	d [mm]	Volume [m3/unit]	Density [kg/m3]	Mass [kg/unit]	Mass [kg/m2]	Energy [MJ/kg]	CO2 [kg/kg]	Energy [MJ/m3]	CO2 [kg/m3]	Energy (Wall) [MJ/m2]	CO2 (Wall) [kg/m2]	Reference
Ligthweight Structural Concrete Panel	-	-	1.30E-01	1,700	221.00	221.00	1.48	0.17	2,516.00	287.3	327.08	37.35	CES (Eco-Audit)
PU Insulation	-	-	1.70E-01	31	5.27	5.27	69.9	2.9	2,166.90	89.9	368.373	15.283	PU Europe, 2014
Total Environmental Impact	-	-	-	-	-	-	-	-	-	-	**695.45**	**52.63**	

Table 9.19 Environmental impact of design option 3 per square meter.

The total embodied energy is 695.45 MJ/m2 and the CO2 emissions are 52.63 kgCO2/m2. In terms of environmental impact this options exhibits a reduction of 22% and 40.3% respectively, in comparison to the prefab concrete sandwich panels.

4.3) U-value

The same materials as in the previous option are used in this design, therefore the same thermal conductivities of lightweight concrete an polyurethane are used for the calculation. The thermal transmittance value obtained from design option 3 is shown below, in figure 9.29.

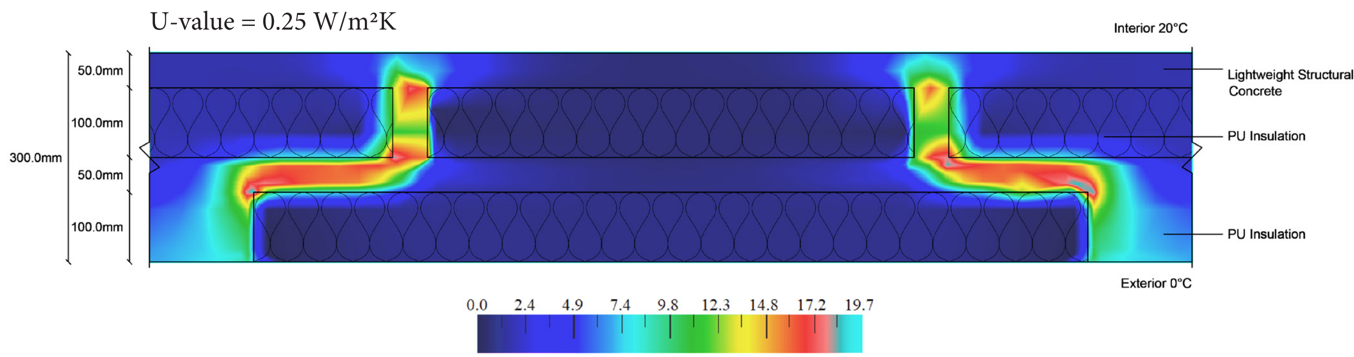


Figure 9.29 U-value of design option 3.

The obtained U-value of 0.25 W/m2K is not as good as the one obtained in option 2, but it is slightly better than the one acquired from the prefab sandwich panel.

4.4) R60

In the same manner as in option 2, the airborne sound insulation of this design option is calculated through the path in which there is more concrete, as it can be observed in figure 9.30 (below):

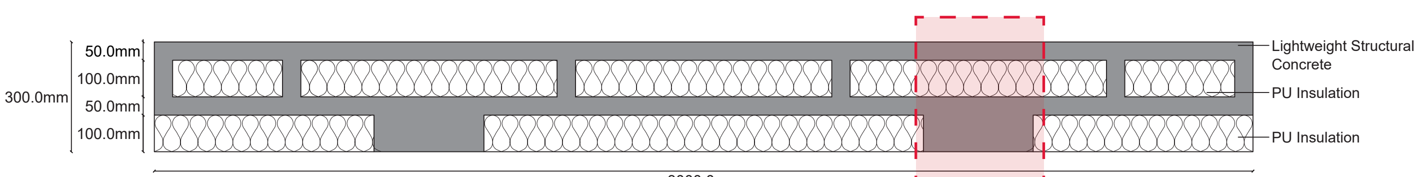


Figure 9.30 Considered section for airborne sound insulation calculation.

The airborne sound insulation in this design can be seen in the table below (table 9.20).

Airborne Sound Insulation of Design Option 3								
	Layers	Type	d [mm]	ρ [kg/m3]	E [N/m2]	*Im (ρ)*	*Im (gam_P)*	Flow Resistivity
1	Ligthweight Concrete	sol	50	1,700.00	1.60E+10	0.00	0.05	0.27
2	PU Insulation	liq	100	31	5.00E+04	0.00	0.00	20000.00
3	Ligthweight Concrete	sol	150	1,700.00	1.60E+10	0.00	0.05	0.27
***f* [Hz]**	**63**	125	250	500	1,000	2,000	4,000	8,000
R60 [dB]	**74.7**	105.7	140.1	189.3	197.0	197.0	197.0	197.0

Table 9.20 Airborne sound insulation of design option 3.

The resulting sound insulation at 63 Hz is 74.7 dB, which is higher than the one obtained from design option 2, and nearly the same as the one from the prefab sandwich panels. This is mainly due to the increment of concrete in this option.

4.5) Outcome

Although the mass reduction achieved in this design option (50.4%) is less than the one achieved in option 2 when compared to the prefab sandwich panel, from all the proposed designs, this variant is the one that shows the parameters closer to the ones established by the evaluation criteria. Thus, it is also a good prospect as an alternative to the prefab sandwich panels.

9.5) Comparison of the Design Options

In this section the previously proposed design options will be compared in order to give insight into their performance and their potential in regards to environmental impact reduction.

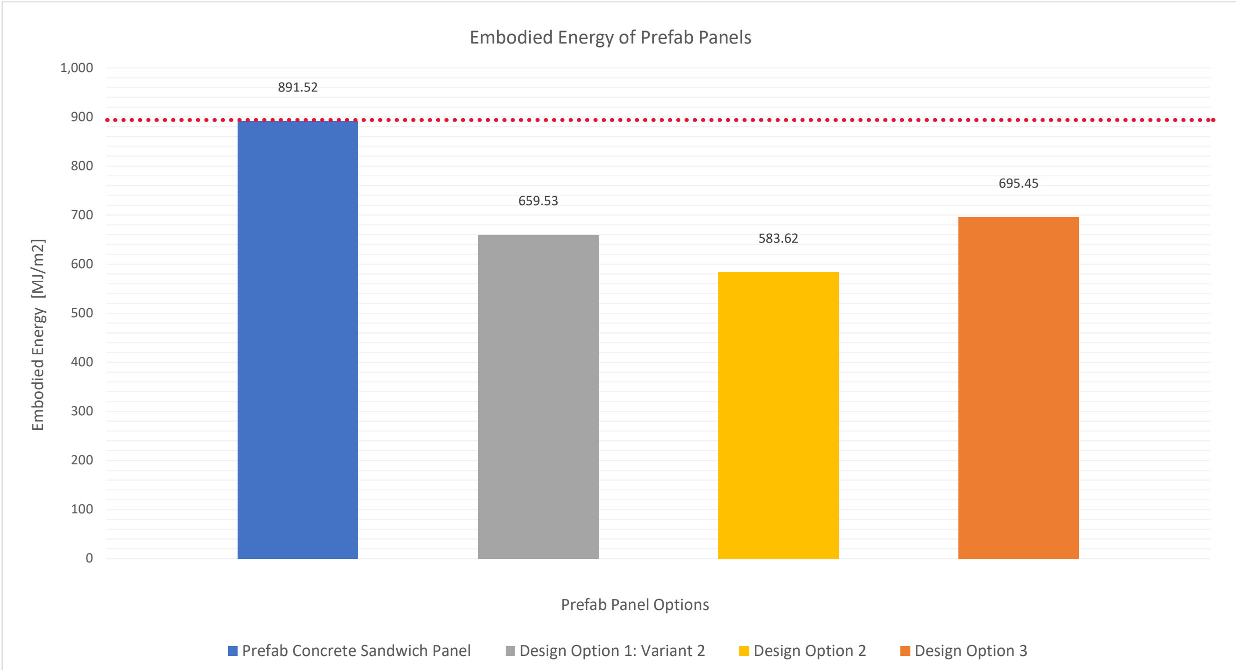
1) Embodied Energy Graph

In this section the results in terms of embodied energy of the prefab sandwich panel and all the proposed options that fulfilled the evaluation criteria are presented in the graph 9.5 below.

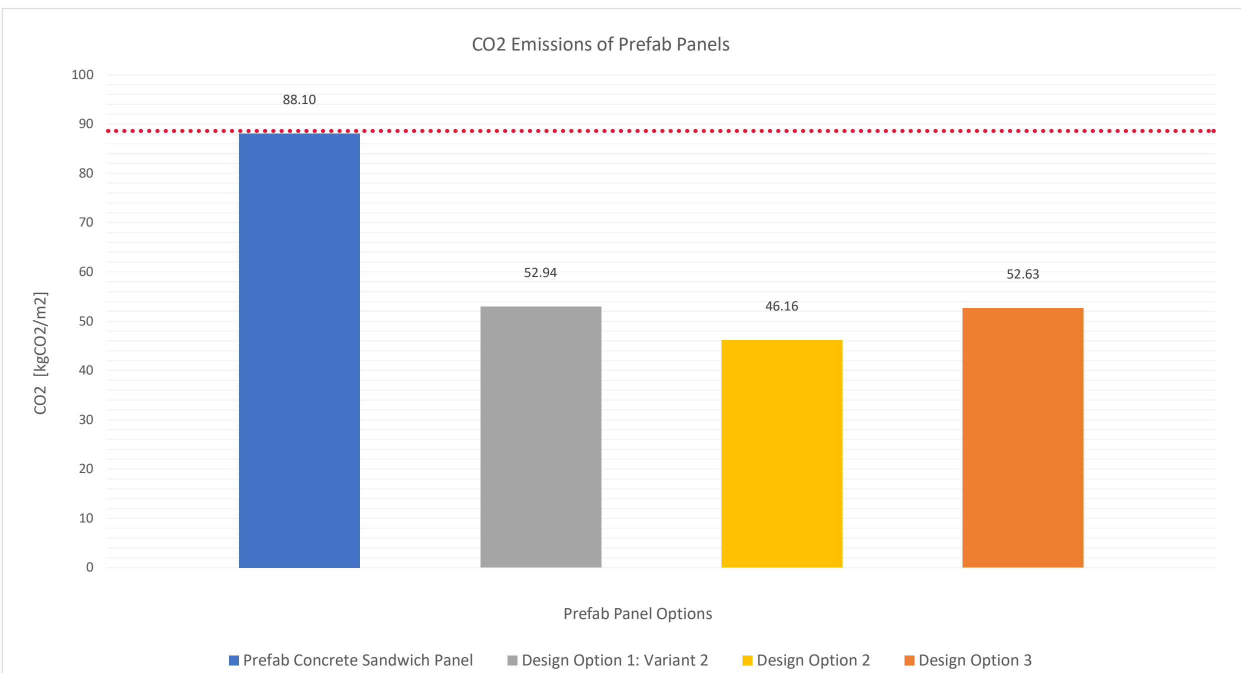
All the options below the red dotted line have less embodied energy than the prefab concrete sandwich panels, which is the case for all the proposed design options. The most environmentally friendly option in regards to this measurement is the design option 2.

2) CO_2 Emissions Graph

The prefab concrete sandwich panel and all the other design alternatives are compared below (graph 9.6) in terms of the CO_2 emissions. All the lined design options are underneath the red dotted line release less carbon dioxide into the atmosphere than the prefab sandwich panels.



Graph 9.5 Embodied energy of the design options.

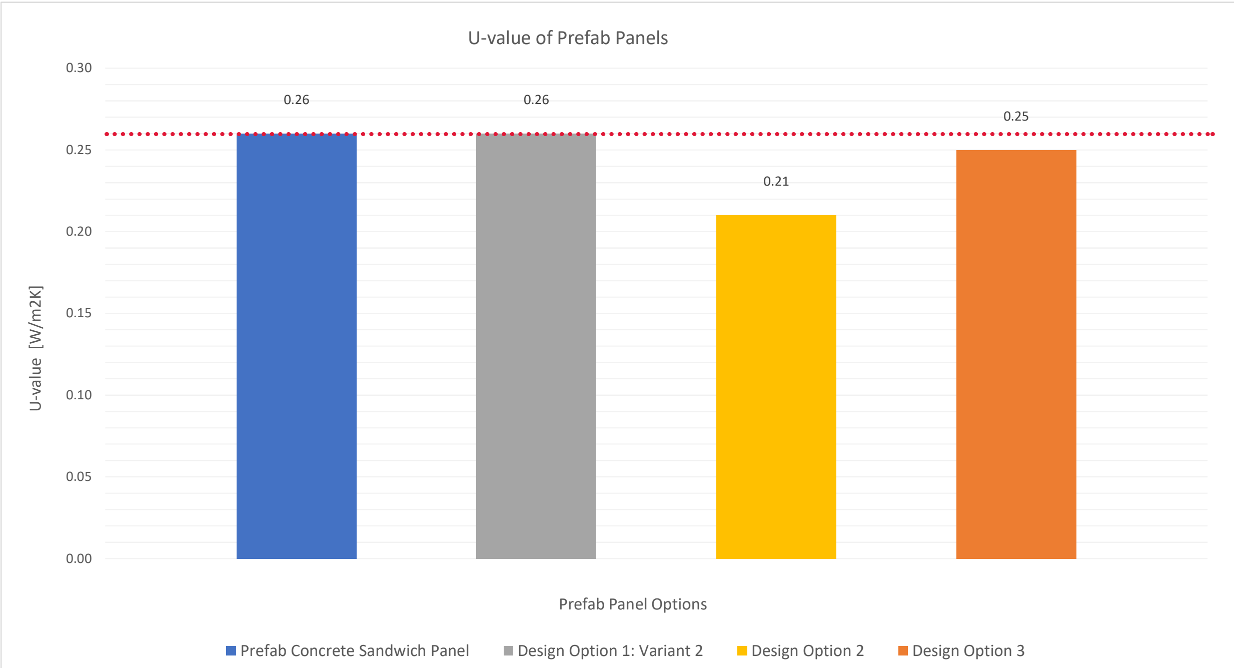


Graph 9.6 Carbon footprint of the design options.

As it can be observed, all the options are better at reducing the carbon dioxide emissions than the prefab sandwich panels. The most promising option in this category is the design option 2.

3) U-value Chart

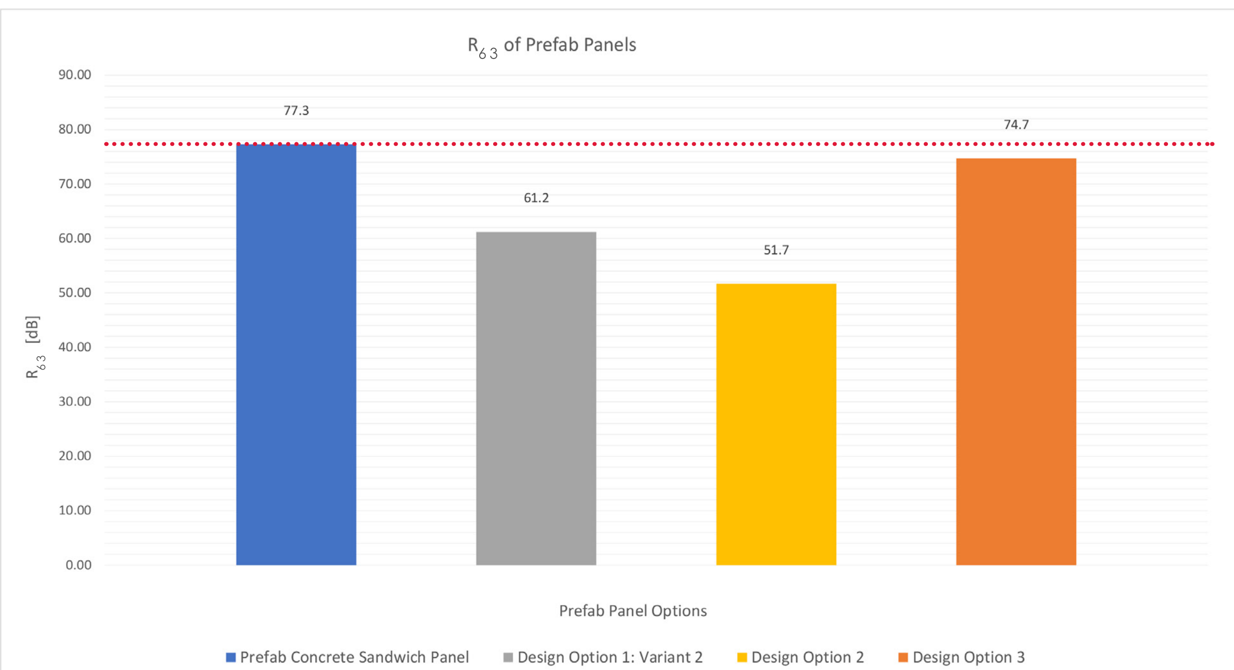
The comparison among the different U-values of the prefab panel options are compared in graph 9.7 (below). The options below the red dotted lines have lower thermal transmittance values, and as consequence provide lower thermal insulation. The best result is the design option 2.



Graph 9.7 U-value of the design options.

4) R63

The airborne sound insulation of the design options under comparison can be seen below in graph 9.8. All of the design options had lower sound insulation than the prefab sandwich panels, but the closest one is the design option 3.



Graph 9.8 Airborne sound insulation of the design options.

10) Comparing the Final Design Options

10.1) A final Evaluation

With all the obtained data in chapter 7, the prefab concrete panel design optimizations can be reinserted into a cavity wall system in order to provide an overall final evaluation. The objective is to compare the newly proposed facade systems with all the other systems evaluated previously in the different graphs of chapter 6. This will give insight into how this new systems behave in comparison to the other facade systems, regarding the terms under evaluation.

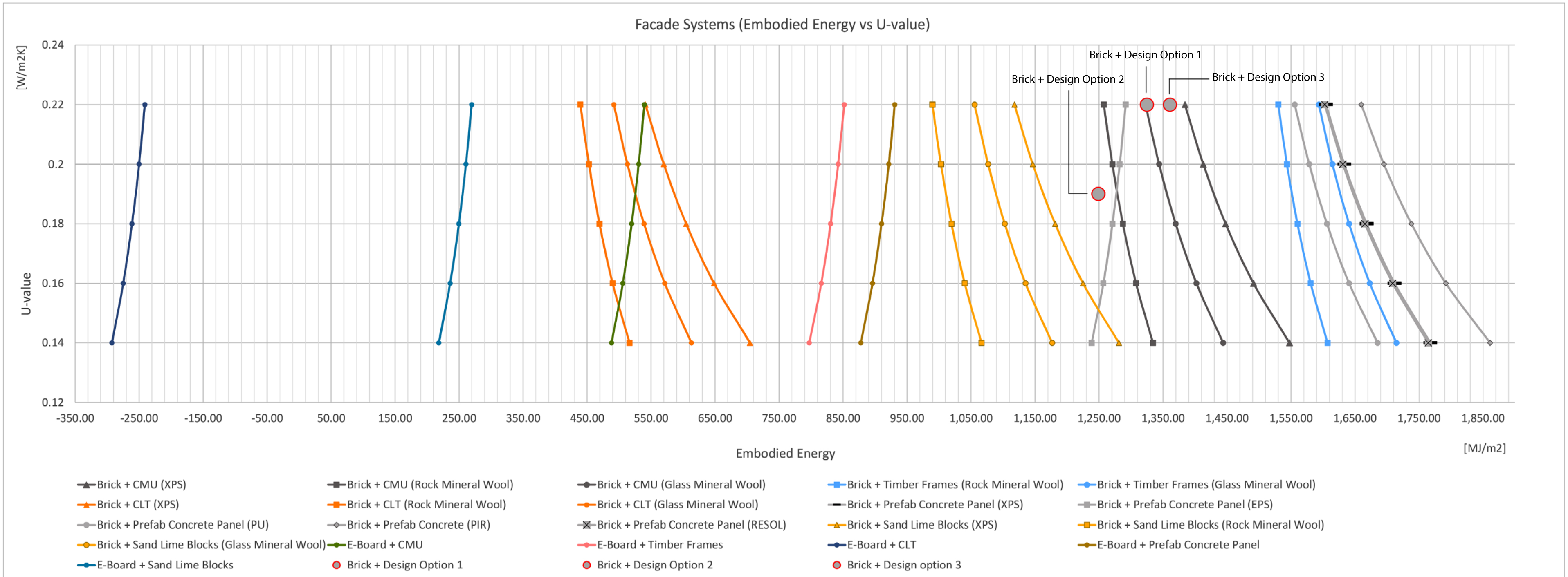
It is worth pointing out that this shows to what extent the assessment or evaluation framework can be useful as a design tool, since many evaluations can be carried out thought many stages of the design phase of a product. These evaluations can be performed indefinitely, depending on how many iterations the design of a product has, which gives guidance in every step, as it provides numerical data.

10.2) Thermal insulation vs Environmental Impact

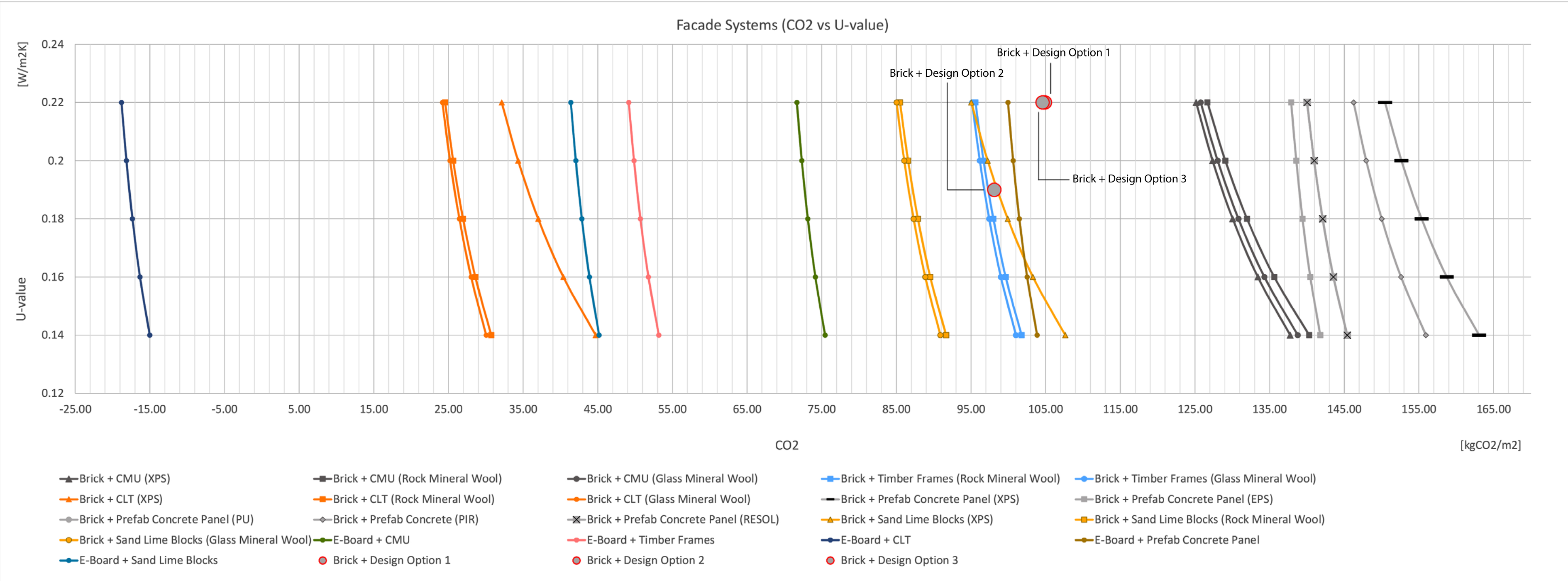
Graphs 10.1 and 10.2 show that there is a significant reduction in embodied energy and CO_2 emissions in the cavity wall systems containing the three proposed design options. This can be easily seen in both graphs since the proposed design options are positioned to the left side of the light gray curves. This means that their embodied energy and carbon footprint is lower than the cavity wall containing the standard prefab concrete sandwich panel.

From all the design options proposed, the cavity wall containing the design option number 2 suggests the most promising results, as it not only shows that its environmental impact is the lowest among the other design options, but it does so at a lower U-value, which is translated to higher efficiency. Especially when looking at graph 10.2, the reduction of CO_2 in this facade system is enough to position it near the carbon footprint of the cavity walls composed of timber frames.

The resistance value (Rc) of the 3 design options is obtained by calculating the reciprocal of the U-value obtained in the previous chapter (7). Moreover, the U-values of the cavity wall systems including the design options are obtained by adding up the sum of their thermal resistances (Rc), and by calculating their reciprocal.



Graph 10.1 Facade Systems (Embodied Energy vs U-value)

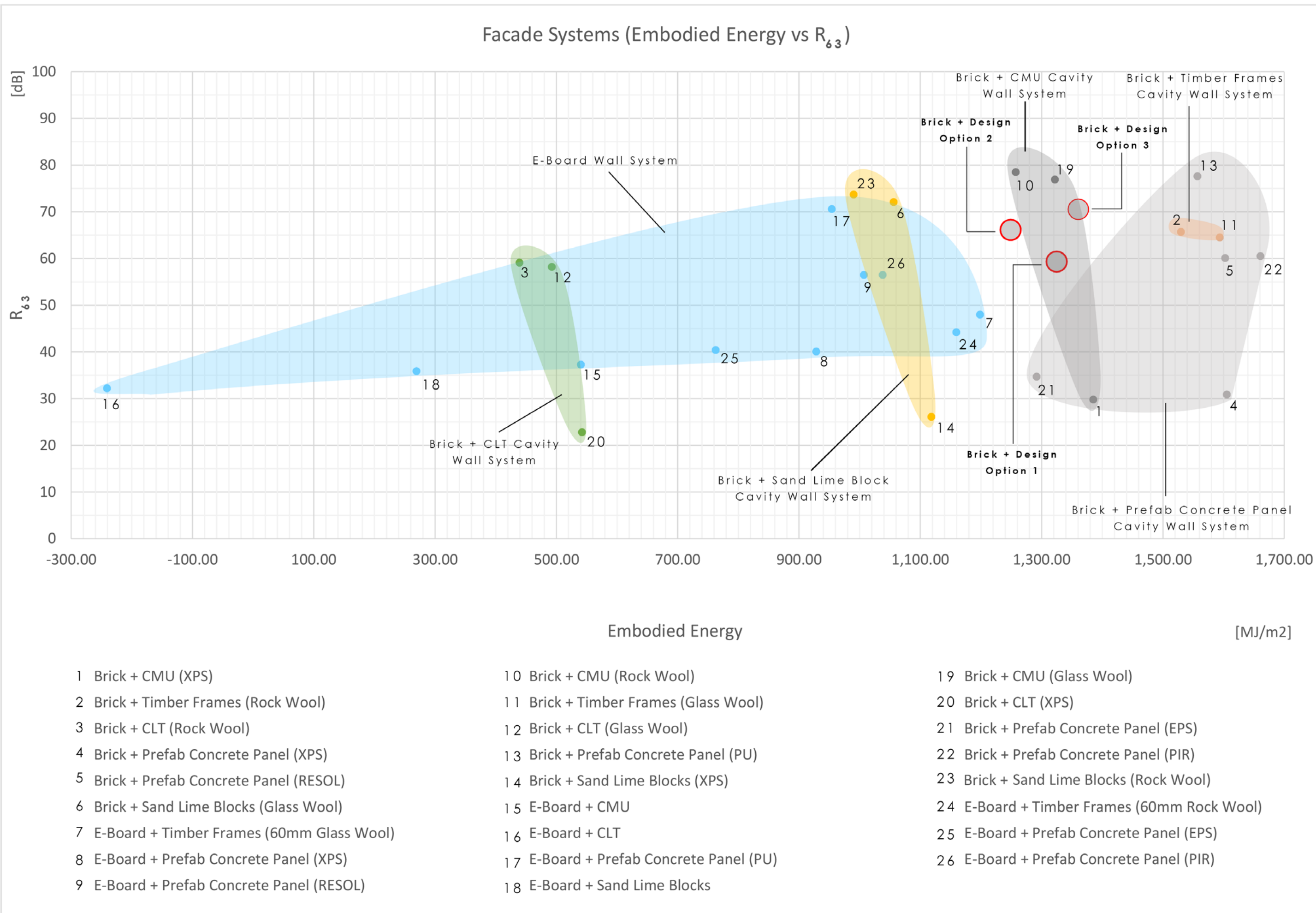


Graph 10.2 Facade Systems (Carbon footprint vs U-value)

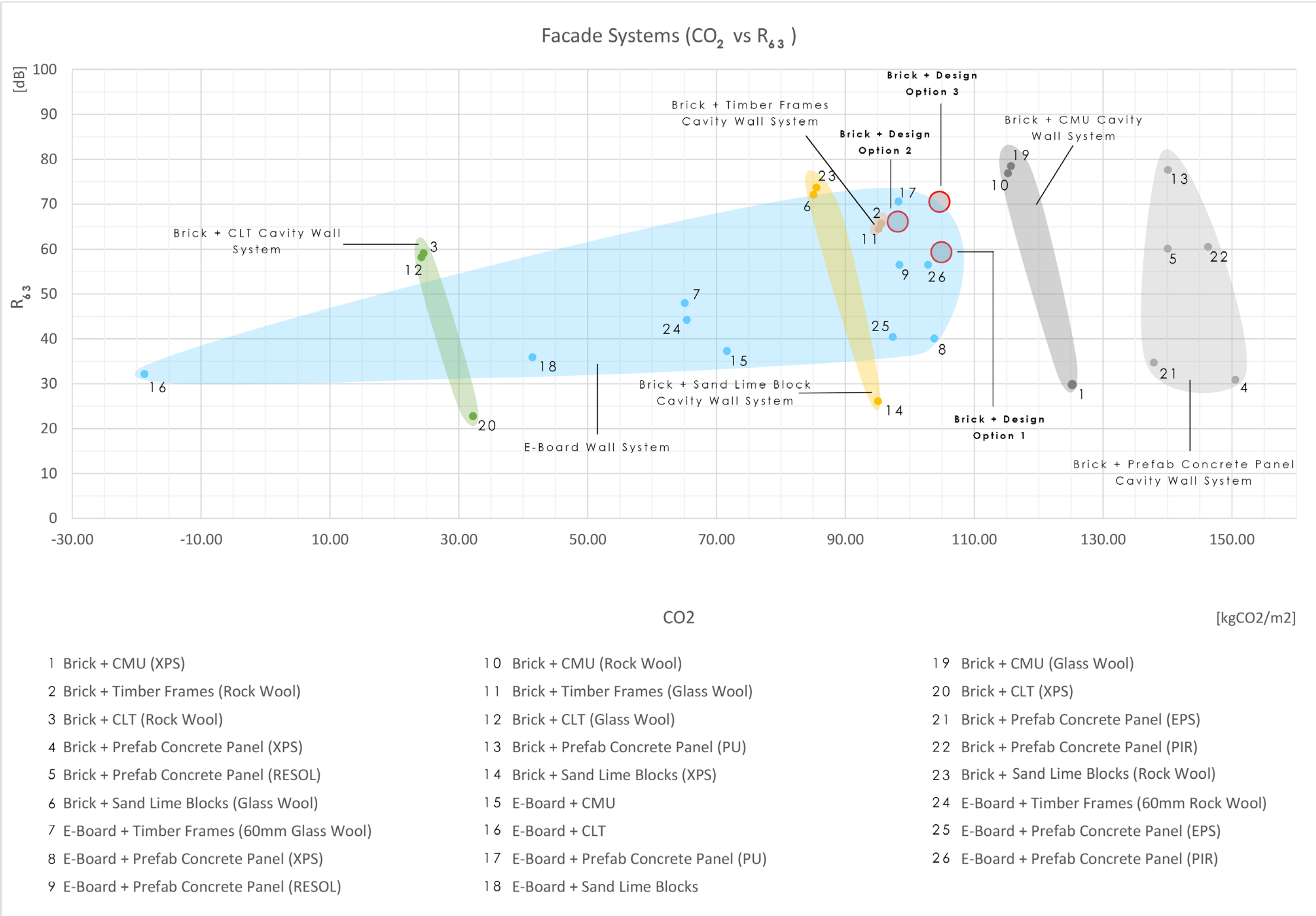
10.3) Acoustic Insulation vs Environmental Impact

The Meer Lagen Model program (MLM) applied for the acoustic calculations of the facade systems in chapter 6 is used in this chapter to calculate the airborne sound insulation of the 3 design options presented earlier inside a cavity wall system with brick on the outer layer.

Graphs 10.3 and 10.4 show that the 3 design options present an average airborne sound insulation in comparison to the rest of the facade systems, but both the embodied energy and the carbon footprint have been considerably reduced when compared to the brick and prefab concrete panel cavity wall system. This is specially true for the CO_2 emissions, which as can be observed in graph xx they are further apart from the brick and prefab concrete panel cluster.



Graph 10.3 Facade Systems (Embodied energy vs airborne sound insulation).



Graph 10.4 Facade systems (airborne sound insulation vs carbon footprint).

10.4) Durability

This last comparative analysis takes into account the technical service lifespan of the different components inside the design options in order to provide a comparative framework with all the previous facade systems presented in chapter 6.

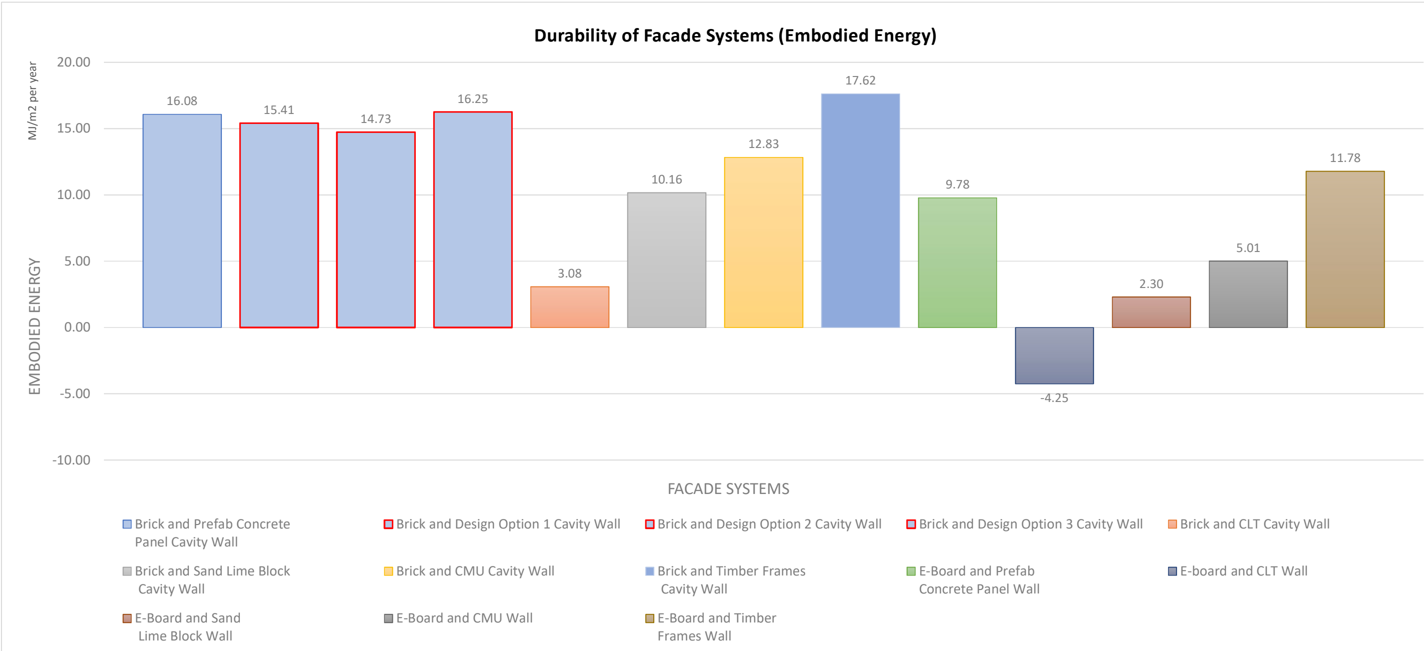
Table 10.1 shows the considered parameters in order to compare the durability of all the facade systems, including the 3 design options developed in the previous chapter (7). Similar to table 8.4, the embodied energy in Megajoule per square meter per year (MJ/m²), and the carbon footprint in kilogram of CO2 per square meter per year (kgCO2/m²) are obtained by calculating the volume of the components inside the different facade systems, including the 3 design options.

Graphs 10.5 and 10.6 compares the environmental impact related to the durability of the 3 design options and the different facade systems. From both the embodied energy and carbon footprint graphs, it is observed that the first 2 design options present a reduction in comparison with the brick and prefab concrete panel cavity wall system. The cavity wall containing design option 3 shows a slightly increase in the embodied energy, but a decrease in the carbon footprint. This increment shows up because this last design option contains a bigger volume of polyurethane (PU) insulation, which has lower durability than concrete.

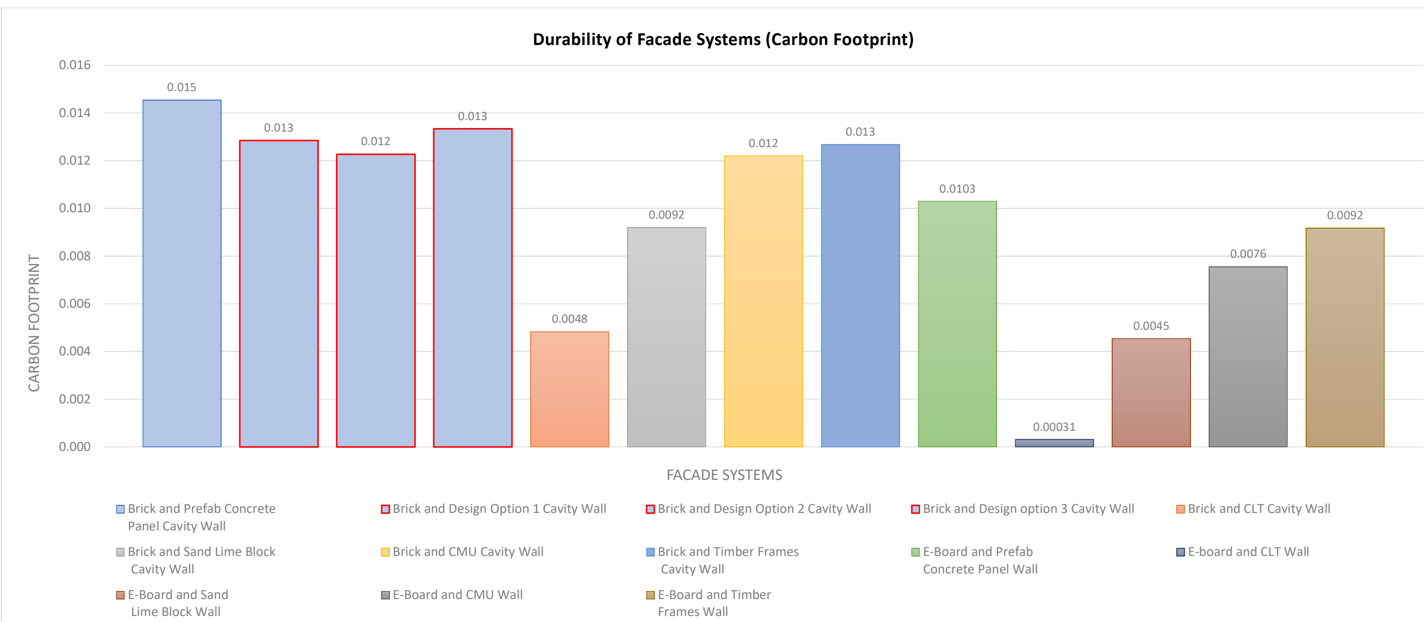
The cavity wall systems containing the design option 2 proved to be the most environmentally friendly from all the design options, and it managed to reach values close to that of the cavity wall systems containing the concrete masonry units (CMU), which are hollow in their core. Even though the cavity wall system containing option 2 presents a reduction of 4.2% in the embodied energy and 20% in the CO_2 emissions, the results are very positive since this panels are widely used.

Durability of Facade Systems							
Group	**Facade System**	**Material**	**Embodied Energy per year [MJ/m3]**	**Carbon Footprint per year [kgCO2/m3]**	**Volume [m3/m2]**	**Embodied Energy per year [MJ/m2]**	**Carbon Footprint per year [kgCO2/m2]**
Panel Systems	Brick and Prefab Concrete Panel Cavity Wall	Clay Bricks	73.20	0.057	8.93E-02	6.53	0.0051
		Concrete Panel Layers	37.00	0.042	1.90E-01	7.03	0.0080
		PU	28.89	0.016	8.70E-02	2.51	0.0014
						16.08	**0.015**
	Brick and CLT Cavity Wall	Clay Bricks	73.20	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.013	1.01E-01	1.21	0.0013
		CLT Board (x4)	-155.38	-0.053	3.00E-02	-4.66	-0.0016
						3.08	**0.0048**
Masonry Systems	Brick and Sand Lime Block Cavity Wall	Clay Bricks	73.20	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.013	1.28E-01	1.53	0.0016
		Sand lime blocks	22.27	0.026	9.42E-02	2.10	0.0024
						10.16	**0.0092**
	Brick and CMU Cavity Wall	Clay Bricks	73.20	0.057	8.93E-02	6.53	0.0051
		Rock Mineral Wool	11.97	0.013	1.26E-01	1.51	0.0016
		CMU	37.00	0.042	1.29E-01	4.79	0.0055
						12.83	**0.012**
Timber Frames System	Brick and Timber Frames Cavity Wall	Clay Bricks	73.20	0.057	8.93E-02	6.53	0.0051
		OSB (x2)	173.33	0.11	3.60E-02	6.24	0.0039
		Rock Mineral Wool	11.97	0.013	1.22E-01	1.46	0.0016
		Vapor Barrier	1,693.42	1.06	2.00E-03	3.39	0.0021
						17.62	**0.0127**
Board Systems	E-Board and Prefab Concrete Panel Wall	Clay Bricks (Strips)	73.20	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	3.40E-02	-0.29	0.00028
		Concrete Panel Layers	37.00	0.042	1.90E-01	7.03	0.0080
		PU	28.89	0.016	6.00E-02	1.73	0.0010
						9.78	**0.010**
	E-board and CLT Wall	Clay Bricks (Slips)	73.20	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	1.05E-01	-0.89	0.00088
		CLT Board (x4)	-155.38	-0.053	3.00E-02	-4.66	-0.0016
						-4.25	**0.00031**
	E-Board and Sand Lime Block Wall	Clay Bricks (Strips)	73.20	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.008	1.30E-01	-1.11	0.0011
		Sand lime blocks	22.27	0.026	9.42E-02	2.10	0.0024
						2.30	**0.0045**
	E-Board and CMU Wall	Clay Bricks (Strips)	73.20	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	1.27E-01	-1.08	0.0011
		CMU	37.00	0.042	1.29E-01	4.79	0.0055
						5.01	**0.0076**
	E-Board and Timber Frames Wall	Clay Bricks (Slips)	73.20	0.057	1.79E-02	1.31	0.0010
		E-Board	-8.51	0.0083	7.20E-02	-0.61	0.00060
		OSB (x2)	173.33	0.11	3.60E-02	6.24	0.0039
		Glass Mineral Wool	11.97	0.013	1.22E-01	1.46	0.0016
		Vapor Barrier	1,693.42	1.06	2.00E-03	3.39	0.0021
						11.78	**0.0092**
Design Options	**Option 1**	Clay Bricks	73.20	0.057	8.93E-02	6.53	0.0051
		Concrete Panel Layers	37.00	0.042	1.29E-01	4.77	0.0055
		PU	28.89	0.016	1.42E-01	4.10	0.0023
						15.41	**0.013**
	Option 2	Clay Bricks	73.20	0.057	8.93E-02	6.53	0.0051
		Concrete Panel Layers	37.00	0.042	1.20E-01	4.44	0.0051
		PU	28.89	0.016	1.30E-01	3.76	0.0021
						14.73	**0.012**
	Option 3	Clay Bricks	73.20	0.057	8.93E-02	6.53	0.0051
		Concrete Panel Layers	37.00	0.042	1.30E-01	4.81	0.0055
		PU	28.89	0.016	1.70E-01	4.91	0.0027
						16.25	**0.013**

Table 10.1 Durability of facade systems and design options.



Graph 10.5 Embodied energy of facade systems.



Graph 10.6 Carbon footprint of facade systems.

11) Conclusion

The first step that should be taken when evaluating or taking into account the environmental impact of a product, is to define which parameters are going to be measured, since the environmental impact is a broad term which can be dealt with in many different ways. The embodied energy and the carbon footprint of a product prove to be broadly understood parameters by designers and engineers, and certainly almost every person. Therefore, by defining the environmental impact in terms of the embodied energy and carbon footprint, an evaluating framework can be developed. This framework can be used to measure the environmental impact of any product, thus it is also suitable to measure any construction component, including facades.

The embodied energy of a material or product, as the name suggests it, is a measurement of the energy required to create them, thus, it is measured in joule (J) or megajoule (MJ), and the carbon footprint, which is the CO_2 that is released in their creation, is measured in kilogram ($kgCO_2$). Since facade components are normally measured in square meters (m^2), a good way of presenting the embodied energy and carbon footprint in a facade system is by measuring them per square meter of wall. Therefore, the embodied energy is measured in megajoule per square meter (MJ/m^2) and the carbon footprint in kilogram of CO_2 per square meter ($kgCO_2/m^2$).

Since the environmental impact of a construction part or component is seldom a design objective, it can be measured along other performance parameters or material properties, which provides a useful performance index that grants guidelines for design optimizations. Two important design goals when planing a facade system are the thermal and acoustic performance, which depend mostly on the quality of the thermal and acoustic insulation. These insulation presents environmental consequences in terms of embodied energy and carbon footprint, since better insulation normally represents bigger material usage, and this subsequently translates into higher embodied energy and CO_2 emissions. Therefore, by comparing the thermal and acoustic properties of a facade system with their attributed environmental impact, data can be provided, which can help to assess the original design, and give insight into new ideas that could be used to improve the design further.

In a similar way than with the environmental impact, the acoustic and thermal insulations can also be defined in their own measurements. On the one hand, the acoustic insulation can be measured in terms of the total airborne sound insulation at a specific frequency. For facade systems its is better to measure the sound insulation at frequencies lower than 250 Hz, since the insulation values tend to decrease significantly at the lower frequencies. Therefore, by designing for the worst case scenario, which is at 63 Hz, better decisions can be taken. This will give the total airborne sound insulation at 63 Hz (R_{63}) in decibels (dB). On the other hand, the thermal insulation of a facade system can be measure in terms of the U-value or thermal transmittance, which is obtained by adding the resistance values (Rc) of all of its components, and obtaining its reciprocal. This gives the U-value in watt per square meter kelvin (W/m^2K).

The environmental impact and the sound and thermal insulations can be related by comparing the amount of embodied energy and CO2 emissions in a facade system in order to reach a certain U-value or an airborne sound insulation level for any desired frequency. In this way, the environmental degradation can be easily understood as the consequence of the material and design decisions taken in the proposal of a facade system, in order to reach a certain thermal or acoustic performance level.

From the different conducted assessments it could be observed that the systems with the higher environmental impact in order to reach certain U-values or airborne sound insulation levels are the more massive systems. For this reason, optimizing these facades focusing on reducing the mass proved to be a good solution in order to reduce their environmental impact. The assessment framework proves to be useful as a design tool, since many evaluations can be carried out thought various design phases of a facade or any other product. The results from the evaluations can give engineers and designers the confidence to optimize or develop further any product, since it is a user-friendly tool that gives a valid output.

11.2) Further Research

There are several aspects in the assessment framework that can be added in order to provide a more complete analysis. First, a way of quantifying the environmental impact of the materials in a facade system regarding the life-stages of construction and use phases can be taken into account. This would give better results on the real embodied energies and CO_2 emissions attributed to a certain facade system, and it could provide opportunities for design or optimization on these phases. Second, the eco-audit tool can be used as the only source to obtain the environmental impact of all the components in a facade system, as long as the composition of these components is known. In this case all the different elements that make up a facade components could be summed in the eco-audit tool in order to obtain the environmental impact. Third, other parameters can be taken into account in this tool to compare with the environmental impact, like structural properties or even cost. This could provide the opportunity to propose or optimize a design considering other parameters. In this way, a more elaborated and complete designs could be provided. Lastly, the assessment framework can be scaled up in order to evaluate not only facade systems, but all the components in a building, which will provide engineers and designers the possibility to analyze a building from different perspectives.

12) Reflection

This research is part of the facade and product design topics, which deals with materials and ways of reducing the environmental impact. Due to the broadness of the topic, there are many ways in which facades or materials can be dealt with in order to reduce the environmental impact. Focusing on circularity is one way to explore and design a product aiming at life-extension strategies. This presents the possibility of increasing service-lifetimes, and as a consequence reduce its environmental impact. Standardization is another possibility of reducing waste and decreasing the ecological harm. Reducing the energy consumption in a building attributed to the performance of a facade is yet another possibility to deal with environmental problems. Therefore, all these possibilities introduce the problem of choosing a direction, since trying to deal with all the problems is likely to end in deficient solutions. For this reason, the research worked out a bit slow at the beginning. Defining the evaluation framework took longer than planed, due to all the possible directions, but it went faster once the framework was established. Additionally, once the assessment tool was defined, the next steps became easier, mainly because the evaluation method was already established and understood. The literature review and the guidance of my two mentors helped me to find this direction. It is important to mention that 1 piece of literature considered in this thesis not only inspired great part of the research, but also taught me many aspects from the world of materials and their relation to the environment, and this is the book Materials and the Environment by Michael F. Ashby. All things considered, I believe that the research approach taken in this thesis lead me to the results I aimed for.

The results obtained in these thesis are very applicable in practice, due to the fact that they provide a methodology for evaluating in a fast and straightforward way the environmental impact attributed to a facade system, which is related to a certain acoustic or thermal performance level. This framework gives results that are easily understood by any architect, designer or engineer, and can be used as a tool to take decision for design or optimization proposals. The framework can also be adapted in order to include other parameters like structural properties or cost. Additionally, it can also be scaled up to not only analyze a facade system, but a whole building.

I believe that this thesis is innovative, because it proposes a framework to assess or evaluate the environmental impact of a facade system with other important technical parameters like acoustic and thermal insulation, in a simplified way and in a way that is easily understandable to both designers and engineers. This method follows the performance index method of evaluating materials proposed by Ashby, but it is scaled up to evaluate entire facade systems. In a similar way it could be scale up further to analyze bigger systems, as mentioned earlier.

This type of assessment tools are very important in the built environment, since they can quantify many parameters that are a consequence of certain design decisions. When designing a building, the spacial quality and the functionality of the space are not be the only important aspects of the design, but it is important to understand that there are many other parameters that are relevant. By taking into consideration environmental aspects in the design of a building, future generations could have the same opportunities to breathe the same pure air as it exists today, and access to the same materials and products will be possible. Thermal and acoustic parameters can affect the comfort of an architectural space, and affect the way a person perceives given space. Focusing on providing good acoustic and thermal performance is also a great opportunity to reduce energetic costs and the release of CO_2 emissions to the environment. Similarly, structural parameters can determine the cost of a building and can affect the spacial layout of a given design, making it rigid, flexible, wide or narrow.

Many designers, including architects focus on the spacial, functional and aesthetic aspects of a space or an object. But a deeper understanding of the materials that make up the designs, and the properties they offer are mostly neglected, event though they present many opportunities in relation to the performance of a product or space. Even the cost can be influence in different way depending on the design and material choices. For this reasons, providing frameworks like the ones developed in this thesis could help the architects and designer to take better informed decisions, which will complement significantly any design.

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