# DEVELOPMENT AND CHARACTERIZATION OF EXTERIOR RADIATA-PINE CLADDING FOR MORE SUSTAINABLE AND ENERGY EFFICIENT FAÇADES IN THE BASQUE COUNTRY

**Ph.D. THESIS**
**presented to obtain the degree of**
**Doctor Philosophy in Industrial Engineering**

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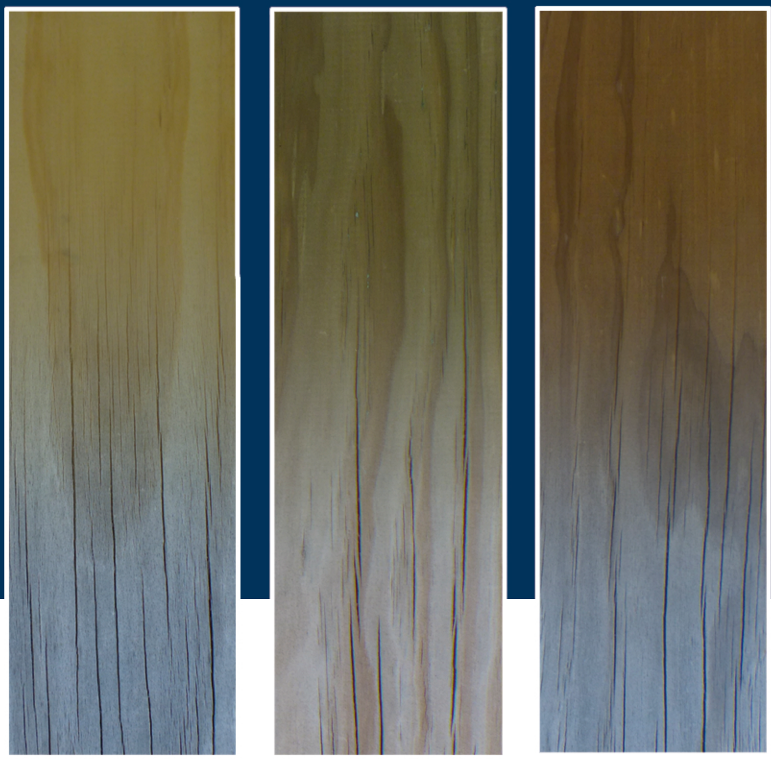

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# *Development and characterization of exterior Radiata-pine cladding for more sustainable and energy efficient façades in the Basque Country*

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# Contents

# Tables

# Figures

# Graphics

*“We may use wood with intelligence only if we understood wood”*

Frank Lloid Wright

1867-1959

# CHAPTER 0
# Introduction

# 0 Introduction

The State of Art is divided into four parts. The first one is focused on the evolution of façades, not only in terms of material but also related to current design and use requirements. The evolution of façades is not only linked to the optimized production of construction materials but also to the necessity of fulfilling habitability and comfort, which at the same time are linked to healthy. The second part is related to energy efficiency in façades. In this case, the attention is pointed to wooden façades and mainly in wood cladding, as the research is based on them. The third part describes the importance of durability in those kinds of elements. Regulation requirements are analysed as its guidelines help us to understand how important is designing properly wooden façades. That is, along this research the Spanish Building Technical Code, CTE, will play an important role. The fourth part of the State of Art explains how sustainable development influences the birth of new sustainable concepts and how the adaptation to climate is important to design more efficient enclosure solutions.

After collecting information about design, durability, energy efficiency, sustainable development and regulation around façades, the methodology used to study the thermal conductivity of wood is presented. For this research a test box is built “ad-hoc” in order to study the heat transfer.

Followed by this presentation, it starts the first phase of the research. This phase corresponds to Chapter 3, *Thermal characterization of Radiata-pine*, and it is organized by four sections and the conclusions, which are presented in all Chapters excluding in the previous ones: *Introduction, State of Art* and *Methodology*.

This phase represents the characterization of Radiata-pine by means of the test box, previously described in Chapter 2, *Methodology*. In this case, the chapter is divided into four sections: An introduction to heat transfer, the characterization of Radiata-pine conductivity, specific heat and resistance to water vapour diffusion. The conductivity characterization is carried out by two different methods based on conduction and convection phenomenon.

In Chapter 4, *Energy simulation*, different energy simulation tools are studied. In this case, different designs for wood cladding and material itself are simulated. In this case, THERM v.7.3 Software is used for the simulation of different joint wood boards for external cladding made of conifer wood. By these simulations, the influence of geometry in energy efficiency is evaluated. After that, both wooden solutions made of continuous layers and Radiata-pine cladding is simulated by WUFI Pro Software. This tool allows the hygrothermal simulation of material such as wood.

Apart from that, in another section, the Computational Fluid Dynamics (CFD) simulation of the interior air of the test box is performed, in order to understand the interior air thermal behaviour and movement.

Once the Radiata-pine characterization is done, its durability is also studied in Chapter 5, *Durability*. In this case, the influence of deterioration in material aesthetic and thermal properties is assessed. For that, this chapter is organized in four sections. The first one is related to the description of the durability test preparation. The second one represents the climate. That is, the registration of weather development during test along its duration, a year. After weathering, in the third part, aesthetic visual defects are studied such as loss of colour, apparition of fissures and crack. The last part corresponds to the thermal characterization of these elder samples to compare its properties before and after deterioration. As well as in the previous chapter, thermal characterization is realized by the test box.

In this research not only Radiata-pine conductivity is for interest but also its sustainable influence in façade solutions. Due to that, an index to evaluate the environmental sustainability of wooden façades, based on MIVES methodology, is presented in Chapter 6, *Sustainability*. In this case, both indicators and criteria are developed and described. Then, the sustainable index of a case study following this method is assessed.

The last phase, Chapter 7, *Wooden façades catalogue*, is a recompilation of different systems of wooden façades. In this case, both traditional timber framed system and Cross Laminated Timber (CLT) load walls are considered with different claddings. Costs, carbon footprint are the parameters to compare. In this case, these parameters are studied in order to analyse the sustainability of the façades with the same transmittance. That is, the aim of this chapter is analyse the sustainability of these solutions excluding the energy efficiency part. For that, a low transmittance value is considered in order to fulfil the Spanish Building Technical Code minimum requirements for any location in the Basque Country.

## 0.1 Aims

The main aim in this research is to study the influence of wooden external cladding in the thermal behaviour of timber façades in terms of energy efficiency and sustainability. For that, Radiata-pine characterization, simulation and evaluation through sustainable approach are required.

The objective in Chapter 3, *Thermal characterization of Radiata-pine*, is focused on the characterization of the material studying not only conductivity but also other properties that may influence the diversity of conductivity results depending on method.

In case of Chapter 4, *Energy simulation*, the objective is to get to know how the geometric and design are influence into the heat transfer of external claddings by THERM v.7.3 software, and how weather influences in the thermal behaviour of a complete wooden façade by WUFI Pro software.

As the test box is a new method to analyse the conductivity of different samples, a simulation of this test by Design Builder software is also planned, whose objective is to analyse the interior air thermal behaviour and movement as the convection coefficients gain importance in the test box procedure.

Once material characterization is done, the influence of its ageing in its thermal properties is also assessed. In this case, the objective in Chapter 5, *Durability*, lies on the study of the influence of weathering in the variation of physical properties of the material.

The aim in Chapter 6, *Sustainability*, is to develop a decision-making methodology that unifies the criteria in relation to the environmental sustainability of timber façades.

Another objective is to compare and analyse different factors that influence the sustainability of complete wooden façades, such as costs, energy efficiency and costs, in order to stablish correlations, which are exposed in Chapter 7, *Wooden façades catalogue*.

*"Any sufficiently advanced technology is indistinguishable from magic"*

Arthur C. Clarke

1917-2008

# CHAPTER 1
# State of art

# 1 State of Art

In this first phase of the research, a summary of the development of façades along decades is realized. Although the aim of this thesis is mainly to analyse the energy efficiency and sustainability of wooden façades made of radiate-pine, a review of the influence of other products in the construction sector is necessary. How materials have evolved and why it is represented in this chapter.

As it is known, wooden façades are not usually in our territory, the Basque Country. However, the production and extraction of this material is highly demanding overall for paper pulp and furniture. Its promotion in construction sector would be interesting, not only due to its revalorization but also in terms if sustainable development.

It is true that depending on its natural durability, this material could need protection treatments, overall when it is exposed to climate. According to that, the Spanish Building Technical Code (CTE), through DB-SE:M, which is a document related to the safety of wooden structures, stablishes the criteria to protect these elements depending on its Class of Use (CU).

Apart from that, the aesthetic deterioration of the material is analysed. This effect also interferes in its selection for façade use, as social knowledge about the importance of sustainability is not as spread in our territory as it is in northern countries.

The importance of sustainability development knowledge is also presented in this chapter, as its principles are the basis of this research. Building terminology related to different aspects of sustainability is also described, such as Green Building and Nearly Zero Energy

Buildings. The management of this terminology allows us to understand the diversity in criteria.

The influence of climate in the energy efficiency of façades has to be considered. Due to that, an analysis of Bilbao climate and different tools to stablish passive actions are also included.

## 1.1 Evolution of façades

Building enclosure is the skin which envelops the construction. Its function is to protect the construction against weather. Two main parts are distinguished, exclusion the part in contact with ground, which are the façade and roof. Façades are disposed mainly in vertical direction, while roofs are horizontal or inclined.

Façade evolution has taken place due to numerous factors, starting with the growth of knowledge around their behaviour in response to exterior agents. Abundant rainfall and variable temperature along time, not only in terms of seasons but also during day and night, make this system to adapt to these instabilities.

Because of that, nowadays, more thermal insulated solutions are getting more and more influence to keep comfort temperature continuously inside buildings without high and low temperature peeks that produces discomfort.

Acquisition of raw material and technological evolution of fabrication and assembly are factors that have also influenced in the development of new construction systems.

In order to understand façade evolution, a study of the path of different solution along decades, from stone and brick walls to ventilated and curtain walls, which are getting more and more used in our urban setting. For this evolution analysis, this group of façades is selected:

- Stone façade
- Brick façade
- Concrete façades
- Metal façade
- Curtain wall

- Plastic façade
- Wooden façade

The use of stone load-bearing walls for external façades was characteristic of antiques buildings such as "*caserios*", which are singular constructions from our territory, the Basque Country. In this kind of buildings lived both tenants and animals, the last ones in the ground floor. It was not only dwellings but also agricultural and livestock production places [1]. Nowadays, some are still preserved. Their walls are very wide, until 1 m thickness, as they were also used as load-bearing walls. The development of this typology took place because of various reasons.

In the first place, its protection condition against external agents. Its high thickness avoids water enter into the house by capillarity, protecting the interior from moisture. On the other hand, it was able to use as part of the structure, taking part as perimeter load-bearing walls. For the interior, they were commonly used timber structures and wooden slabs. Those slabs were supported by both elements, the perimeter load-bearing walls and the interior timber structure. Sometimes these façades were not only made of stone, and it combines also timber frames into them. In case of upper floors, brick walls were also introduced along decades as they were lighter and allowed taller buildings.

The thermal behaviour of these kinds of façades highly differs from currently systems. Nowadays, there is a search towards more energy efficient solutions mainly through the use of highly insulated products. However, stone material has high thermal inertia, which implies that its energy efficiency is directly linked to exploitation of thermal energy, capturing heat and releasing it when the temperature inside buildings goes up or down. However, this process takes long and reach the thermal comfort is not easy when low energy consumption is pretended.

Thermal inertia is a property that indicates the amount of heat a material can store and the velocity this is absorbed or released. This property depends on its mass, specific heat and thermal conductivity. In construction, the thermal inertia is used to absorb heat that it comes from solar radiation when there is sunlight by high mass façades such as stone ones, which allow release this heat during night, when outside temperature goes down.

Brick façades, at first, were used to replace stone ones as load-bearing external walls. Among its beneficial characteristics there were its easy-to-work with and transport, due to its size, geometry and weight. The brick composition is basically based on clay. The first civilization which used it were the farmers of pre-ceramic Neolithic of the Levant, 9500

B.C., due to the lack of wood and stone in this region. In our territory, however, both stone and wood are abundant raw material, because of that, they have been more used.

In our country, brick did not appear until middle age in some relevant civil buildings, from the hand of Mudejar art. However, until last 50 year this product was not used for the construction of residential buildings. From that moment, its use has been exponential spread and it became the material most used for façades.

In case of concrete façades, currently, this solution is taking more and more relevance in the construction of residential blocks. The façades are configured through prefabricated concrete slabs, as they are easy to transport and assembly. Their prefabrication also allows more finishing quality. Although being more expensive than other products such as bricks, it has some advantages.

In the first place, the risk of the behaviour variation after the assembly of the prefabricated products is more assumable than those carried out in site. The prefabricated products are easily fabricated under controlled conditions, which allow verifying the product characteristics.

At the same time, the transport efficiency and assembly is more attended. When the product goes out of the factory its mechanical properties keep equal, avoiding alterations that can take place during spill and hardened such as segregation of arid.

The use of metal façades is not as common as in industrial buildings. During the industrial revolution this kind of enclosure was used to factory façades and it was pulled apart from the typology of façades that involves other type of buildings, as it is described in the Law Construction Planning, "*Ley de Ordenación de la Edificación"* (LOE)[2]. Depending on the use of the building, classified by LOE, their requirements are different in terms of thermal insulation, health standards and safety against fire.

On the other hand, the aesthetic appearance has also played an important role in façade evolution, in general terms. In case of metal façade, this solution has started to be relevant with the growth of knowledge and use around the ventilated façades, not only as sandwich panels but also steel frame with external cladding made of perforated sheets are nowadays under research [3, 4].

If metal sheets as external cladding have been historically characteristic of industrial buildings, the curtain walls have been characteristic of administration buildings. That is due to various factors, such as taking advantage of sunlight and landscape views, which are known that interferes in productivity as well as thermal, acoustic, and physical comfort [5].

However, in terms of energy efficiency, it supposes some disadvantages. During cold days, the use of large glass panels implies less insulated enclosures and, as a result, heat losses are higher. In case of warm days, glass panels allow sun radiation that increases the temperature inside the building making necessary the implementation of air conditioning systems for refrigeration.

Residential buildings are different in design and concept. For single family dwellings, which are not especially tall, wood construction has been very common worldwide with different forms depending on local culture and availability. Wood has been universal material for façades. The first complex buildings were built in the Neolithic. These constructions were made of logs and branches forming a framework to enclosure and cover the living space.

While envelope has been transforming towards more complex and competitive solutions, such as the brick revolution, other conditioners have appeared which have been derived to new needs in order to reach comfort. Thermal and acoustic insulation, vapour and water barriers are some of the products which have been developed not only to fulfil the requirements stablished by Regulation, but also to guarantee the requirements demanded by current society in terms of health and comfort.

Another turning point, in relation with the development of this construction system, is the use of air cavities as intermediate insulation. Air cavity allows dividing the façade in two main parts, which are commonly named as exterior and interior sheet or layer. With the implementation of this part a new concept of external walls appears which substitutes to traditional mass walls.

If attention is focused on building protection against inclement weather, such as rainfall, wind or extreme temperatures, the air cavity not only works as thermal barrier but also it buffers wind efforts and avoid the interior sheet getting wet. When this cavity is discontinues along façade due to horizontal slabs, a half-round piece of mortar is placed inside it, covering the joint between slabs and the interior walls, making easy the evacuation of water in case it enters.

It has been demonstrated that enclosed air in this cavity supposes a cheaper way of increment of insulation. It also plays an important role around health, as it avoids moisture inside housing. This moisture can result in condensations on the interior cladding that can derive in the apparition of spots and fungi.

In Spain, the minimum requirements to guarantee that a building is habitable are compiled in the Spanish Building Technical Code, "*Código Técnico de la Edificación*" (CTE) [6], based on a series of documents to satisfy habitability, comfort and people safety inside buildings.

Apart from the suitability of façades according to technical issues, new concepts such as sustainability are getting more and more relevant when construction products are selected, due to its relation with climate change and pollution.

Sustainable development concept is known since the first publication of *Brundtland Report* in 1987 about Climate change. In 1997, *Kyoto Protocol* was written, although it did not become effective until 2005. It was a statement of intents of a group of countries to reduce pollution. This document has been became one of the most relevant initiatives to preserve our environment.

Currently, the main objective of Europe Union (EU) to 2020 is oriented to reduce Greenhouse gases. In the case of building construction repercussion, *Energy Performance of Buildings Directive* (EDPB) was published.

The building façade improvement to reach more energy efficiency is essential if we want to achieve the European objectives previously mentioned, which are overall focused on cutting down on energy consumption and demand to reduce the carbon footprint which, as a result, promotes the Climate change.

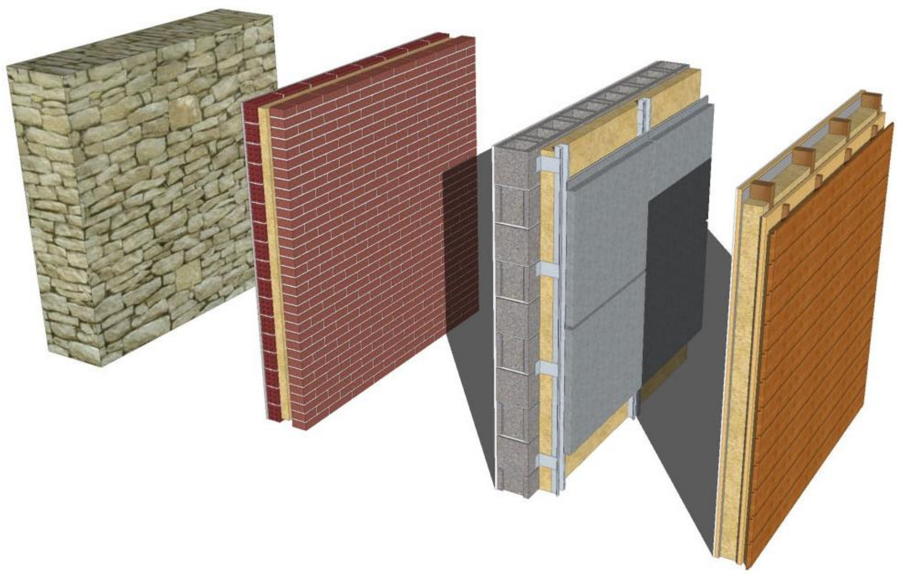


**Figure 1.1. Different façade models**

In Figure 1.1, it can be seen that the technological development of façades has been produced looking for more efficient solution and narrower, without giving up its mechanical and durability performance.

As it was previously mentioned, in relation to the evolution of the constructive system, the most used materials have been the stone, ceramic, concrete, metal, glass and wood. In special cases, plastic products have been used too.

From all of these materials, a high diversity of layer combinations has been taken place in the development of façades. Depending on these combinations two main types of enclosures are distinguished, multilayer or simple façade.

The simple façade is mainly composed by one material, which used to be also structural part. Churches, cathedrals and civil antiques buildings made of stone walls are examples of that. On the other hand, multilayer façades are composed by different material layers joint together. The aim of these solutions is getting more efficient and narrower façades combining products. These solutions are the current type of façades.

When façades have an intermediate air cavity, this part implies that façade is divided into two main constructive elements, which are commonly known as exterior and interior façade sheet. As it was previously mentioned, the installation of air cavities implies some benefits.

If terms and concepts are analysed, it can be appreciated that there is a disagreement when façades are catalogued or named. Normally, they are defined by the material used for external cladding. That is, if the external cladding of a façade is made of metal it is commonly defined as metal façade, although this material is supported by a brick wall. The complexes of the composition of current systems makes difficult to name them in a term without using a global description.

Each material and product has a predominant function in the structuration of the façades due to their different properties. Coming up next, the development of materials used for façades along time is studied.

### 1.1.1 Façade materials

Along the history, a diversity of materials for façades has been used. A lot of them have been transformed by more efficient industrial processes which have derived to better performance. The most common materials have been the next ones.

#### Stone

The first building in the history of humanity appeared because of local circumstances. From its origin, buildings were an interpretation of natural structures such as caves. In this case, they were built piling stones. Although these first walls offered stability and safety, then in the history, they were transformed to more accurate and aesthetic solutions, as it was demanded by society.

During centuries, the development of stone façades has been linked to masonry development. Stone is one of the most antiques construction materials. The first civilizations, such as Mesopotamia and Egyptian, used this material for mass or load-bearing walls.

The extraction of it for building construction started in 5000 B.C. However, its manipulation was not able until the apparition of copper (2500 B.C.) as with this material was possible to produce new tools.

Previous techniques to model stone by Egyptians were improved during the erection of Greek Architecture which was focused on the study of the curvature and entasis to model this material and visually compose modular façades.

The Romanians developed these techniques further, and their practice experience was possible from the hand of Marco Vitruvius, by his ten architecture books [7]. As a results, the first general rules of application in Europe, between the Romanian Imperia boundaries, were stablished 200 years ago.

The modular prefabrication, was an often practice during miles of in the form of blocks. However, it was not until principles of middle ages when the ashlar appeared to construct enormous cathedrals. The construction techniques for the construction of stone façades continued developing, making possible the fabrication of larger pieces.

On the other hand, the duration of construction works were also reduced with the apparition of structural solutions elaborated by means of joining horizontal layers. This construction way was developed during Romanic period reaching maximum level with the Gothic cathedrals of 13$^{th}$ century and later.

When Renascence began to flourish, the desire to express an upper power by architecture started to grow up. The exterior appearance of civil buildings and palace was getting more and more relevant.

In many cases, the façade is separated from the central body of the building turning into an independent architectural element for the first time. Lots of examples are located overall in Italy.

In a technic variance, they were created façades which external cladding was composed by a thinner external stone layer made of panels carefully stick on the supported wall by mortar, creating mosaics with different colours and shapes. This craftwork combines different types of stone and it took place overall in Toscana and Umbria [8].

**Figure 1.2. Santa Maria del Fiore © E. Buchot**

An example of this craftworks is the Basilic of "*Santa Maria del Fiore*" in Florence, work of Arnolfo di Cambio and Filippo Brunelleschi, where it can be distinguised its separation from the concept of mass or load-bearing wall. This disassociation was not only in terms of stile, but also the material treatment.

From exterior, it is appreciated the assembly of stone pieces that draws a mosaic of relieves and colours. Until the arriving of transparent glass panels, thin pieces of stone worked as weather protection slightly allowing the pass of natural light.

Currently, a lot of architects and engineers use and develop new stone applications for some singular projects.

### Ceramic

Products made of clay, which is the main component of ceramic material, have been used from more than 7000 years.

Although currently the production of ceramic products has changed, the tendency of using clay for new products is important yet. The origin of this component was in Nilo Valley, where they were found remains of antique buildings made of handmade mud bricks. These building were very fragile when they were exposed to climate agents, as the mud, which is a mixture of clay and sand, was vulnerable material to rain and humid ground. Besides, mud during its desiccation it is not stable, it only hardens. This means that when material is exposed to water, it softens and loses its mechanical resistance.

Similar solutions have been developed worldwide to protect buildings against erosion. 50000 B.C. appeared the first techniques to build masonries more durable, from the fire of the material. When material is heated until 1000°C, this is synthetized and it becomes more resistant.

From that moment, it was possible to enamel the surface of bricks even colour them. Brick masonry becomes very common during miles of years. It was used in different structures depending on localization, geological conditions, and local weather, as well as, different aesthetic and social contexts. The progress to mass production of fire bricks was developed at first by the Romanians.

**Figure 1.3. House Ratschow in Rostock © Bernd H. Schuldes**

Throughout the Roman Empire, numerous buildings and architectural projects made of brick masonry are founded.

In Germany, the fire clay gained relevance during the Middle Ages, in *backsteingotik* buildings. This style is one of the most amazing and significant version of Gothic, also known as *Baltic Gothic*.

Its peak was extended to countries where stone, as raw material, was limited resource. The invention of the extrusion and the cylindrical oven in the S.XVIII made possible the mass production of ceramic bricks, thanks to the fire process of the clay. This material is easy to dissolve into water and it acquires easily physical and chemical stability with this process. It also has high resistance to dirty, smug, fungi growth and freezing. Due to that, it is suitable material to be exposed to the weather.

During the search of Germanic Modernism, toward the end of 19$^{th}$ century, the fire clay block, known as ceramic brick, gradually became to the standard material for the outer face of masonry façades which conform a diversity of historic decoration and ornamentation of the urban space in many places.

*Stony Berlin* is characterized by its huge buildings made of masonry. The use of bricks took place in relevant works from the hand of known architects like Alvar Aalto and Ludwing Mies van der Rohe. Since the middle of 20$^{th}$ century, other recognised professionals like Eladio Dieste, who was the civil engineer that enhanced the reinforced ceramic, continued with this tradition from works like the "*Parroquia del Cristo Obrero*" (Estación Atlántida, Uruguay), where the fire clay configures the load structure. At the same time, this material transmits lightness waving the enclosure [8].

Nowadays, the ceramic enclosure with less thickness is possible and due to its high durability is particularly suitable to protect the thermal insulation layer.

### Concrete

Concrete has been very influent in the development of the Modern Architecture. In case of composition, it is antique material. From 12000 B.C., lime mortar was used as construction material and its development permitted the discover of *opus caementitium* or concrete in 2dn century B.C. This material allowed Romanians to create architectural and engineer works with great skill, like the Pantheon in Rome in 118 A.C. However, after the fall of the Roman Empire 1500 years ago, the *opus caementitium* lost its meaning as construction material.

It was the discovery of Portland cement in 1824, which enabled the development of the concrete as it is known nowadays. The first samples of reinforced concrete were tested in the middle of 19th century in France and England. The first aim was replacing wood and stone because the new material promised more protection against moisture. The first patent was registered in England, in 1854, to a reinforced concrete slab with steel. In this age, François Coignet discovered the concrete aggregate method and built a three storey building based on this technique.

This pioneer way of construction was accompanied by numerous experimental researches around the behaviour of this material and the elaboration of calculus methods to stablish a general theory for concrete works. All of this opened new applications more oriented to the sizing of structures to cover large spans.

This new material was stabilized in 20th century, mainly for industrial and commercial buildings such as factories and markets. However, it did it as structural component based on the portico, composed by beams and pillars.

In 1903 from the hand of Auguste Perret, this material was shown as façade material for the first time. It was a block of apartments built in 1903 and located in the *Rue Franklin*, in Paris. Then, in 1910, appeared new concepts which influenced the construction of reinforced concrete.

The Urban Planning of Tony Garnier to the design of an ideal city, the "*Cité Industrielle"* (1901-17), the "*Domino System"* (1914) of Le Corbusier, and the design of an administration building made of concrete from the hand of Ludwig Mies van der Rohe in Berlín (1922), where some examples which illustrate the use of concrete blocks and panels [8].

Concrete was the first artificial and heterogeneous construction material that has played an important role in construction history. It is characterized for being extremely durable, easy-to-work and it also has great load capacity together with steel. Reinforced concrete is used to high variety of structural elements and, thanks to its malleability, it is open to new shapes and construction applications.

Concrete has also been used as monolithic element made of blocks, due to its easy-to-work and joint. It exists a high repertoire of solutions, from large panels to small blocks for masonry.

**Figure 1.4. Frank Lloyd Wright designer ©2014 Ennis House Foundation**

In Figure 1.4, it is shown one of the buildings designed by the known architect Frank Lloyd Wright in 1923. In this case, he chose a façade made of concrete blocks from two moulds, one flat and the other one with relieve. This allowed him to introduce elements with decoration shapes to compose volumetric buildings with monumental appearance, like a temple made of stone.

If the union between more technological materials promotes the construction of symbolic projects, in practice, a lot of these materials are not extended or developed in the same way, due to economic and cultural reasons.

### Metal

In many places, the advancement of humanity has gone from the hand of the development of metallurgy technologies. The discovery of the bronze (2500 B.C.) and the iron (750 B.C.) supposed a revolution. Materials which at first represented an improvement to the fabrication of tools and arms, passed to form part of a cultural global revolution on a large scale.

Apart from the melting, which was the way metal was transformed, appeared other mould techniques such as the forging. Gradually, the different techniques were improved until the discovery of new metals and alloys which allowed its use for more applications.

This technological progress in metallurgy takes more relevance in armament because, apart from its protection function, it had to satisfy other requirements such as identity, prestige and representation. These different needs allowed the development of different ways of metallurgy.

In the building field, metal was commercialized from the earliest times. Bronze, copper and lead have been very used since ancient times, initially to erect roofs. Greeks also used high amount of copper and iron as connectors, in order to join the stones of their walls and temples, sometimes, they also melted the material to seal the joints. Many of these structures were later destroyed to recover the metal, as it was very demanding in wartime.

Although it is not visible, many Gothic buildings are stable due to the fact that the stones are reinforced with iron such as bars and bolts, mostly hidden.

During a lot of time, the use of metals was limited to joint pieces, local claddings and borders, canopies, among others. With the apparition of extended glass panels the metals gain importance and started to be shown in façades, with new shapes and for larger windows. From this perspective, it can be said that the metal development was linked to glass.

After 1720 the use of coal and coke, instead of firewood, made possible the mass production of the cast iron. Towards the middle of 18$^{th}$ century they were produced the first iron sheets.

The use of metals in façades coincided with the development of rail production derived from the emergence of the railway industry in 1830, and the steel introduction in 1855. The first forging iron for I-beams was produced in France in 1854. This year, James Bogardus built the office building for the editorial *Harper & Brothers.* Its five storey façade was composed of prefabricated elements made o melted steel.

During this period of time, steel exposed and iron pieces put on façades formed part of the load structure. They appeared significant examples together with the glass development, like the works carried out by the architect Carl Ludwig Althans (1828-30), and also together with the brick development, as it can be seen in the emblematic factory of chocolate *Menier* designed by Jules Saulnier in Nogent-Sur-Marne, France (1871-72).

Another extended application of the melted iron in 19th century was the creation of prefabricated balustrades in balconies and in the spandrels of pergolas, which were predominated in the French district of New Orleans. The production method from melting the metal was cheap and it allowed to reach opener and detailed solutions. Due to that, it was very produced in this period of time.

On the other hand, one of the first examples of metal façade practically blind is the office building in the *Rue Réaumur* of Paris (1905), an architectural work of Georges Chédanne. In this case, the façade is composed by a steel structure whose intermediate planes are filled with riveted metal sheets.

### Glass

Glass is one of the most antiques materials. There are evidences of its use before 5000 B.C. from volcanic origin to make weapons and knives. A significant invention was its production by blowing glass in 2nd century B.C. by Syrians. This discovery made possible the production of pans and containers for the first time. Later, the melting allowed Romanians to create the first glass plate, although it was not transparent.

Towards the first century A.C., the improvements of the glass formulation and the discovery of the production process by cylindrical blowing make possible the creation of the first transparent plate. Then, the glass crown method allowed smoother surfaces. These two methods, which were discovered by Syrians, brought a continuous development of glass keeping them as the most dominant production methods until 19th century.

After 1905, the production of glass plate from stretching the material became. In this case, heat glass mass, viscous yet, was passed between rollers or along a fire ceramic nozzle to be cooled after. For the first time, it was possible to produce cheaper and larger amount of glass.

The most important step towards the economic and profitable production of high quality glass was the invention of the floating method in 1959 by Alastair Pilkington. In this case, the viscous and melted glass passed on a bath of melted tin 1000 °C temperature approximately. As glass has minor specific weight it floats until the surface and it is extended along it at the same level. When it goes out the bath, practically solid, it is transported through rollers, it is carefully cooled, and finally the plates are cut tailor-made.

This method, which is worldwide extended, makes possible the mass production and with high performances for multitude of variants.

Another peculiar invention was the glass blocks by Gustave Falconnier in 1886. Later, recognized architects like Guimard, Perret and Le Corbusier used these blocks in some of their works. Glass blocks with reinforced concrete have lateral slots to be connected to one another. This design was introduced since 1907. For the first time, it was possible to fabricate large glass panels permeable to light and self-supporting.

They were also created some solutions from glass hollow blocks as a shell that could be collocated facing the interior or the exterior. These applications can be found in singular roofs made of glass in Prague, Budapest and other European countries. The glass brick, as it is nowadays known, came up in 1930, when two hot shells were pressed together and became stuck [8].

### Plastic

The majority of plastics that have played an important role in the construction modern industry were invented and developed to their mass production between 1931 and 1938.

Polyvinyl Chloride (PVC) was previously commercialized to tubes and accessories in 1935. Initially, plastics were used to interior equipment and furniture fabrication. It was not until the last fifties, when it started to intensely work in the development of buildings made of this synthetic material. This was possible due to the use of new processes like the lamination and moulding reinforced with glass fibres.

Among its advantages, as cladding material, it stands out its durability, flexure and compression resistance, transparent possibilities, hardness, elasticity, low density, thermal stability, electric insulation and low thermal conductivity, low permeability, chemical resistance, easy-to-work and assembly, high quality surface.

However, its behavior against fire requires consideration, taking into account that it is an inflammable material and toxic when it is decomposed. In case of inflammability, they exist some retardants to reduce the fire effects, however, toxic smug control is more complex and it is also a key to guarantee the safety of users. Besides, the gases may have corrosive effects on the rest of materials.

## Wood

From the prehistory until the beginning of the industrial age, wood has played an important role in our relation with nature. During more than a mile of years, the knowledge about wood construction and its architectural language has been extended worldwide without cultural and geographic boundaries [9].

From the availability of the resource, the first construction methods were developed and the need of knowledge and skills to manage this material to use it in construction made gradually possible its mould.

At first, wood was used to simple and small buildings but, nowadays, wood is used to larger structures and it is developing to more complex shapes.

The most used methods, such as sawing and chipping, are from a thousand years ago but its use was not extended until the reach of the Industrial Revolution. The predecessors of modern engineering of wood are mainly found in 19th and 20th centuries.

The current state of wooden façade technology is extended from the craftwork, both construction and assembly, to more advanced prefabricated wooden walls.

**Figure 1.5. Red House, Ross-shire @Brennan & Wilson Architects**

Between them, it stands out the prefabricated elements in shape of modules and panels that are fabricated by automatic processes and them they are assembly in site easily and fast.

Some of the most relevant technical properties of the wood are the next ones: High mechanical resistance according to its weight, easy-to-work and process from advanced techniques, high thermal resistance, and hygrothermal behaviour.

Depending on specimen the natural durability differs. Some specimens stand out due to its high resistance to external agents without requiring protector treatments.

### 1.1.2 Design requirements

In Table 1.1, they are shown design requirements and determinants facing the execution of optimized façades that allow the comfort of tenants and take advantage of environmental resources.

This table is divided into three parts, where they are presented requirements, measurements and supplementary services that can occur in the external and internal face of the façade.

| Interior | | Façade | Exterior | |
|---|---|---|---|---|
| **Requirements** | | **Protection against permanent and variable determinants** | **Specific local conditions** | |
| Range of temperature/<br>Humidity comfort/<br>Quantity and Quality of light (natural)/<br>Air renovation/<br>clean air supply/<br>Comfort air speed/<br>Acoustic comfort | Minimum air tightness | Insulation/ attenuation<br>Seals/ barriers<br>Filters<br>Storage<br>Redirection<br>Physical barriers | Air tightness from exterior | Solar radiation<br>Temperature<br>Humidity<br>Precipitations<br>Wind |
| | | | Noise sources<br>Gas and dust presence<br>Mechanical loads<br>Electromagnetic radiation<br>Urban planning<br>Local resources<br>Social and cultural context | |
| **Supplementary measures of direct impact** | | **Control** | **Supplementary measures of direct impact** | |
| Glare protection<br>Privacy<br>Sunlight redirection | (Ex.: curtains) | Control/ regulation<br>Response /change | (Ex.: Shutters, blinds, sun screens) | Thermal insulation<br>Shading |
| Storage and distribution elements of heat/ cool | (Floors, walls, roofs) | | (Ex.: Vegetation, waterbody ) | Measures that influence microclimate |
| **Supplementary services** | | **Integrated services** | **Supplementary services** | |
| Artificial light<br>Radiators/ convectors<br>Air conditioned | (Centralised / individual) | Air cavity/ water collectors<br>Solar walls<br>Energy transport/ distribution<br>Heat recovery | Exterior collectors<br>Photovoltaic panels<br>Heat probes, radiant tubes, etc. | |

**Table 1.1. Façade requirements**

### 1.1.3 Use requirements

As the enclosure has evolved searching for the improvement of some aspects, such as lightness which promoted the apparition of bricks, other determinants have appeared that also resulted in the need of new products such as the thermal and acoustic insulation, waterproof sheets and vapour barriers, to fulfil the requirements of tightness and comfort, defining the living space.

Another important point about the development of façades is the use of air cavities as intermediate insulation element. Air cavity allows dividing the enclosure in two main parts, commonly known as exterior and interior sheet. In this moment appeared the concept of hollow wall as a contrast of the traditional mass wall.

If the attention is focused on building protection against weather agents, such as rainfalls, wind, exterior high and low temperatures, the air cavity works as thermal and wind load attenuator and also allows water evacuation in case it passes through the wall or external sheet. That is, this element avoids moisture inside housing that can derive in the apparition of spots and fungi, as it was previously mentioned in section 1.1 .

In Spain, the minimum requirements to guarantee that a building is habitable are compiled in the Spanish Building Technical Code, "*Código Técnico de la Edificación"* (CTE) [6], through a series of documents depending on the issue, which are; Salubrity (DB-HS), Energy management (DB-HE), Safety against noise (DB-HR), Structural safety (DB-HSE), Safety against fire (DB-SI), Accessibility and use safety (DB-SUA). The main aim of this Regulation is guarantee the habitability, comfort and people safety inside buildings.

In order to justify these requirements, material properties and enclosure characteristics have to be analysed, in order to demonstrate the suitability of the façade system in terms of; mechanical resistance, thermal, acoustic and moisture control, ventilation need and safety against fire and use safety. The last point more linked to design and to material properties.

In Table 1.2 there are exposed not only the advantages and drawbacks of using wooden façades but also technical and design strategies to reach a successful management.

| Aspects to consider | Drawbacks |
| --- | --- |
| Durability | Condensation risks |
| Easy-to-produce and assembly | Energy and cost saving |
| Costs | Competitiveness |
| **Technical strategies** | |
| • Increment of the thermal insulation inside the air cavity | |
| • Installation of insulated cladding | |
| • Improvement of the thermal resistance of materials | |
| • Reduction of thermal bridges: Timber frame (studs and posts) | |
| • Tightness construction | |
| ↓ | Knowledge transfer<br>Repercussion in terms of architectural set |
| **Construction detail of the façade** | |
| Joints between building systems: | Façade- roof |
| | Slab-façade |
| | Façade-ground |
| | Façade-Openings (doors, windows) |
| Fulfilment of current Regulation (CTE): | Energy management (DB-HE) |
| | Salubrity (DB-HS) |
| | Noise safety (DB-HR) |
| Aesthetic composition | Overview |

**Table 1.2. Advantages and drawbacks of wooden façade**

## 1.2 Thermal resistance in façades

In general terms and taking into account our climate, during the winter it interests that the generated heat inside buildings to condition them keeps. For that, the building has to be as insulated as possible. Besides, it is advisable to stablish mechanisms to take advantage of solar energy to warm the interior of the different rooms and supply them with natural light.

If in winter it interests a high insulated façade, in summer the main objective is avoiding the entrance of the out heat, that is, the heat transfer from the exterior to the interior. At the same time, it interests that heat gain can be dissipated to the exterior [10].

It was studied the thermal behaviour of different ventilated façades to warmer climates, such as Mediterranean, during summer [11]. The design of the cladding panels, including their joints, emissivity and kind of material, and the sizing of the air cavity, are some of the parameters to study in order to reach more energy efficient enclosures.

However, due to our geographic localization and climate profile, the high temperatures are less predominant along year, covering more importance the winter season to stablish the comfort temperature inside buildings.

Currently, the façades of new residential buildings are built with insulation and sometimes accompanied by an air cavity, not only to fulfill Regulation requirements (D*ocumento Básico de Ahorro Energético*, DB-HE) but also because it has been demonstrated that it supposes important energy and cost savings over the life of the building.

The energy consumption in the Basque Country is shot up in winter, due to heat consumption. However, in the South of the peninsula the energy consumption is shot up because of air conditioning installation.

It has been demonstrated that an enclosure well insulated supposes energy savings and better use of resources. Due to that, the studies related to the energy efficiency of façades have been increased during the last decade. Taking into account that 40% of energy consumption in Europe becomes from the construction sector, and between 70 and 90% of residential areas were built more than twenty years ago, it is foreseen an increment of energy refurbishments [12]. Because of the thermal characteristics of wood, it is an ideal construction material to improve elder buildings. Besides, it is gaining importance due to the fact that it becomes from renewable sources.

The Spanish Building Technical Code, *Código Técnico de la Edificación* (CTE), was published in 2006 at first time, and the fulfilment of its requirements was obligatory from 2008. This norm establishes the criteria to fulfil current demands of energy efficiency, which are presented in the previously mentioned document DB-HE, *Documento Básico de Ahorro Energético*, related to energy saving for both new constructions and refurbishments.

### 1.2.1 Thermal behaviour of wooden façades

The hygrothermal behaviour of timber frame façades is the result of the combination behaviour of all layers that conforms this enclosure system. If almost every timber frame façades are structurally similar, the way this solution is insulated differs depending on the continent. In Europe, the tendency is towards External Thermal Insulation Composite systems (ETICS), which are solutions based on continuous insulation from exterior. These solutions are characterized by its thickness and material, which is usually Expanded Polystyrene (EPS), while in America the systems are thinner and the most common insulation is the glass wool [13].

The thermal properties of the different layers that conform a façade can be known, although its behaviour as a group is not easy to predict when it is exposed to climate. Temperature and humidity variation along the day and the seasons make necessary the study of the system with real conditions taking into account all the parameters that can influence its thermal response. That is, the orientation, its higher or lower exposed to sun, the presence of rainfalls and wind taking into account its frequency, direction and intensity, are some of the factors that influence in the study of the thermal envelope [14].

In this aspect, they are differenced two scales, the thermal behaviour of the façade during a day (24 h), considering the temperature and humidity oscillation, and during a year, taking into account the different seasons, that is, the chance of the temperature and humidity range. The configuration of the façade also influences in the response to weather agents. Due to that, it is necessary to test materials and systems exposing them to climate [15].

The multilayer façades allow realising solutions that contents one or more insulation layers and intermediate air cavities, to be thermally improved. However, some construction materials, such as wood, are characterized by hygroscopic material, which means that although having low thermal conductivity when it is dry, the increment of water content in the material alters its conductivity. Due to that, the global thermal analysis of façades is necessary in order to foreseen the response of the façade combining different types of materials [16].

On the other hand, the thermal insulation of wooden façades is taking more and more relevance as it is necessary to reach higher thermal resistance, which has derived to solutions combining different insulation layers with different density and thickness. In terms of construction details, there is also an interest in the reduction of thermal bridges to reach more energy efficiency [17].

### 1.2.2 Thermal properties of Radiata-pine

There are thermal characteristic values defined by the norm ISO UNE-EN 10456 to construction products and materials [18]. In this norm, thermal conductivity, specific heat and resistance factor to water vapour diffusion are defined for each material. In case of wood, the norm distinguishes between solid wood and chipboards. In Table 1.3, there are shown the thermal conductivity (λ), the specific heat capacity ($C_p$) and resistance factor to water vapour diffusion (μ) of solid wood, depending on its density (ρ).

| | ρ | λ | $C_p$ | μ [-] | |
|---|---|---|---|---|---|
| | [kg/m$^3$] | [W/(m·K)] | [J/(kg·K)] | Dry | Humid |
| Wood | 450 | 0,12 | 1600 | 50 | 20 |
| | 500 | 0,13 | 1600 | 50 | 20 |
| | 700 | 0,18 | 1600 | 200 | 50 |

**Table 1.3. Wood thermal properties, ISO UNE-EN 10456 standard**

As it can be seen in the previous table, the thermal conductivity (λ) highly varies, as well as the resistance factor to water vapour diffusion (μ). However, this norm does not distinguish values according to specimen, taking a reference value depending only on density.

On the other hand, other recognised documents such as the “Constructive Elements Catalogue” presented by the Spanish Building Technical Code (CTE) [19] distinguishes between softwood and hardwood with lower range of densities in order to take more accurate values of thermal conductivity (λ), specific heat capacity ($C_p$) and resistance factor to water vapour diffusion (μ), although the last one it is not divided into dry and humid factor, as it can be seen in Table 1.4.

| | Description | ρ | λ | $C_p$ | μ |
|---|---|---|---|---|---|
| | | [kg/m³] | [W/(m·K)] | [J/(kg·K)] | [-] |
| Softwood | Very weight | ρ > 610 | 0,23 | 1600 | 20 |
| | Weight | 520 < ρ ≤ 610 | 0,18 | 1600 | 20 |
| | Medium weight | 435 < ρ ≤ 520 | 0,15 | 1600 | 20 |
| | Light | ρ ≤ 435 | 0,13 | 1600 | 20 |
| | Balsa wood | ρ ≤ 200 | 0,057 | 1600 | 20 |
| Hardwood | Very weight | ρ > 870 | 0,29 | 1600 | 50 |
| | Weight | 750 < ρ ≤ 870 | 0,23 | 1600 | 50 |
| | Medium weight | 565 < ρ ≤ 750 | 0,18 | 1600 | 50 |
| | Light | 435 < ρ ≤ 565 | 0,15 | 1600 | 50 |
| | Very light | 200 < ρ ≤ 435 | 0,13 | 1600 | 50 |

**Table 1.4. Wood thermal conductivity according to CTE norm**

If we take as reference an interval between 500 y 700 kg/m$^3$, it can be seen that ISO UNE-EN 10456 stablishes a thermal conductivity value between 0.13 and 0.18 W/(m·K), while if we take the values obtained by the Spanish Building Technical Code (CTE), the thermal conductivity interval is between 0,18 y 0,23 W/(m·K). The difference of these values can generate confusion when we want to select the most accurate value according to our material.

In our case, the Radiata-pine has between 517 and 576 kg/m$^3$ density, when material is 12% relative humidity approximately. That is, the thermal conductivity of this material is estimated between 0.15 and 0.18 W/(m·K) according to CTE, and between 0.13 and 0.18 W/(m·K) according to ISO UNE-EN 12664.

In case of other products such as thermal insulation, their specifications are provided by the manufactures as this material is specifically produced to insulate.

## 1.3 Wood natural durability

In this section it will be analysed the pathologies that usually appear in construction systems made of wood. These can be divided into two main groups; structural and durability pathologies.

The structural pathologies come from the wrong design and sizing of the elements that form part of the construction system, such as timber frames, bearing walls made of CLT (Cross Laminated Timber) or wood structures made of posts and large laminated beams in order to cover large spans. The mechanical resistance of wood is known and it differs depending on the direction of the fibres and the presence of noodles, which are catalogued as defects.

Apart from structural ones, durability pathologies are also detected due to the response of material to biotic and abiotic agents.

The biotic agents are the weather agents, which affect to exposed materials. Wood is hygroscopic material and due to that it absorbers and releases humidity when there is a moisture source. Because of that, when it is raining it swells and when it stops raining the material is contracted due to drying, which produces drying fissures and cracks parallel to the fibres, it is also twisted and curved.

This characteristic behaviour, movements and deformations, have to be into account in the design of construction wood elements which are more susceptible to be in contact with water. For that, strategies such as the design of joints which allow wood movement and air spaces where moisture can be accumulated in order to make easier its ventilation and water evacuation are usually followed.

Apart from the rain water, there is other deterioration agent, the solar radiation. This phenomenon (photo degradation) affects superficially the material. The ultraviolet (UV) rays destroy the wood lignin, which makes it to become grey gradually, and the infrared (IR) radiation makes it to release resin and other material substances by exudation.

These two agents are usually presented in our climate along year. Consequently, the material deterioration takes place from the outer face of the material toward the interior.

On the other hand, there are the biotic agents. Between them, they are distinguished the fungi and the larval cycle insects.

Inside the group of fungi, there are two classes; chromogenic and rot fungi. The chromogenic fungi, as their name points, are characterized by colorizing wood, although they do not affect to the mechanical resistance of the material. However, rot fungi are harmful. These fungi eat the wood cellulose and hollow the interior of the material setting aside the lignin, which surrounds the cellulose.

The last agents are larval cycle insects. Between them, the most common are; powder-post beetles, death watch and drugstore beetles, weevils-snout beetles, longhorn beetles, and termites. The last insect, in contrast to the other insects, also eats wood when it is adult, the rest of insects only eat wood during their larval phase. The termites are very destructive and their behaviour differs from the rest, being harder to remove.

### 1.3.1 Wood protection

The wood protection is not always necessary as it depends on its natural durability and Class of Use. This classification is based on five degrees from 1 to 5, and it is based on its grade of exposition to weather agents, which deteriorate the material.

Some species do not need protection treatments for some Classes of Use, due to their natural durability. In case of protection treatments, they have to be suitable for the material considering its impregnability, which at the same time depends on the type of wood, softwood or hardwood, and specimen.

In the Basque Country (Spain), the most common species are: Radiata-pine (*Pinus Radiata, D.Don.*), Douglas-fir (*Pseudotsuga Menziesii, Mirbel*), Oak-tree (*Quercus Robur, L.*), Lawson-cypress (*Chamaecyparis Lawsoniana, A. Murray*), and larch-tree (Larix Decidua, Mil.).

If the kind of specie is relevant in order to know the absorption capacity of the protection treatment, the permeability to impregnation also differs depending on the specimen, heartwood and sapwood, being the sapwood the most impregnable part [20]. In contrast, the heartwood is the part that has the most natural durability, which means that it has more resistance to deterioration agents, biotic and abiotic.

An important factor to take into account when a product is applied to wood is that its mechanical strength is reduced in major or minor quantity depending on if it is superficial or deep protection and the type of product or substance, such as CCA (chromated copper arsenate), ACQ (alkaline copper quaternary), Tanalith-E, Wolmanit CX-8 or CDDC (copper dimethyldithocarbamate) [21].

The chemical products used to protect wood from exterior climate and increase its durability cutting down its degradation, alter the physical properties of the material which varies its mechanical strength [22].

In addition to the most common chemical treatments, such as copper components, they are in study others based on nanoparticles of $TiO_2$ (titanium dioxide) and clay nanoparticles, with optimal results in terms of wood ageing giving rise to nanomaterials as future application in the field of wood protectors [23].

Another alternative to conventional chemical treatments to protect wood is the heat-treatment. This method consists on introduce wood into a heat chamber to 190 and 210 °C temperature, depending on wood specie and grade of exposition to weather. This method extracts the wood resin which is the most vulnerable part of this material against the majority of biotic agents. However, there is a variation of the physical properties of the material such as the rigidity, hardness and superficial roughness, after this process [24].

The variation of the wood physical properties is also presented during the natural drying process when it is exposed to climate. Both heat and mass transfer deform materials and produce tensions in the material [25]. In case of the wood heat-treatment, as well as in the case of natural drying, exothermic reactions appear and depending on the distribution of the wood products these reactions are not distribute in the same way. This calculus is complex and has been presented in various studies [26], trying to simulate the real behavior of each piece of wood when they dry.

If during the dry process of wood deformations and tensions appear, during the wood life cycle, when this material is exposed to climate, it also suffers constant dry and wet processes due to weather agents, such as rain, wind and sun. In case of the design of wooden façades, there are different designs and compositions taking into account that this material is curved and twisted after these processes, overall in locations such as Bilbao where rainy days are frequent. That is, it is important to stablish a design which considers the swelling and contraction movements of this material [27, 28].

Apart from that, the rain water and solar radiation, which are abiotic agents, also accelerate the deterioration and ageing of wood. If both weather effects are harmful when they take place in short periods of time, solar radiation mainly alters the most superficial exposed part of the material, and it is revealed by means of colour loss, turning it into grey.

This effect supposes a larger perception of deterioration, which can be attenuated with stabilizers that protect wood slowing down the loss of colour and brightness [29].

They exist some treatments which are applicable to heat-treated wood, such as acrylic paints made of polyurethane with extracts of bark and lignin stabilizers, this last substance gives to wood its characteristic colour avoiding its degradation due to abiotic agents, although its efficiency also depends on the wood species [30].

In case of the north hemisphere, the façades which are oriented to the south are more exposed to solar radiation. Because of that, the loss of colour in wooden façades is higher when these are placed facing the south.

If the behaviour of façades made of timber frame and intermediate insulation are analysed, it is known that the northern façades are more prone to suffer harms, which are derived to the condensations produced due to the thermal jump between the interior and the exterior. In case of enclosures orientated to south, this effect takes place in less measure as it is more exposed to solar radiation, that is, the superficial cladding absorbs the direct solar radiation and it is released in form of heat. On the other hand, the façades which are facing the north are more susceptible to suffer condensations. Due to that, materials with high inertia and thermal mass are recommended, as they absorb heat and release it gradually when the exterior temperature goes down, avoiding a high heat jump in specific points. In case of the current solutions, which are highly insulated and made of various material layers, this phenomenon has to be studied in order to avoid interstitial condensations [31].

## 1.4 Sustainable construction

From the publication of the *Brundtland Report* in 1987 by the World Commission on Environment and Development, Our Common Future, it is defined the Sustainable Development as that which satisfies the current needs of people without compromising the ability of future generations to meet theirs.

The Gothenburg European Council, in June of 2001, agreed to stablish a European strategy toward the sustainable development, and invited to the European Members (EEMM) to collaborate in stablish their own strategies under the principle that the success of any sustainable development strategy depends on the daily decisions that millions of people make in terms of consumption, production, employment and transportation.

As it was introduced in the previous section, the sustainability could be defined as the ability to develop without compromising the future in terms of resources consumption, environment damage or economic and social impacts. In Figure 1.6, there are represented these aspects, in relation with the building field.

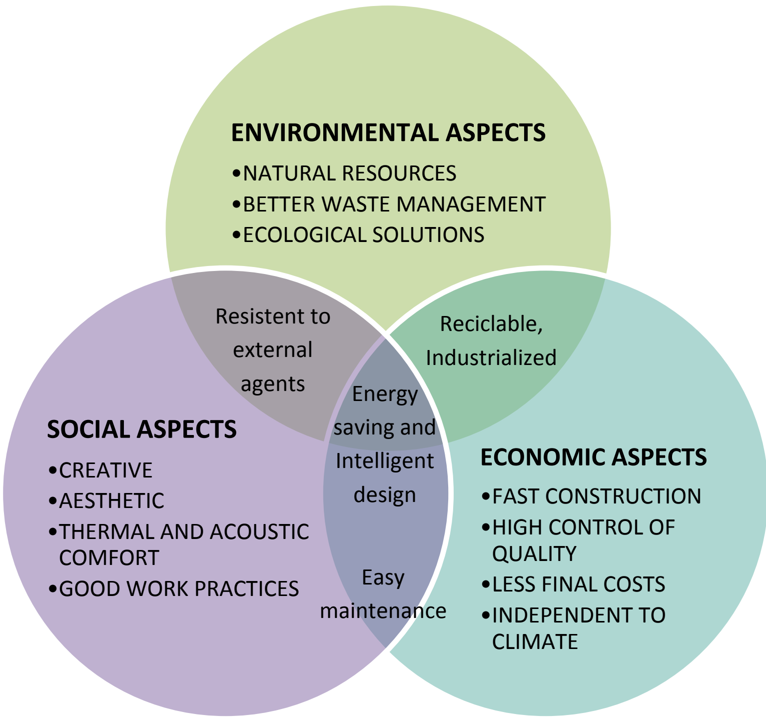



**Figure 1.6. Aspects of sustainable construction**

The *Horizon 2020 Energy Challenge* program is part of the Europe strategy. It is a financial tool to enhance the research and innovation to develop new technologies more sustainable and promote the economy and competitiveness of companies in this field.

On one hand, there are the policies related to building energy savings, such as the *Energy Performance of Buildings Directive* (EPBD). This directive is focused on the reduction of the energy consumption in building to reduce the *Greenhouse Gas* (GHG), which is derived from energy production inside the buildings to satisfy the user needs. Due to that, the European façades are getting more and more insulated, with higher insulation thickness.

On the other hand, there are the norms that limit the emission of *Volatic Organic Compounds* (VOCs) to the atmosphere in some products, such as wood protectors. In this case, there are innovation projects working to reach the objectives of *Horizon 2020 Energy Challenge* based on the use of more eco-efficient construction products [32].

The European guidelines are getting more and more restrictive, and bring the development of less emissive products. In case of coating protectors, the respect to environment and the necessity of fabricate less harmful products promote the apparition of new protectors with less toxicity [33], such as natural waxes, oil base paints and the heat-treatment previously mentioned, which is also defined as low emissive protectors.

The promotion of low emissive products whose production and transformation phase imply less embodied energy consumption is also manifested, as an extension of the sustainable development. However, if we are focused on the production of the materials and its energy consumption, such as in the case of wood treatments, it is not easy to catalogue them as low emissive material, being necessary comparative evaluations between products [34].

The European Union has agreed energy objectives to reduce the Greenhouse Gas (GHG), which are responsible of the climate change, beyond 2020, by means of the increment of renewables and energy efficiency. Reaching these objectives allows the European Members (EEMM) to be more competitive and reach more energy supply safety.

Nowadays, sustainable development supposes a key in all activities that are developed by human. In case of *Sustainable Building*, it appears a list of terms that suit in more or less amount detailed aspects to improve the building sustainability.

In Table 1.5, they are numerated some of these terms, which are the most used, such as *Nearly* and *Zero Energy Building*, which are focused on the equilibrium between the “clean energy” generated, which is obtained by renewables, and the energy consumption during the life cycle of buildings [35]. These terms were defined by the *Energy Performance of Building Directive*, EPBD, toward a specification according future lines and needs [36].

| Terminology | Aims and characteristics |
|---|---|
| *Solar architecture* | Maximize the use of solar energy, through active and passive systems. |
| *Active solar architecture* | Use of solar energy through active collection systems (such as photovoltaic and thermal panels) |
| *Passive solar architecture* | Use of passive solar energy in the most efficient way |
| *Passive House* | Maximize heat gains and minimize winter losses; In summer in reverse |
| *Passivhaus* | Housing that maintains comfort conditions without using conventional systems of heating and cooling |
| *Passivhaus Standard* | Establishment of heating and cooling limitation to promote *Passivhaus* |
| *Bioclimatic architecture* | Architectural design that seeks the most suitable geometry, orientation and construction to adapt to the climatic conditions of the environment, in search of interior comfort, energy efficiency and reduction of environmental impact |
| *Efficient architecture* | Reduction of energy and water consumption without sacrificing user comfort |
| *Ecological architecture* | Search of the environmental impact reduction of the building considering the whole life cycle |
| *Eco-efficient architecture* | Construction based on reduction of resource consumption and use of non-hazardous products |
| *Bio-construction* | Construction with low environmental impact materials, recycled, recyclable, and easy to extract |
| *Self-sufficient construction* | Construction that interacts with the environment to self-sustain |
| *Low-energy building* | Construction of low energy consumption, more efficient facilities |
| *Sustainable architecture* | Architecture that meets the needs of present generations without compromising those of the future |
| *Zero emission building* | Building whose CO2 emissions balance is equal to zero, and therefore is able to cover all its energy needs without emitting Greenhouse Gas (GHG) |
| *Green construction* | It uses in an integral way limited resources to cause the least possible damage to the environment, saving energy and natural resources, and guaranteeing the safety and comfort of the user |
| *Zero Energy Building /* *Net-Zero energy Building* | Constructions with a high level of energy efficiency, where the annual energy consumption is equal to or less than that produced in the building from renewable sources. According to *Energy Performance of Buildings Directive* (EPBD) |
| *Zero Stand Alone Building* | Building without connecting to network (excluding support). Energy storage for night and winter supplies |
| *Plus Energy Building* | Positive buildings. The energy produced is greater than the consumed |

**Table 1.5. Terminology applied to sustainable buildings**

No wonder that they are appearing new methodologies to help to stablish improvement strategies in order to foreseen building energy behavior from the design phase. The parameters are defined depending on weather, localization and use, such as administrative, commercial, industrial or residential building, estimating their energy consumption [36] and costs [37, 38], in order to promote knowledge and measures to make easier the process toward the auto-consumption [39].

Inside the group of strategies, they stand out the programming and control of facilities and energy storage to take advantage of it during peaks of consumption, by means of advanced management systems that allow the use of renewables and their connection to the electric grid [40].

### 1.4.1 Characteristics of the environment

#### Collection of Climate data

As it was previously mentioned, the climate is one of the aspects to be analysed before the façade design. The need of satisfy the habitability conditions in the interior of buildings makes the façade to be more resistant and insulated. That is, besides protecting us from the outside it also keeps suitable comfort and health conditions.

There are some tools, such as Olgay and Givoni bioclimatic charts, which help us to understand the necessary requirements to reach the comfort inside buildings, taking into account exterior maximum and minimum temperature and humidity, in average.

Apart from these tools, others such as solar charts, cylindrical and stereographic, are also available. These ones allow realising a study based on the sun path and the obstacles that interferes in the direct incidence of solar radiation in the buildings and influences in the use of solar energy.

In Table 1.6, they are collected the climate data of Bilbao. In terms of region, Vizcaya presents mesothermic climate, with moderate temperatures and presence of rain throughout the year. Its proximity to the Atlantic Ocean makes lower temperature oscillations between day and night, as well as, summer and winter. On the other hand, the territory orography explains the prevalence of rainfalls during all the year.

| | **Altitud: 42 m; Latitud: 43° 17' 53'' N; Longitud: 2° 54' 21'' O** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **E** | **F** | **M** | **A** | **MY** | **J** | **JL** | **A** | **S** | **O** | **N** | **D** |
| $T_{MAX\_media}$ [ ºC] | 13 | 15 | 16 | 17 | 20 | 23 | 25 | 26 | 24 | 21 | 16 | 14 |
| $T_{MED}$ [ºC] | 9 | 9.8 | 10.8 | 11.9 | 15.1 | 17.6 | 20 | 20.3 | 18.8 | 15.8 | 12 | 10 |
| $T_{MIN\_media}$ [ºC] | 4.7 | 5.1 | 5.7 | 7.1 | 10.1 | 12.6 | 14.8 | 15.2 | 13.2 | 10.8 | 7.6 | 6 |
| $T_{MAX\_registrada}$ | 21 | 27 | 30 | 33 | 35 | 37 | 42 | 40 | 41 | 37 | 27 | 25 |
| $T_{MIN\_registrada}$ | -6 | -5 | -2 | - | 2 | 2 | 8 | 7 | 5 | -1 | -5 | -2 |
| Precip. [mm] | 126 | 97 | 94 | 124 | 90 | 64 | 62 | 82 | 74 | 121 | 141 | 116 |
| Precip. [Nº días] | 15 | 14 | 16 | 17 | 17 | 13 | 12 | 12 | 11 | 15 | 15 | 15 |
| $HR_{MAX}$ [%] | 80 | 79 | 83 | 84 | 86 | 89 | 90 | 92 | 88 | 83 | 81 | 79 |
| $HR_{MED}$ [%] | 72 | 70 | 70 | 71 | 71 | 72 | 73 | 74 | 73 | 73 | 74 | 73 |
| $HR_{MIN}$ [%] | 63 | 58 | 58 | 61 | 61 | 62 | 60 | 61 | 59 | 60 | 62 | 63 |
| $T_{MEDIA\_ROCIO}$ [ºC] | 3 | 3 | 5 | 6 | 9 | 12 | 15 | 15 | 13 | 10 | 7 | 5 |
| Rad.global.hor. [mj/m$^2$] | 140 | 207 | 326 | 417 | 501 | 544 | 545 | 480 | 377 | 245 | 151 | 117 |
| $Rad_{DIRECTA}$ [mj/m$^2$] | 255 | 305 | 416 | 442 | 499 | 540 | 563 | 526 | 467 | 347 | 251 | 218 |
| $Rad_{DIFUSA}$ [mj/m$^2$] | 59 | 85 | 118 | 161 | 191 | 201 | 189 | 162 | 128 | 94 | 66 | 52 |
| $Rad_{REFLEJADA}$ [mj/m$^2$] | 250 | 300 | 406 | 433 | 461 | 473 | 485 | 474 | 438 | 347 | 251 | 217 |
| Horas de sol/día | 9.9 | 11 | 12.5 | 14 | 15.3 | 15.9 | 15.6 | 14.4 | 12.9 | 12 | 10 | 9.6 |
| Horas de sol | 86 | 97 | 128 | 128 | 160 | 173 | 188 | 179 | 157 | 123 | 93 | 78 |
| Nº días nieve | 1 | 1 | - | - | - | - | - | - | - | - | - | - |
| Nº días con niebla | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 4 | 3 | 2 | 2 |
| Nº días despejados | 3 | 2 | 2 | 2 | 2 | 3 | 5 | 4 | 4 | 3 | 3 | 3 |
| Nº dias tmax>32ºC | - | - | - | - | 1 | 1 | 3 | 2 | 3 | - | - | - |
| Nº dias tmax<0ºC | 3 | 2 | 1 | - | - | - | - | - | - | - | 1 | 2 |
| Vel. viento m/s | 6 | 8 | 19 | 19 | 17 | 17 | 16 | 16 | 16 | 6 | 6 | 8 |
| Viento dominante | SEE | SEE | SSE | SSE | SEE | SSE | SSE | SSE | SSE | NOO | SEE | NOO |

**Table 1.6. Climate data from Bilbao**

Next, the previously mentioned bioclimatic charts are applied to Bilbao. By them, passive strategies are described as recommendations to reach the comfort in this placement.

### Olgyay bioclimatic chart

The bioclimatic chart of Olgyay, which is shown in Figure 1.7, represents the relative humidity in the axis of abscises and temperature in ordinates one, as the basic conditions that affect to sensitive temperature of the human body. Inside this chart, it is represented the *Comfort Zone*, where the human body requires less energy consumption to adapt itself to environment. The points that are below the *Comfort Zone*, can be enhance by means of solar radiation, direct or indirect.

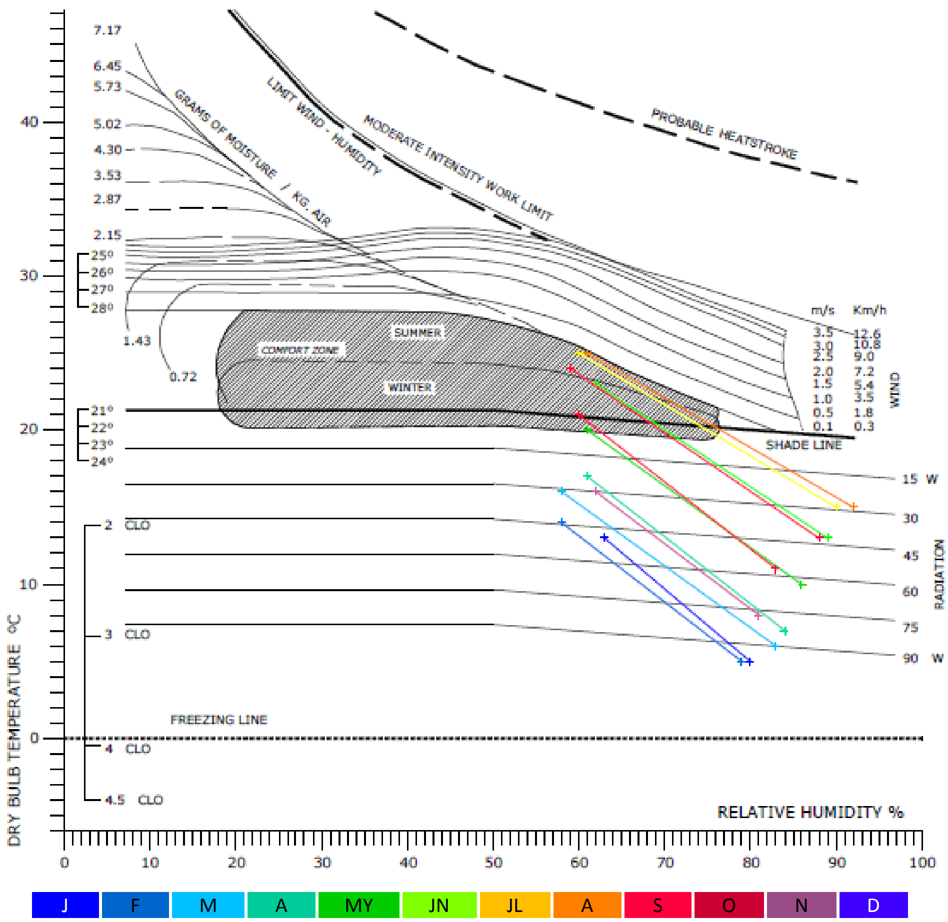



**Figure 1.7. Olgyay bioclimatic chart applied to Bilbao, from January (J) to December (D)**

The inferior limit of the *Comfort Zone*, which is 21.5 °C, stablishes the separation between places which needs solar radiation and those that need air movements to reach the *Comfort Zone.*

The points that are under the *Comfort Zone* would correspond to climate conditions where an excess of heat is presented. In this case, measures such as solar protectors or blinds, and the use of wind or mechanisms to produce air movements, could be adopted.

In this case, the chart is focused on the use of environmental resources to stablish passive strategies in terms of design, and place the building in the best way to adapt it to the environment. On the other hand, the Givoni bioclimatic chart, which is explained below, is orientated to adapt energy equipment to fulfill habitat needs inside the buildings.

### Givoni bioclimatic chart

The Givoni chart, which is shown in Figure 1.8, is a diagram in which the temperature is represented in the axis of abscises and in forms of curves the humidity values, as the basic conditions that affect to the sensitive temperature of the human body.

In this case, the chart distinguishes different zones, from 1 to 14, where are stablished different strategies in order to reach the thermal comfort. This study is representative in the first phase of the construction project, that is, the design phase, in order to detect critical aspects related to energy and foreseen needs before designing and simulating the building by energy simulation software.

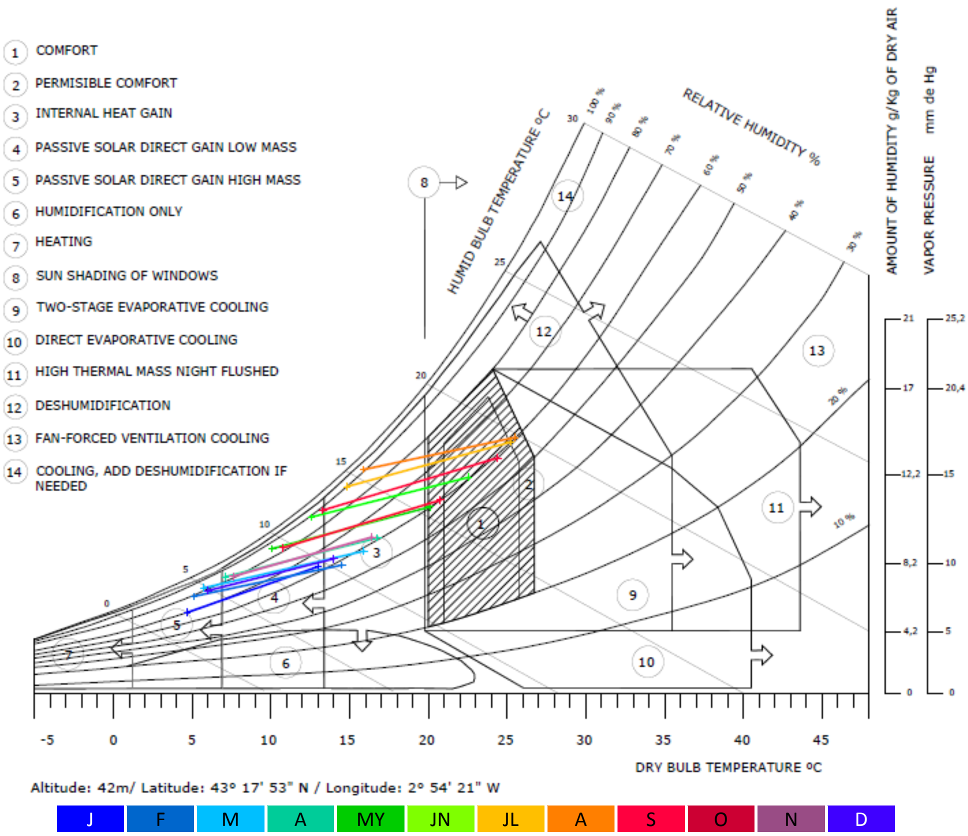



**Figure 1.8. Givoni bioclimatic chart applied to Bilbao, from January (J) to December (D)**

*"The best way to predict your future is to create it"*

Alan Key

1940

# CHAPTER 2
# Methodology

# 2 Methodology

Sustainability of wooden façades implies not only environmental assessment along its life cycle, but also costs optimization and social awareness. In Figure 2.1, there is represented the majority of parameters which influence sustainability development, that is, in order to achieve economic, social and environmental sustainability, previously described in section 1.4.

In this research, the main focus lies on the energy efficiency, as it influences the energy consumption of dwellings. In Spain, 30% of the energy consumption comes from construction sector. On the other hand, Wood is moreover locally abundant in the Basque Country, where more than 55% of the region is forested some of which on a sustainable basis [41]. At the same time, Radiata-pine production implies 90% of wood production in our territory. Due to this, the characterization of this specimen is assessed [42]. For this characterization, test box is built “ad-hoc”.

Apart from material properties, its geometry and design also interfere in the energy efficiency of façades. In this case, a bench of simulations are also performed in order to point this importance, not only in terms of design but also assembly and definition of material properties.

Wood is ecological material that is deteriorated along time because of biotic and abiotic agents. In this research, durability is also studied as it influences both aesthetical appearance, which takes part in the social awareness about the use of this material, and thermal properties.

When this material is exposed to climate, and depending on its natural durability, it can require the application of protector products. The most affected part of a wooden façade is the external cladding due to its direct exposure to climate. The thermal characterization of Radiata-pine when it is treated with this kind of products is also characterized. That is, the influence in the thermal behaviour of wood depending on its protection condition is also assessed by test box.


**Figure 2.1. Graphical abstract of the research**

After that, a global sustainability index to evaluate wooden façades is developed through MIVES methodology. This evaluation methodology implies the definition of criteria and indicators to evaluate façades sustainability. In this case, the indicators are; characterization of timber products, manufacturing and assembly, optimization of resources, impact control and waste management. The first one is related to the amount of product used that is environmental certificated. The second indicator is based on production companies, how many of them are environmental accredited and their proximity to the building in construction. The third one, it refers to the material origin, that is, its extraction site. In this case, its proximity to the consumption point is also evaluated. The fourth indicator is based on the class of use of the wood as depending on it the material can need protectors that release particles and gases into the air. The last indicator is related to the waste management such as separating waste by fractions. This methodology is applied to a case study.

Finally, a wooden façades catalogue is made. Through it, costs, carbon footprint and transmittance are analysed. In this case, the influence of both structure and cladding selection for the construction of wooden façades are compared.

## 2.1 Test box procedure

To determinate the thermal resistance of a system by the heat flow meter method, there are two main norms to apply for construction materials, depending on if the material has high or medium thermal resistance [43] and if the product is also dried or wet [44].

In order to apply the first norm, UNE-EN 12667:2002, the material has to have more than 0.5 $m^2·K/W$ of thermal resistance. However, for the other norm, UNE-EN 12664:2002, the thermal resistance has to exceed 0.1 $m^2K/W$, being the previous norm more recommended if the material exceeds 0.5 $m^2·K/W$.

Apart from characterise the material through norm, in this thesis an “ad-hoc” test box is built as an alternative method, which is shown in Figure 2.2, in order to analyse the thermal behaviour of material. The description of its procedure and equipment are presented in the next sections of this chapter. This box has its sides highly insulated, and the samples are easily placed inside through a small window. The sample dimensions were similar in size to the window: 100mm wide, 300mm long and 22mm thick.

Inside the box, an electric resistance is deposited to generate heat. The interior temperature is controlled by a thermostat which is placed on the outside.

**Figure 2.2. Test box photographs**

The temperature inside and outside the box, and the superficial temperature of the two exposed faces of the wood sample are registered by an acquisition data equipment. For that, four thermocouples are necessary for each point.

In this case, the heat percentage estimation going out through the wood sample is analysed. The insulation thermal resistance and the conductivity value of wood depending on its type and density according to the Regulation are known [19].

The heat loss by transmission ($Q_T$) throughout the box enclosure is calculated by the next expression:

$$Q_T = \mathrm{A} \cdot \mathrm{U} \cdot (T_i - T_e) \qquad \textbf{(2-1)}$$

*$Q_T$ : Total heat loss through the test box[W]*
*A : Area perpendicular to the heat flux [m²]*
*U : Thermal transmittance, as appendix E of DB HE 1 [W/(m²·°C)]*
*$T_i$ : Interior temperature [°C]*
*$T_e$: Exterior temperature [°C]*

Considering the unit as the correction factor, and assuming all the surfaces of the test box, the expression would be (2-4), which corresponds to the development of the expression (2-2) and (2-3).

$$Q_T = \sum Q = Q_w + Q_b \quad \textbf{(2-2)}$$

*$Q_T$ : Total thermal loss [W]*
*$Q_w$ : Thermal loss through the wood sample [W]*
*$Q_b$ : Thermal loss through the test box [W]*

$$Q_T = A_T \cdot U_T \cdot \Delta T = A_w \cdot U_w \cdot \Delta T + A_b \cdot U_b \cdot \Delta T \quad \textbf{(2-3)}$$

Where;

$$A_T \cdot U_T = A_w \cdot U_w + A_b \cdot U_b \quad \textbf{(2-4)}$$

*$Q_T$ : Total thermal loss [W]*
*$A_T$ : Total area [$m^2$]*
*$A_w$ : Area of the sample [$m^2$]*
*$A_b$ : Area of the box [$m^2$]*
*$U_T$ : Total thermal transmittance [$W/(m^2 \cdot °C)$]*
*$U_w$ : Transmittance of the wood sample[$W/(m^2 \cdot °C)$]*
*$U_b$ : Transmittance of the test box[$W/(m^2 \cdot °C)$]*

The area of the wood sample is 15,625 % of the box frontal area, and the rest of this side represents 84,375%. Taking into account those values the expression (2-5) is deduced.

$$U_T = 15{,}625 \cdot U_w + 84{,}275 \cdot U_b \quad \textbf{(2-5)}$$

*$U_T$ : Total thermal transmittance [$W/(m^2 \cdot °C)$]*
*$U_w$ : Transmittance of the wood sample[$W/(m^2 \cdot °C)$]*
*$U_b$ : Transmittance of the test box[$W/(m^2 \cdot °C)$]*

The test box is composed of four layers, three of them are made of insulation and the other is the wood box made of chipboard where the insulation is supported. The thermal resistance of each insulation layer is 2.50 $m^2$·°C/W. On the other hand, the thermal resistance of the wood box is 0.08 $m^2$·°C/W. The total resistance of the box, excluding the window where the sample is located, is 7.58 $m^2$°C/W. Continuing with the expression (2-6), the thermal transmittance the box is obtained ($U_c$), which is shown in the expression (2-7).

$$R_b = \frac{1}{U_b} \qquad \textbf{(2-6)}$$

*$R_b$ : Therma resistance of the test box[($m^2$·°C)/W]*
*$U_b$ : Box transmittance [W/($m^2$·°C)]*

$$U_T = 14{,}29 \cdot U_w + 85{,}71 \cdot 0{,}1318 \qquad \textbf{(2-7)}$$

*$U_T$ : Total transmittance [W/($m^2$·°C)]*
*$U_w$ : Wood sample transmittance [W/($m^2$·°C)]*

If the thermal conductivity of the wood sample is 0.13 W/$m^2$·°C, taking into account the UNE-EN ISO 10456 [18] for wood material with 500 kg/$m^3$ density, it is demonstrate that almost 90 % of heat goes out across it, as it is deduced by the expression (2-8) and whose result is shown in (2-9).

$$U_T = 84{,}4409 + 11{,}2971 = 95{,}7380\ [W/m^2 °C] \qquad \textbf{(2-8)}$$

Where;

$$Q_{\%m} = 88{,}2 \qquad \textbf{(2-9)}$$

*$U_T$ : Total thermal transmittance [W/($m^2$·°C)]*
*$Q_{\%m}$ : Percentage of heat transfer accross the wood sample [%]*

Considering the six sides of the test box, and taking into account that the sample is placed in the front side, the percentage of heat loss for each one is presented in Figure 2.3.

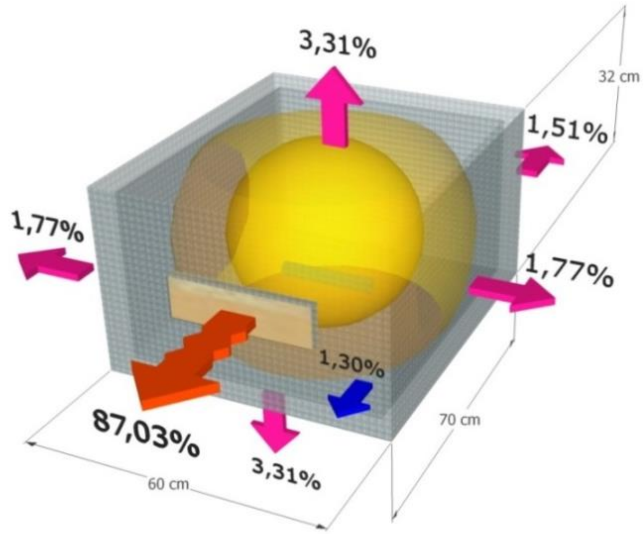



**Figure 2.3. Heat loss percentages**

If 88.33% of the generated heat inside the test box is dissipated through the front side, 1.30% corresponds to the energy transferred across the insulated plane, while 87.03% of heat goes out across the wood sample.

In this case, the superficial thermal resistance of the wall in contact with interior and exterior air, $R_{si}$ and $R_{se}$, has not been considered due to their variation depending on the heat flux direction.

If the interior and exterior superficial thermal resistances are analysed, the Basic Document of Energy saving (DB-HE) which belongs to the Spanish Building Technical Code (CTE) [45] stablishes different values which are constant and depend on the heat flux direction, as it is shown in Table 2.1.

| Envelope position and flux direction | $R_{si}$ | $R_{se}$ |
|---|---|---|
| Vertical envelopes or >60° inclination and horizontal flux | 0,04 | 0,13 |
| Horizontal envelopes or ≤60° inclination and ascendent flux (ceiling) | 0,04 | 0,10 |
| Horizontal envelopes and descendent flux (ground) | 0,04 | 0,17 |

**Table 2.1. Interior and exterior superficial thermal resistance ($R_{si}$, $R_{se}$) [$(m^2 \cdot °C)/W$]**

Taking into account the position of the box and its size, the exterior superficial thermal resistance for each side is represented in Figure 2.4. In this case, the superficial resistance of the upper horizontal plane of the box is the lowest. That means that the heat loss through this plane per square meters is slightly higher than through the others. On the other hand, the thermal resistance through the lower horizontal plane is the highest, which means that the heat loss in this plane per square meters is the lowest.

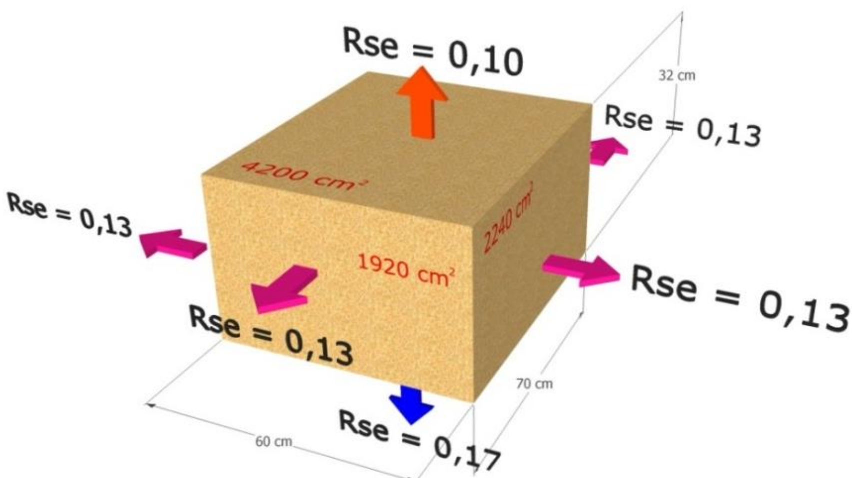



**Figure 2.4. Superficial thermal resistance from the exterior side**

If an average of the different exterior thermal resistances is calculated by the expression (2-10), the resulted resistance corresponds to 0.1325 (m$^2$·°C)/W, as it is demonstrated in (2-11).

$$R_{sem} = \frac{\sum(R_{se} \cdot A)}{\sum A} = \frac{R_{se1} \cdot A_v + R_{se2} \cdot A_{hu} + R_{se3} \cdot A_{hl}}{A_v + A_{hu} + A_{hl}} \quad \textbf{(2-10)}$$

$$R_{sem} = \frac{0{,}13 \cdot (1920 + 2240) \cdot 2 + 0{,}10 \cdot 4200 + 0{,}17 \cdot 4200}{(1920 + 2240 + 4200) \cdot 2} = 0{,}1325 \quad \textbf{(2-11)}$$

$R_{sem}$ *: Average of the exterior superficial thermal resistance [(m²·°C)/W]*
$R_{se}$ *: Exterior superficial thermal resistance [(m²·°C)/W]*
$R_{se1}$ *: Exterior superficial thermal resistance of vertical planes [(m²·°C)/W]*
$R_{se2}$*: Exterior superficial thermal resistance of upper planes [(m²·°C)/W]*
$R_{se3}$*: Exterior superficial thermal resistance of lower planes [(m²·°C)/W]*
$A$*: Area [cm²]*
$A_v$*: Vertical plane area [cm²]*
$A_{hu}$*: Upper horizontal plane area[cm²]*
$A_{hl}$*: Lower horizontal plane area[cm²]*

Due to the slightly difference of the average value and the superficial thermal resistance of the box front plane, where the sample is placed, which is 0.13 (m2·°C)/W, this resistance has not been taken into consideration in the previous estimation of heat loss percentage through each sides.

### 2.1.1 Equipment

In Table 2.2, it is presented the necessary equipment to realize the tests. As it is previously mentioned, a high insulated test box is built. The insulation is composed by three layers with 2.5 m$^2$·°C/W thermal resistance each one. In the front face, there is a window where the samples are placed. In this case, the window is 300 x 100 mm size, such as the size of the different samples. The sample to test is embedded in the window. The borders are sealed against thermal bridges.

Inside this chamber, there is a silicon resistance to generate heat. In order to control the temperature a thermostat is installed. Its accuracy is ±1°C and it is placed outside the test box while the temperature sensor keeps inside.

| Equipment | Technical specifications |
|---|---|
| Fine-wire thermocouples: RS 409-4908 (PTFE) | ▪ Type: K<br>▪ Class 1 (± 1.5 °C ± 0.25 °C)<br>▪ From -100 to 250 °C |
| Data acquisition equipment: Hottinger Baldwin Messtechnik (HBM) | ▪ Software MGC Plus: Catman Easy 3.1 |
| Proteccion wooden box (30x60x70 cm) | ▪ Chipboard 19 mm thickness (density < 1200 kg/$m^3$) |
| Thermal insulation | ▪ Multilayer blanket 7.5 $m^2$°C/W thermal resistance |
| Silicon flexible resistance | ▪ 90 W, 230 V |
| Digital thermostat: ELIWELL ID961 | ▪ Power supply: 230 V<br>▪ Power relay: 20 amp<br>▪ Temperature sensor NTC |





**Table 2.2. Technical specifications of test equipment**

For this test, four thermocouples are required to detect the temperatures $T_i$, $T_1$, $T_2$ and $T_e$, described bellow:

$T_i$: Temperature inside the box
$T_1$: Superficial temperature of the interior surface of the sample
$T_2$: Superficial temperature of the exterior surface of the sample
$T_e$: Temperature outside the box

The thermocouples are connected to data acquisition equipment where temperatures are registered along a period of time. Thereby, the temperature variation can be assessed.

The registered temperatures allow us to obtain the thermal conductivity of material, estimated by means of the convection expressions shown in section 3.2.2.1, and the heat flux expressions presented in the next section 2.1.2.

### 2.1.2 Obtaining the thermal conductivity

In order to obtain the conductivity value of the material through the test box method, the expression (2-12) of heat flux is assessed. The test is characterized by registering $T_i$, $T_1$, $T_2$ and $T_e$ temperatures by means of thermocouples. These temperatures were previously described in section 2.1.1.

In Figure 2.5 it is represented the heat transfer through a plane sample. As it can be seen, there is a superficial thermal resistance in both interior and exterior sides, $R_{si}$ and $R_{se}$, which varies the superficial temperature of the sample, $T_1$ and $T_2$. In this case, the superficial thermal resistance of each surface is the inverse of their convection coefficients.

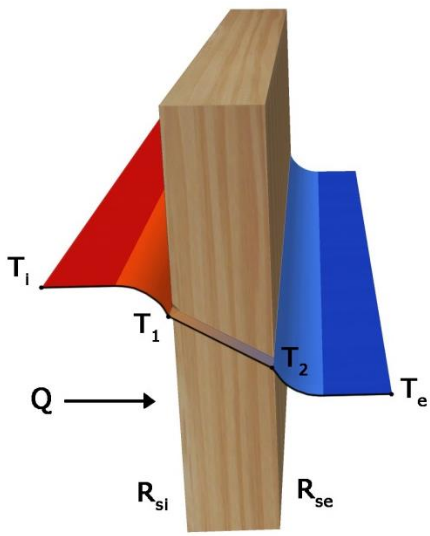



**Figure 2.5. Heat transfer through a plane sample**

The convection coefficients are obtained through the hypothesis explained in section 3.2.2.1. Taking into account this hypothesis, having registered $T_i$, $T_1$, $T_2$ and $T_e$ temperatures and considering the expression (2-12), the material conductivity is deduced.

$$q = U \cdot \Delta T = \frac{\Delta T}{R} \tag{2-12}$$

*q : Heat flux [W/m²]*
*U : Thermal transmittance [W/(m²·°C)]*
*ΔT : Gradient of temperature [°C]*
*R : Thermal resistance [(m²·°C)/W]*

It is known that the heat loss across the sample is the same as the total heat loss by transmission, as it is represented in the expression (2-13).

$$\begin{gathered} Q_T = Q_m \\ \mathrm{A} \cdot \mathrm{U}_T \cdot (T_i - T_e) = \mathrm{A} \cdot \mathrm{U}_m \cdot (T_1 - T_2) \end{gathered} \tag{2-13}$$

$Q_T$ *: Total heat loss by transmission [W]*
$Q_m$ *: Heat loss across the sample [W]*
*A : Area of the surface crossed by heat flux [m2]*
$U_T$ *: Total thermal transmittance [W/(m2·°C)]*
$U_m$ *: Thermal transmittance of the sample [W/(m2·°C)]*
$T_i$ *: Interior temperature [°C]*
$T_e$*: Exterior temperature [°C]*
$T_1$ *: Temperature on the inner face of the sample[°C]*
$T_2$*: Temperature on the outer face of the sample[°C]*

The thermal resistance of the wall is inversely proportional to its transmittance, which is represented in the expression (2-14).

$$R = \frac{1}{U} \tag{2-14}$$

*R : Thermal resistance [(m²·°C)/W]*
*U : Thermal transmittance [W/(m2·°C)]*

It is known that the total thermal resistance is the sum of every resistance of the different homogenous layers, which conforms the system, including the superficial resistances, $R_{se}$ and $R_{si}$, as it is represented in the expression (2-15).

$$R_T = \sum R = R_{se} + R_n + \cdots + R_{si} \qquad \textbf{(2-15)}$$

*$R_T$: Total thermal resistance [(m²·°C)/W]*
*$R_{se}$: Exterior superficial thermal resistance [(m²·°C)/W]*
*$R_n$: Thermal resistance of each homogenous layer [(m²·°C)/W]*
*$R_{si}$: Interior superficial thermal resistance [(m²·°C)/W]*

Having the registered temperatures by test and considering the laminar flux of exterior convection, the thermal resistance of the material can be obtained. At the same time, if the sample thickness is known, its thermal conductivity is also deduced by means of the expression (2-16).

$$\lambda = \frac{e}{R_m} \qquad \textbf{(2-16)}$$

*$\lambda$: Thermal conductivity of the material [W/ (m K)]*
*$e$: Thickness of the homogenous sample [m]*
*$R_m$: Thermal resistance of the material[(m²·°C)/W]*

*“Genius is 1% talent and 99% hard work”*

Albert Einstein

1879-1909

# CHAPTER 3
# Characterization

# 3 Thermal characterization of Radiata-pine

Wood is natural material and traditionally widely used for great variety of construction applications, not only due to its mechanical properties, but also because of its easy-to-work property. Wood market is growing up because it is easy to transport, transform and installed in construction works, and also because of its sustainability as raw material. For those reasons, wood is becoming one of the most influential materials in order to mitigate the greenhouse gas [46-48].

It is also known that it is environmental friendly material, as it is ecological and renewable. In fact, in the construction field it is demonstrated that wood is low carbon material, not only as a raw material but also in terms of wood products which requires industrial processes [49-51].

There is also a tendency towards green building considering wood as proper material [52]. Although its conductivity is higher than insulation materials, it has more thermal resistance than other construction products, like bricks or concrete, used in structure, façade or interior walls. Because of that, it is common to build wood houses in order to promote both ecological products and energy savings.

When efficiency in construction is analysed, it is necessary to characterise the thermal resistance of materials in order to promote building energy savings in their use phase. The R-value (thermal resistance) of wood has been tested in some studies in order to analyse its thermal behaviour when it is exposed to climate [53, 54]. The thermal resistance value depends on the wood natural properties, specimen and density. The density is difficult to analyse as it is hygroscopic and its inner humidity varies. Because of that, the normative establish the temperature and relative humidity test parameters in order to estimate a suitable value.

The Building Technical Code (CTE), based on Spanish normative, distinguishes between softwood and hardwood, but it does not specify which the specimen [19]. It also establishes the conductivity value of wood depending on its density, when this is balanced at twenty Celsius degrees and sixty five percent of relative humidity, including the water hygroscopic mass.

When wood is exposed to environment, it is common to use treated wood to enhance its durability because it is cheaper than more durable wood and the results are similar. That is, in order to break down its deterioration. There are two types of deterioration promoters: biotic and abiotic agents.

The abiotic agents are the climate ones, these affect to all material exposed to the environment: rain, wind and sun. Wood is hygroscopic material and when it rains it absorbers humidity. When this happens wood swells and then, when the atmosphere becomes dry, it retracts cracks appear. On the other hand, there are the biotic ones, which are fungus and larval cycle insects. Those eat the material and break down wood physical and mechanical properties.

Wood protection is not always necessary as it depends on wood natural durability and the use class, that is, its exposition degree to the exterior. For example, wood in façades or exterior flooring usually require preservative products. However, depending on wood impregnability it is necessary to use some specific treatments. The impregnability is directly linked not only to wood specie, but also to the part of the tree; heartwood or sapwood.

The heartwood is the oldest part of the log, where wood density is higher. Because of that, it has less pores and its absorption is lower. The sapwood, in contrast, is the youngest part of the log and its absorption is higher, which means that this part is more impregnable [20]. However, the heartwood has more natural durability, so it has less dependency to preservatives. In terms of mechanical resistance, the lower is its density, the lower its strength, so the heartwood is the hardest part.

It is also known that preservatives and heat-treatment can, in some cases, reduce the wood strength. That depends on the type of treatment; CCA (chromated copper arsenate), ACQ (alkaline copper quaternary), Tanalith-E, Wolmanit CX-8 o CDDC (copper dimethyldithocarbamate) [21].

Chemical products, which are used to protect and enhance the durability of exposed wood, alter its morphology and making its physical and mechanical characteristics vary [22].

Apart from the more common chemical preservatives, such as copper composed ones, there are others in study based on $TiO_2$ (titanium dioxide) nanoparticles and clay nanoparticles, both with optimal results against ageing. This opens a path towards the nanomaterial as future application in wood preservatives field [23].

Another alternative to protect wood is the thermal treatment. That method consists in introducing the wood into an airtight chamber at 190 and 210ºC, depending on the wood specie and the place where it will be exposed, that is, its class use mentioned previously.

The effectiveness of this treatment derives from the extraction of the wood resin. In this way, wood is protected against biotic agents that feed on this substance. However, it has to be taken into account the variation of the physical wood properties, such as strength, hardness and superficial roughness, after treatment [24].

In the Basque country, the most common species are: Radiata pine (Pinus Radiata, D.Don.), Oregon pine (Pseudotsuga Menziesii, Mirbel), European oak (Quercus Robur, L.), Lawson cypress (Chamaecyparis Lawsoniana, A. Murray), and larch tree (Larix Decidua, Mil.).

In this territory, more than 70% of forests are Government property, and the main production is related with *Radiata Pine* [42]. Because of that, this specie is chosen to characterize. In this case the wood is characterized with and without preservatives.

## 3.1 Introduction to heat transfer

Heat transfer can be presented as three modes: by means of conduction, convection and radiation.

Physically, the convection process is linked to the conduction process, as it is related to the contact of the material surface and the air. In both cases, the Fourier law is applied. However, in the convection phenomenon the fluid mechanical role has to be taken into account in order to estimate the gradient of temperature between the material surface and the interior environment, getting to know the thermal resistance of the superficial air layer.

In case of the radiation phenomenon, the heat transfer implies a different physical mechanism, where electromagnetic energy propagation takes place. For the study of this mode of heat transfer, the *black body* concept is introduced as ideal radiator. This is characterised for radiating the energy proportional to its absolute temperature elevated to forth power [55].

In order to apply the heat transfer science to practical situations, it is essential to have knowledge of the three modes: conduction, convection and radiation. In Figure 3.1, there are represented the different phenomena.

It is easy to imagine different cases where these phenomena take place. As an example, the Figure 3.2 is shown. In this case, a double enclosure is presented as a ventilated façade, which is based on external sun-blinds and an interior glass.

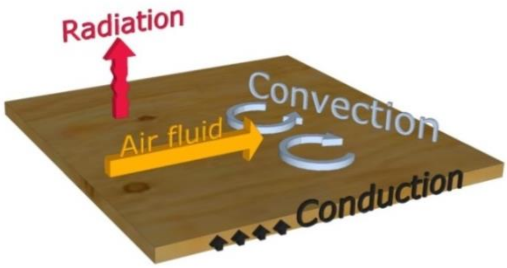



**Figure 3.1. Combinations of heat transfer in a plane**

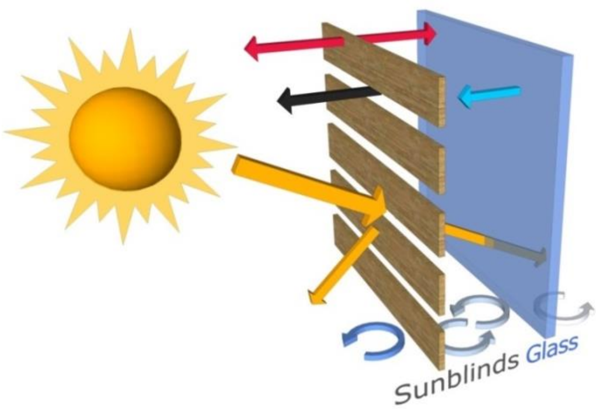



**Figure 3.2. Heat transfer through a ventilated façade**

In this research, the thermal properties of wood cladding are assessed. In this case, the thermal conductivity property of the material is the most relevant as the Regulation, the Spanish Technical Code (CTE) [45, 56], stablishes the transmittance limit value depending on the climate zone. This zone is defined for each localization by a letter (A B, C, D, E and α) and a number (I, II, III, IV, V). The letter corresponds to the severity of the temperatures from the hottest regions (A) to the coldest (E), while "α" represents a special case for Canarias as the climate in this region, subtropical oceanic, highly differs from the rest of the country. On the other hand, the number defines the degree of solar radiation, from the regions more radiative (V) to the least one (I). Figure 3.3 represents this definition.

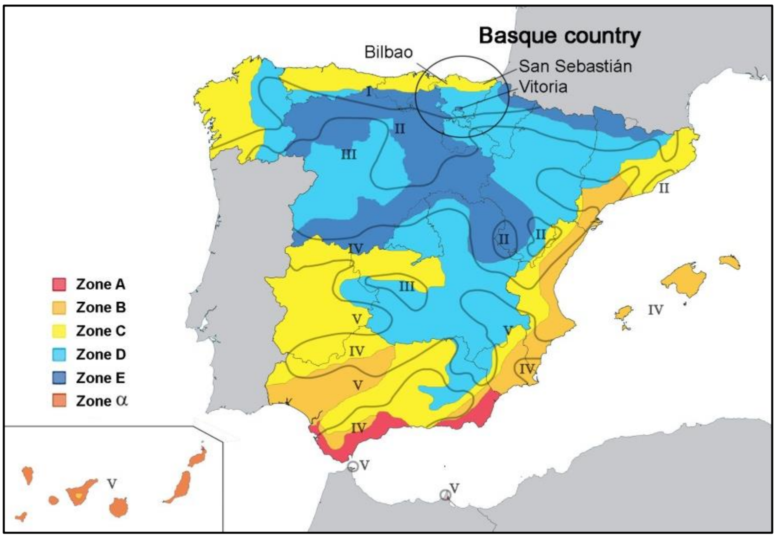



**Figure 3.3. CTE climate zones in Spain**

The Basque country, situated in northern Spain, has two main climate zones (C1 and D1). Consequently, winter temperatures differ according to the location and are lower in Vitoria, which is 512m above sea level and 65km away from the coast, compared with Bilbao, which is 10km from the coast, and San Sebastian, which is at sea level. While in Bilbao and San Sebastian the transmittance limit established by regulation is between 0.73 and 0.66 W/(m$^2$·°C), in Vitoria the value goes down to 0.57 W/(m$^2$·°C), which means that the cost of energy refurbishment increases in colder zones.

In order to estimate the transmittance, both the convection coefficients and the conductivity of the different layers that compound a façade will be necessary. In this case, the characterization of Radiata-pine is realized, as one of our aims is get to know the thermal behaviour of this kind of wood applied to the external cladding of a multilayer façade located in our territory.

## 3.2 Radiata-pine conductivity

If the conductivity values of the standard UNE-EN ISO 10456:2012 are taken, the thermal conductivity of wood such as Radiata-pine, which has between 450 and 700 kg/m$^3$ density, would be between 0.12 and 0.18 W/(m·K) [18], as it was previously presented in section 1.2.2.

On the other hand, if the Construction Elements Catalogue of the CTE is consulted [19], the conductivity values differ. In this case, it considers 0,15 y 0,23 [W/(m·K)] conductivity for conifer wood between 450 y 700 kg/m$^3$ density, as it was previously shown in Table 1.4.

In case of Radiata-pine, the material collected in our territory normally has less than 580 kg/m$^3$ density, which means that its conductivity value is around the interval mentioned. If a wood sample with 2 cm thickness and 610 kg/m$^3$ density is considered, its conductivity would be between 0.16 and 0.11 m$^2$K/W according to UNE-EN ISO 10456:2012, therefore, this product would have between low and medium thermal resistance.

In this research, the influence of protection treatments in wood conductivity is assessed, as this kind of wood applied to external enclosures and exposed to climate have to be protected against biotic agents, as it was mentioned in section 1.3, Chapter 1.

To study the Radiata-pine conductivity three types of sample are tested; natural wood, protected wood with chemical substances and heat-treated wood. In this case, the most common treatments in our territory were selected. The first one is a chemical treatment compounded with copper-HDO and Boro, chromium and arsenic free, similar to WOLMANIT CX-8 product [23, 33, 57]. The second one is heat-treated wood; in this case wood is heated with high temperature (210 °C) and water vapour. Both of protection treatments gives to Radiata-pine the required durability for external exposed façades made of this type of wood.

In case of wood protection, the Spanish Building Technical Code (CTE), by means of the document DB-SE-M [58], classifies the wooden construction products depending on their *Class of Use* (CU), whose description are presented in Table 3.1. In this case, wood samples for external cladding are analysed. It is very common to separate the inferior part of wooden façades from ground, in order to prevent humidity and the absorption of water by capillarity. Due to that, this material is classified as CU 3.2.

| CU | Location | Humidity | Example |
|---|---|---|---|
| CU 1 | Protected against exterior climate and no exposed to humidity source. | < 20% | Interior rooms without humidity source near |
| CU 2 | Protected against exterior climate and occasionally exposed to humidity source. | Occasionally > 20% | Interior rooms near to humidty sources (ceiling of a swimming pool, etc.) |
| CU 3.1 | Outdoor, without contact with ground and protected | Occasionally >20% | Outdoor beam with copings or sacrifice pieces to protect the exposed heads |
| CU 3.2 | Outdoor, without contact with ground or fresh water | Frequency > 20% | Unprotected pieces in uppper faces or heads, subject to splashing rain and snow accumulations |
| CU 4 | In contact with ground or fresh water | Permanent > 20% | Construction in fresh water. Pilars in direct contact with ground |
| CU 5 | In contact with salad water | > 20% | Construction in salat water |

**Table 3.1. Class of use to wooden elements**

The Regulation, CTE, also stablishes the protection requirements according to the *Class of Use*. Mainly, there are three types of protection: Superficial, medium and deep. These requirements are shown in Table 3.2.

The natural wood samples have between 560 and 580 kg/m$^3$ density, the samples treated with chemical substances between 510 and 530 kg/m$^3$ density, and the samples protected by heat-treatment 490 and 510 kg/m$^3$.

<table>
<tr><th>CU</th><th>Protection</th><th>Penetration of product</th><th>Product</th><th>Treatment</th><th>CP</th></tr>
<tr><td>CU 1-2</td><td>Superficial</td><td>Without specific requirements – Treat all faces</td><td>Organic<br>Hidrosoluble salts</td><td>Varnishing<br>Pulverization<br>Inmersion</td><td>NP1</td></tr>
<tr><td>CU 3.1</td><td>Medium</td><td>At least 3 mm in sapwood of all faces</td><td>Organic<br>Hidrosoluble salts<br>Prod. Double vacuum</td><td>Varnishing<br>Inmersion<br>Autoclave</td><td>NP2</td></tr>
<tr><td>CU 3.2</td><td>Medium</td><td>At least 3 mm in sapwood of all faces</td><td>Organic<br>Hidrosoluble salts<br>Prod. Double vacuum</td><td>Varnishing<br>Inmersion<br>Autoclave</td><td>NP3</td></tr>
<tr><td rowspan="2">CU 4</td><td rowspan="2">Deep</td><td>At least 25 mm in all faces.</td><td rowspan="2">Hidrosoluble salts</td><td rowspan="2">Autoclave</td><td>NP4</td></tr>
<tr><td>Total penetration in sapwood</td><td>NP5</td></tr>
<tr><td>CU 5</td><td>Deep</td><td>Total penetration in sapwood and at least 6mm in exposed heartwood</td><td>Hidrosoluble salts</td><td>Autoclave</td><td>NP6</td></tr>
</table>

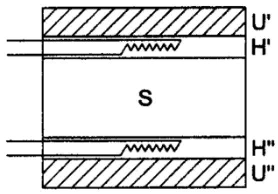
**Table 3.2. Protection requirements and penetration class (CP)**

In the next sections, Radiata-pine is thermally characterized by two different methods. The first one is based on UNE-EN 12664 standard [44]. The second one is based on the test box procedure, previously described in Chapter 2, which corresponds to an alternative method to obtain thermal the material thermal conductivity, based on heat transfer by convection instead of conduction.

### 3.2.1 Thermal characterization of Radiata-pine by conduction

In order to analyse the thermal conductivity of material, UNE-EN 12664 norm is followed [44]. In all cases, the samples were previously conditioned to 23°C temperature and 50% relative humidity in a climate chamber.

In this case, the European norm stablishes a minimum of three samples of each type, in order to obtain results closer to reality. In Figure 3.4, they are shown the heat and cooler units used for tests, as well as a diagram. In this case, the system is symmetric and simple, which means that an only sample is required for each test. Both heater and cooler have heat flux measurements in order to estimate the material conductivity. Table 3.3 represents the technical specifications of this equipment.


U', U'' : Heater and cooler units
H', H'' : Heat flux measurers

**Figure 3.4. λ-Meter EP-500, thermal conductivity measure equipment**

| Technical specifications | |
|---|---|
| Test temperature | 10 to 40 °C |
| Gradient of temperature | 5 to 15 K |
| Material thickness | 10 to 200 mm |
| Thermal conductivity | 3 to 500 mW/m·K |
| Thermal resistance | 0,125 to 5 $m^2$·K/W |
| Accuracy | < 1% |
| Reproducibility | < 0.5% |
| Software | EP500-Control Program |

**Table 3.3. Technical Specifications of λ-Meter EP-500 equipment**

In order to stablish the conductivity linear function depending on sample temperature, a bench of tests with 10, 25 and 40°C of sample temperature are carried out by this method. For the gradient of temperature, it is stablished 15 °C temperature between material surfaces. The results are exposed in Table 3.4.

| | ΔT [ºC] | T [°C] | λ [W/(m·K)] | | e [m] |
|---|---|---|---|---|---|
| **Natural *554.7 kg/m³** | 15 | 10 | 0.1294 | 0.1342 | 0.0238 |
| | | 25 | 0.1331 | | 0.0238 |
| | | 40 | 0.1400 | | 0.0238 |
| **Chemical treated *513.4 kg/m³** | 15 | 10 | 0.1279 | 0.1307 | 0.0238 |
| | | 25 | 0.1304 | | 0.0238 |
| | | 40 | 0.1338 | | 0.0238 |
| **heat-treated *502.5 kg/m³** | 15 | 10 | 0.1142 | 0.1158 | 0.0202 |
| | | 25 | 0.1152 | | 0.0202 |
| | | 40 | 0.1181 | | 0.0202 |

*Apparent volume mass

**Table 3.4. Conductivity results by UNE-EN 12664**

However, if these tests are realized changing the gradient of temperature from 15 to 10 and 5 °C, the conductivity differs following this procedure. As it can be seen in Table 3.5, in all cases, the minimum thermal conductivity for each sample (natural, chemical treated and heat-treated Radiata-pine) is registered when material has 10 °C temperature gradient between surfaces. The less is the material temperature the minor is its thermal conductivity. That is, both gradient and material temperature influences their thermal behaviour. These measures were obtained by constant heat flux.

| | Natural | | | Chemical treated | | | Heat-treated | | |
|---|---|---|---|---|---|---|---|---|---|
| T [°C] | $\lambda_5$ | $\lambda_{10}$ | $\lambda_{15}$ | $\lambda_5$ | $\lambda_{10}$ | $\lambda_{15}$ | $\lambda_5$ | $\lambda_{10}$ | $\lambda_{15}$ |
| 10 | 0.1214 | 0.1201 | 0.1294 | 0.1199 | 0.1183 | 0.1279 | 0.1057 | 0.1040 | 0.1142 |
| 25 | 0.1238 | 0.1239 | 0.1331 | 0.1211 | 0.1217 | 0.1304 | 0.1069 | 0.1051 | 0.1152 |
| 40 | 0.1299 | 0.1305 | 0.1400 | 0.1260 | 0.1262 | 0.1338 | 0.1100 | 0.1083 | 0.1181 |
| Average | 0.1248 | 0.1230 | 0.1346 | 0.1224 | 0.1224 | 0.1304 | 0.1062 | 0.1045 | 0.1158 |
| | 0.1275 | | | 0.1250 | | | 0.1088 | | |

**Table 3.5. Thermal conductivity of each sample, gradient 10 and 15°C ($\lambda_{10}$, $\lambda_{15}$)**

On the other hand, the highest values of conductivity are detected when both material temperature and gradient difference of temperature between surfaces are the highest. However, this difference can come of condensation on the hottest surface of the sample.

### 3.2.2 Thermal characterization of Radiata-pine by convection: Test box

In this section, the conductivity of natural (1), chemical treated (2) and heat-treated (3) Radiata-pine is obtained by test box procedure, described in Chapter 2. In this case, both convection phenomena and material properties are analysed through the data registration of both air and superficial temperatures inside and outside the test box.

The aim of this characterization is not only getting to know the conductivity of Radiata pine depending on its condition, treated or natural, but also understand its thermal behaviour in relation with its contact with air, as in the previous characterization convection does not take place.

The tests are realized by means of the test box previously described in section 2.1. In this case, the inner air is heated until reach a controlled temperature. On the other hand, the exterior air temperature keeps constant, which is the temperature inside the laboratory.

Different controlled temperatures inside the box are considered in order to analyse the material conductivity depending on the gradient of temperature. In this case, 40, 36, 32 and 28 °C controlled temperature tests are realized. In order to distinguish them, they are named as test “a”, “b”, “c”, and “d” respectively. The temperature of the laboratory is 22 °C in all cases.

By means of the registration of the superficial temperatures in both faces of the sample and the air temperature inside and outside the test box, it is able to obtain the interior and exterior superficial thermal resistance and material conductivity.

In terms of Regulation, the Spanish Building Technical Code (CTE), stablishes the interior and exterior superficial thermal resistance such as 0.04 ($m^2$·°C)/W for the exterior face and 0.13 ($m^2$·°C)/W for the interior face of façades. Those values are estimated in relation to standard environmental conditions [45].

In this study, the test box is located into a big room where there is no humidity variability and air movement. Because of that, the superficial resistance has to be different in comparison to the value considered by CTE, as the norm takes an average value considering real cases. Due to that, the exterior convection coefficient in the tests is different. In case of interior convection coefficient it also differs, as the heater inside the box makes air to move in different directions close to the enclosure.

Although in this research mass transfer it is not assessed, a difference of relative humidity between the interior of the box and the exterior takes place. In this case, the exterior values of humidity along tests were between 70 and 73%. When the interior temperature is heated to reach a specific grade of temperature, the relative humidity goes down. The resulted relative humidity inside the test box depends on the relative humidity and temperature outside the test box and the interior temperature. That is, for the test “a” the interior humidity is estimated between 25.29 and 26.37 %, for the test “b” this is between 31.24 and 32.59, for the test “c” this is between 40.61 and 39.94%, and for the last test “d” this is between 51.05 and 48.96%. These tests (a, b, c, d) correspond to 40, 36, 32 and 28 °C interior temperature respectively, as it was previously mentioned. In this case, it is considered that the test box, as a whole, has high resistance to water vapour diffusion.

#### 3.2.2.1 Natural convection coefficient

It is considered that natural convection of fluid takes place when on the surface of a plate; in this case the external face of the wood sample, the fluid movement is produced due to natural media (flotation) in which there are no other external forces, as it can be seen in Figure 3.5. In this case, the fluid velocity is considered lower than 1m/s.

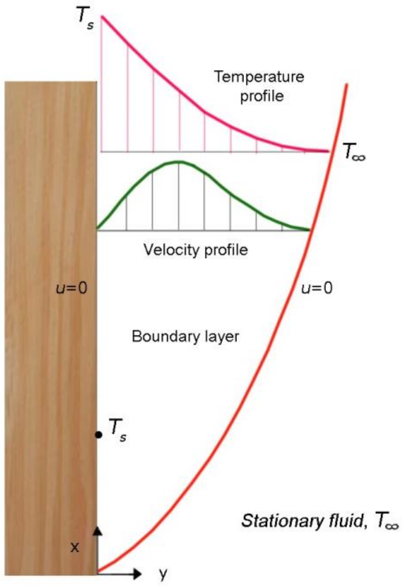



**Figure 3.5. Velocity and temperature profile for the natural convection flux on a hot vertical slab with $T_s$ temperature inside a fluid with $T_\infty$ temperature**

There is a correlation between natural convection and the dimensionless Nusselt number, as it is expressed in (3-1). At the same time, there is a relation between the Nusselt and the Rayleigh numbers. The second one is the product of Grashof and Prandtl dimensionless numbers.

$$Nu = \frac{h \cdot L_c}{k} \quad \textbf{(3-1)}$$

*$Nu$: Dimensionless Nusselt number*
*$h$: Average of natural convection coefficient of the surface [W/(m²·°C)]*
*$L_c$: Characteristic length of the geometric configuration [m]*
*K : Thermal conductivity of the fluid [W/(m∘C)]*

Depending on the heat flux and the geometric configuration of the element, the expression that relates the numbers of Nusselt and Rayleigh differs. In our case, it is a vertical plate with horizontal heat flux and whose Rayleigh number is from $10^4$ to $10^9$, which corresponds to laminar natural convection [59]. The expressions that represent this state are (3-2) and (3-3).

$$\mathrm{Nu} = \frac{\mathrm{h}_c \cdot \mathrm{L_c}}{\mathrm{k}} = \left\{ 0.825 + \frac{0.387\mathrm{Ra}^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{\mathrm{Pr}}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\}^2 \tag{3-2}$$

Where;

$$Ra_L = Gr_L \cdot Pr = \frac{g \cdot \beta \cdot (T_s - T_\infty) \cdot {L_c}^3}{v^2} \cdot Pr \tag{3-3}$$

*$Ra_L$: Rayleigh number*
*$Gr_L$: Grashof number*
*$Pr$: Prandtl number*
*$g$: Gravitational acceleration [m/s$^2$]*
*$\beta$: Volumetric expansion coefficient, 1/K ($\beta$=1/T for ideal gas), where T is the temperatura of the film*
*$L_c$: Characteristic length of the geometric configuration [m]*
*$v$: Cinematic viscosity of the fluid [m$^2$/s]*
*$T_s$: Superficial temperature [°C]*
*$T_\infty$: Temperature of the stationary fluid [°C]*

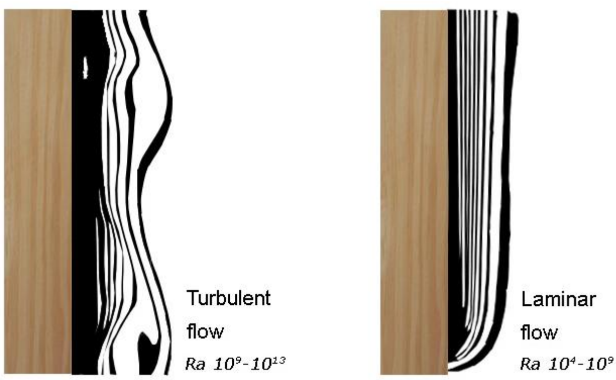



**Figure 3.6. Natural convection: Isotherms on a hot plate**

Taking into account that the thermal conductivity of the air (k) with 1 atm pressure and 20°C temperature is 0.02514 W/(m·°C), the cinematic viscosity (v) is 1.516 x $10^{-5}$ $m^2$/s, and Prandtl number (Pr) is 0.7309. If the temperature distribution registered by tests is known, the convection coefficient (he) is obtained through the expression (3-2), which corresponds to the exterior surface of the testing sample.

On the other hand, knowing the exterior convection coefficient, and considering that the heat transfer is linear and perpendicular to the sample surface, the interior convection coefficient is deduced by the correlation shown in the expression (3-4).

$$he \cdot (T_{se} - T_e) = hi \cdot (T_{si} - T_i) \quad \textbf{(3-4)}$$

*$he$: Exterior convection coefficient [W/(m·°C)]*
*$hi$: Interior convection coefficient [W/(m·°C)]*
*$T_{se}$: Exterior superficial temperature of the material [°C]*
*$T_{si}$: Interior supeficial temperature of the material [°C]*
*$T_e$: Exterior temperature [°C]*
*$T_i$: Interior temperature [°C]*

Knowing the convection coefficients, the superficial thermal resistance of the exterior and interior air (Rse, Rsi) are deduced by the expression (3-5).

$$R_s = \frac{1}{h} \quad \textbf{(3-5)}$$

*$R_s$: Superficial thermal resistance [($m^2$·°C)/W]*
*h: Convection coeficient [W/($m^2$·°C)]*

#### 3.2.2.1.1 Radiative coefficient

In case of radiation, this phenomenon is included through Stefan-Boltzmann law, which is supported by the expression (3-6) and (3-7) [59]. The relation of convection and radiative coefficients is including in the expression (3-8).

$$hr = \epsilon \cdot hr_0 \quad \textbf{(3-6)}$$

Where,

$$hr_0 = 4 \cdot \sigma \cdot {T_m}^3 \quad \textbf{(3-7)}$$

*$hr$: Radiative coefficient [W/[(m²·°C³)]*
*$hr_0$: Radiative coefficient for a black-body surface [W/[(m²·°C³)]*
*∈: Hemispherical emissivity of the surface [W/[(m²·°C³)]*
*$\sigma$: Stefan-Boltzmann constant [5.67·10⁻⁸ W/[(m²·°C⁴)]*
*$T_m$: Mean thermodynamic temperature of the surface and of ts surroundings [°C⁴]*

$$h = hc + hr \quad \textbf{(3-8)}$$

*$h$: Convection coeficient [W/(m2·°C)]*
*$hc$: Convective coefficient [W/[(m²·°C³)]*
*$hr$: Radiative coefficient [W/[(m²·°C³)]*

#### 3.2.2.1.2 Emissivity

In order to estimate natural (1), chemical treated (2) and heat-treated (3) Radiata-pine emissivity (ϵ), the infrared camera shown in Figure 3.7 was used. The followed procedure was based on the estimation of material emissivity compared with other material whose emissivity is known. In this case, a piece of plastic black tape is used as reference material, whose emissivity is 0.95. The tape is stick on the material to test. After realize the thermography, wood emissivity is obtained as the temperature of both materials is the same. The three cases, natural, chemical treated and heat-treated Radiata-pine, have been analysed.

Figure 3.7. Infrared Camera with Super Resolution ©TESTO 875-1i

| Technical specifications | |
|---|---|
| Measuring range | -30 to +100°C; 0 to +350 °C (switchable) |
| Accuracy | ±2 °C, ±2 % of m.v. (±3 °C of m.v. at -30 to -22 °C) |
| Thermal sensitivity | < 50 mK at +30 °C |
| Software | TESTO IRSoft |

**Table 3.6. Technical specifications of Testo 875-1i infrared camera**

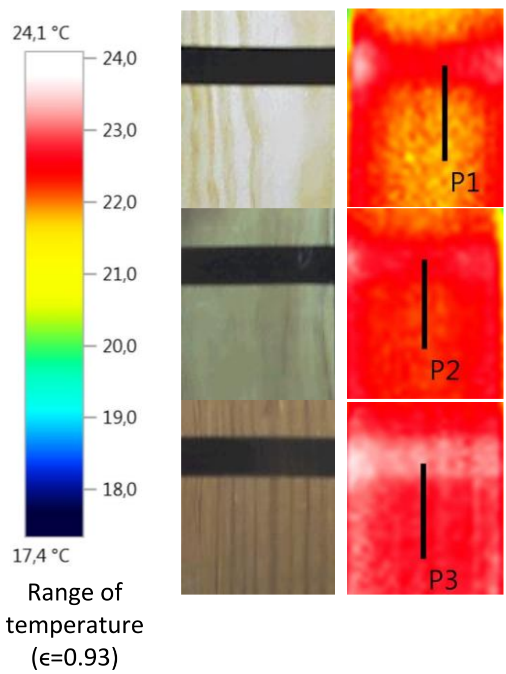



**Figure 3.8. Natural (1), chemical treated (2) and heat-treated (3) Radiata-pine thermography**

In this case, three lines of temperature (P1, P2, P3) are analysed for each sample; natural, chemical treated and heat-treated Radiata-pine, as it is shown in Figure 3.8. These lines are proportionally divided into 18 points of temperature. As the plastic and sample temperature is the same, the emissivity of wood is estimated.

In this case, natural wood is 0.927, chemical treated wood is 0.934 and heat-treated wood is 0.929 of emissivity. That is, the three samples are 0.93 of emissivity with an error of ±0.005, which means that in origin the treatments do not specially affect this property.

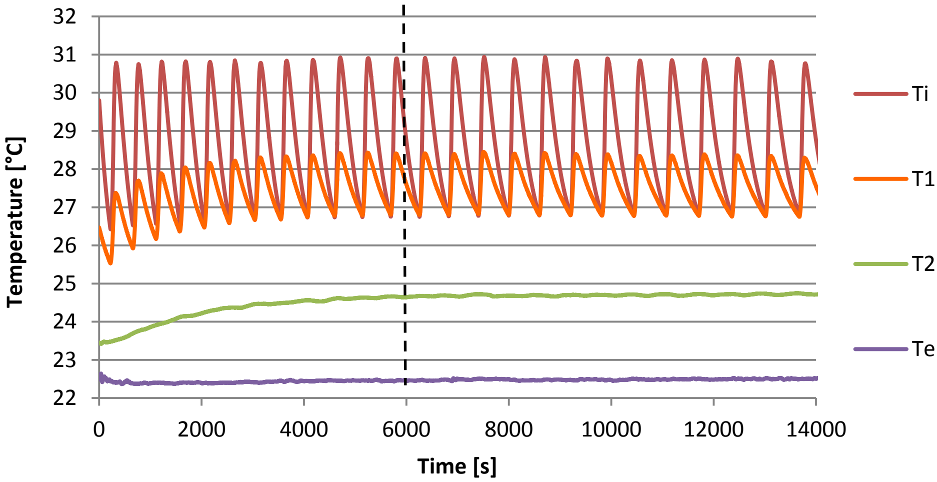
Apart from the emissivity, the difference of temperature between them with the same surrounding temperature is also possible to know. In this case, the natural sample is 23.47 °C, the chemical treated sample is 23.58 °C, and the heat-treated sample is 24.21 °C temperature. That is, the heat-treated Radiata-pine is the hottest sample in that instance.

#### 3.2.2.2 Data analysis

While the test is running the data acquisition equipment registers the thermocouples temperatures along time. In this case, the duration of each test is more than 5 hours, as in the first period of time the sample is not thermally conditioned, which difficult the conductivity estimation.

In Graphic 3.1, the temperature registration of the different thermocouples installed for a test is shown. These thermocouples detect $T_i$, $T_1$, $T_2$ and $T_e$ temperatures, which were previously described in Chapter 2. As it can be seen, before 6000 s the curve is increasing and the cycles are not constant.

However, after this period of time there are constant and repetitive cycles of temperatures getting constant frequency. These cycles are influenced by the thermal resistance, as it runs and stops several times. Although a thermostat controls the inside temperature of the box, the heater does not work in a gradually mode. Due to that, it is not possible to regulate the heat flow. Besides, the thermostat has an error margin because of both technology and position of the detection sensor inside the box, in terms of heat distribution.



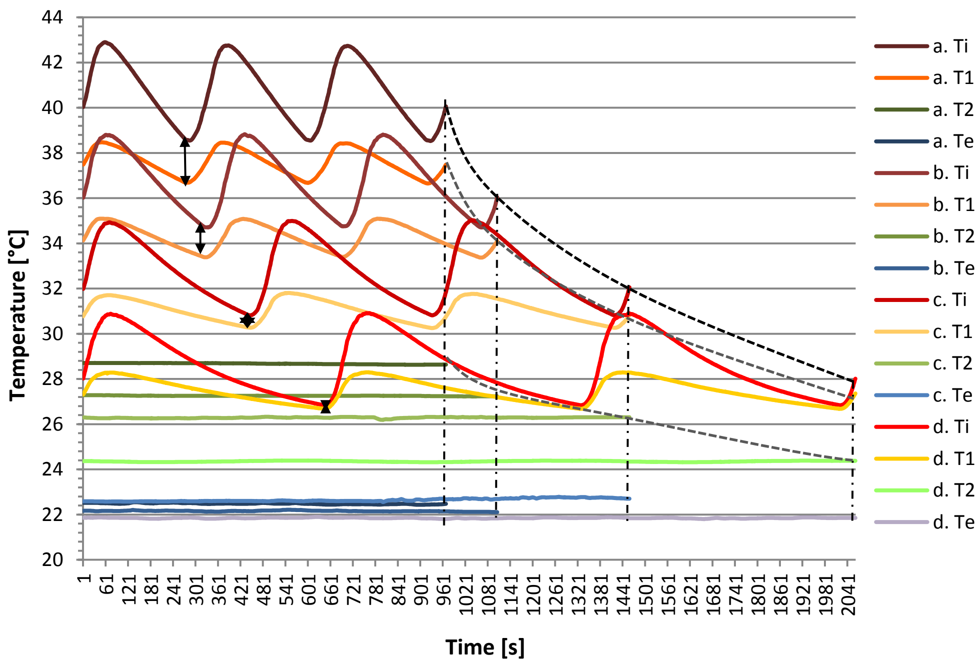

**Graphic 3.1. Registration of temperatures during a test**

As it can be seen in Graphic 3.1, the temperature inside the test box is variable, although the controlled temperature is 28 °C. In case of the upper limit of temperature, this is increased almost 2.5 °C due to the inertia of electric resistance and the high insulated box, while the lowest limit is decreased 1 °C because of the thermostat tolerance, which in this case is ±1°C.

The box size also makes difficult the control of the inner air temperature. However, the exterior side of the box is completely constant and controlled, which makes easier the estimation of the external convection coefficient. As previously mentioned in section 3.2.2.1, the interior convection coefficient is deduced by the correlation shown previously in the expression (3-4).

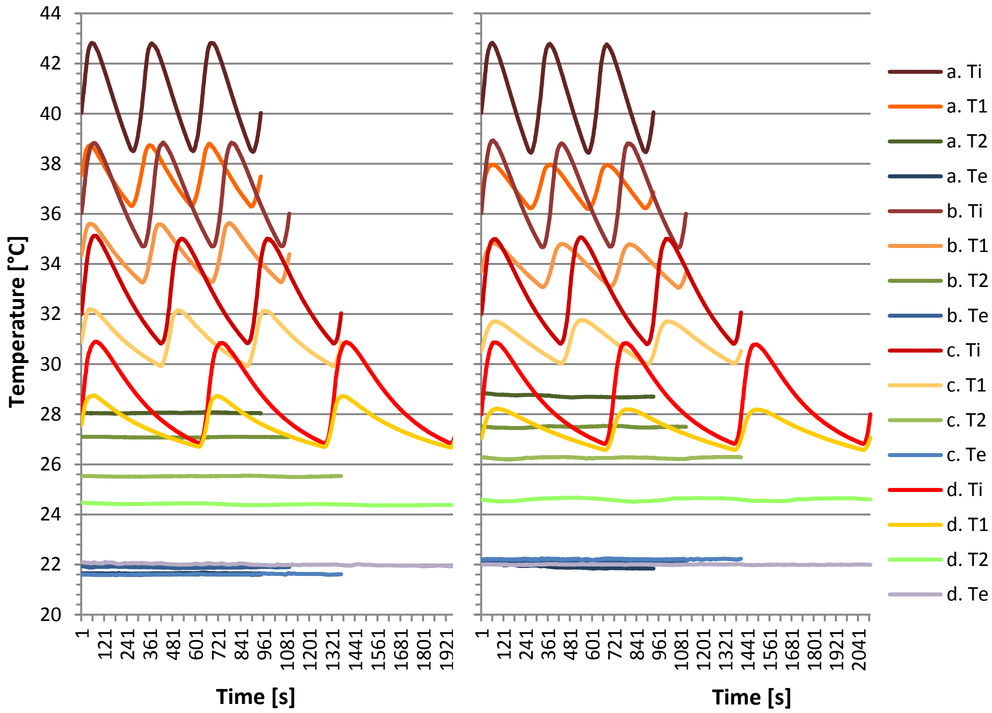
As it was mentioned in section 3.2, different gradient of temperatures were test. For the temperature inside the test box, 40, 36, 32 and 28 °C controlled temperatures are used. In case of the exterior temperature, it is 22°C for the four cases. In Graphic 3.2, there are shown different intervals of cycle for each test, which were named as “a”, “b”, “c” and “d”, corresponding to the different temperature gradients mentioned respectively. In this case, a wood sample treated with chemical substances is analysed.

If this graphic is analysed, the length of each cycle depends on the controlled temperature. That is, the lowest is the test temperature, the wider are these cycles. In this case three cycles for each test (a, b, c, d) are represented. As it can be seen, the variation of the length of these cycles is exponential. However, the amplitude keeps the same, 3.5°C approximately, which correspond to an increment of 2.5 °C from the controlled temperature (28, 32, 36, 40 °C), and 1 °C decrement, as it was previously mentioned.




**Graphic 3.2. Three cycles interval of temperatures in each test (a, b, c and d)**

If chemical treated wood is compared to natural and heated-treated wood, as t can be seen in Graphic 3.3, their thermal behaviour is similar. However, the cycles of both treated wood are slightly bigger than natural wood ones. In all cases, the heater heats the inner of the test box rapidly. If the heater stops in less time means that the test box is more insulated due to sample, as the used box is the same one.




**Graphic 3.3. Three cycles interval of temperatures in each test (a, b, c and d) for natural wood (right) and heat-treated wood (left)**

In the next section 3.2.2.3, the results of conductivity obtain through test temperatures are assessed.

### 3.2.2.3 Thermal conductivity

Through the different temperatures registered by data acquisition equipment and the expression shown in section 3.2 and 3.2.2.1, the conductivity of each sample is obtained.

In Table 3.7 there are shown the different temperatures; $T_i$, $T_1$, $T_2$ and $T_e$ registered by each test for natural Radiata-pine, according to different gradients, as it was explained in section 3.2. The tests "a", "b", "c" *and* "d" corresponds to 28, 32, 36 and 40°C temperature inside the test box, while the exterior one keeps 22 °C. The variation of temperature inside the box is due to functional limitations such as the thermostat, which has a precision of ±1°C, and the heater, whose heat generation is not gradually as it was mentioned in previous section 3.2.2.2. It is also represented the superficial coefficients $h_i$ and $h_e$.

| | | $T_i$ | $T_1$ | $T_2$ | $T_e$ | λ | $U_T$ | $h_i$ | $h_e$ |
|---|---|---|---|---|---|---|---|---|---|
| | | °C | °C | °C | °C | W/(m·°C) | W/(m²·°C) | W/(m²·°C) | W/(m²·°C) |
| a | $T_{med}$ | 40.7 | 37.6 | 28.0 | 21.6 | 0.1202 | 2.5081 | 15.0858 | 7.4431 |
| | $T_{max}$ | 42.9 | 38.7 | 28.0 | 21.6 | 0.1064 | 2.2437 | 11.4066 | 7.4397 |
| | $T_{min}$ | 38.5 | 36.4 | 28.0 | 21.6 | 0.1355 | 2.8198 | 22.4503 | 7.4385 |
| b | $T_{med}$ | 36.8 | 34.4 | 27.1 | 21.9 | 0.1188 | 2.4570 | 15.4370 | 7.0466 |
| | $T_{max}$ | 38.9 | 35.6 | 27.1 | 22.0 | 0.1026 | 2.1578 | 11.1898 | 7.0362 |
| | $T_{min}$ | 34.7 | 33.3 | 27.1 | 21.9 | 0.1412 | 2.8591 | 25.4776 | 7.0434 |
| c | $T_{med}$ | 32.9 | 31.1 | 25.7 | 21.8 | 0.1122 | 2.2846 | 13.5698 | 6.5862 |
| | $T_{max}$ | 35.1 | 32.2 | 25.7 | 21.8 | 0.0930 | 1.9211 | 8.9250 | 6.5541 |
| | $T_{min}$ | 30.8 | 30.0 | 25.7 | 21.8 | 0.1408 | 2.8311 | 31.5150 | 6.5584 |
| d | $T_{med}$ | 28.7 | 27.7 | 24.1 | 21.5 | 0.1031 | 2.0825 | 13.1443 | 5.7712 |
| | $T_{max}$ | 31.0 | 28.8 | 24.1 | 21.5 | 0.0795 | 1.6320 | 6.9088 | 5.9332 |
| | $T_{min}$ | 26.8 | 26.7 | 24.1 | 21.5 | 0.1395 | 2.9112 | 239.8796 | 5.9278 |

**Table 3.7. Natural wood data of temperatures and conductivity**

As it can be in the results the conductivity value (λ) taking into account the average temperatures ($T_{med}$) in the four cases are lower than the conductivity stablished by "*Catálogo de Elementos Constructivos*", which belongs to the Spanish Building Code (CTE), and UNE-EN ISO 10456 norm about construction materials. In both cases, the estimated value for the thermal conductivity of 560 kg/m$^3$ density wood is 0.15 W/(m·°C) [18, 19], between 40.45 and 24.69 % higher than the tested one, depending on its gradient. In this case, its conductivity varies from 0.1068 to 0.1211. In general terms, the higher is the gradient of temperature, the higher is the thermal conductivity of the material.

In Table 3.8, it is shown the thermal data of the treated sample of Radiata-pine with chemical substances compounded with Copper and Boro [23, 57], previously described in section 3.2. It is followed the same procedure as the previous sample. In this case, the range of thermal conductivity is closer in all tests, and it varies from 0.1160 to 0.1225.

| | | $T_i$ | $T_1$ | $T_2$ | $T_e$ | λ | U | $h_i$ | $h_e$ |
|---|---|---|---|---|---|---|---|---|---|
| | | °C | °C | °C | °C | W/(m·°C) | W/(m²·°C) | W/(m²·°C) | W/(m²·°C) |
| **a** | $T_{med}$ | 40.7 | 37.6 | 28.6 | 22.3 | 0.1205 | 2.4827 | 14.5856 | 7.3111 |
| | $T_{max}$ | 42.8 | 38.4 | 28.6 | 22.3 | 0.1118 | 2.2514 | 10.5006 | 7.3476 |
| | $T_{min}$ | 38.5 | 36.7 | 28.6 | 22.3 | 0.1358 | 2.8468 | 25.0350 | 7.3472 |
| **b** | $T_{med}$ | 36.8 | 34.3 | 27.4 | 22.3 | 0.1207 | 2.4357 | 14.1995 | 6.9947 |
| | $T_{max}$ | 38.9 | 35.1 | 27.4 | 22.3 | 0.1093 | 2.1454 | 9.5100 | 6.9814 |
| | $T_{min}$ | 34.7 | 33.4 | 27.4 | 22.3 | 0.1394 | 2.8604 | 28.0843 | 6.9799 |
| **c** | $T_{med}$ | 32.9 | 31.1 | 26.1 | 22.4 | 0.1173 | 2.2918 | 13.0026 | 6.3928 |
| | $T_{max}$ | 35.0 | 31.9 | 26.1 | 22.4 | 0.0998 | 1.9087 | 7.6634 | 6.4501 |
| | $T_{min}$ | 30.8 | 30.2 | 26.1 | 22.4 | 0.1412 | 2.8612 | 38.3745 | 6.4539 |
| **d** | $T_{med}$ | 28.6 | 27.5 | 24.4 | 21.9 | 0.1123 | 2.1727 | 12.8936 | 5.8554 |
| | $T_{max}$ | 30.9 | 28.3 | 24.4 | 21.9 | 0.0883 | 1.6116 | 5.5558 | 5.8497 |
| | $T_{min}$ | 26.8 | 26.7 | 24.4 | 21.9 | 0.1529 | 2.9728 | 98.7834 | 5.8600 |

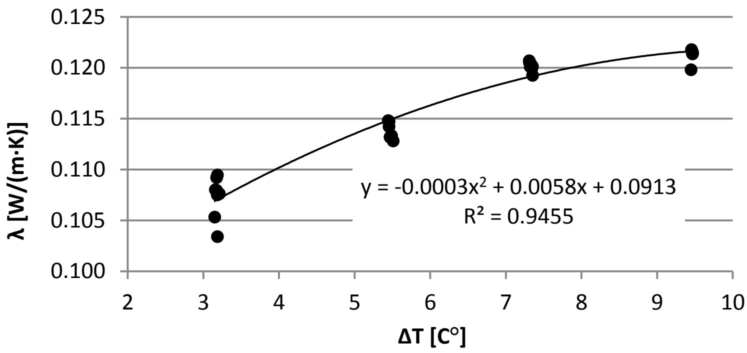
**Table 3.8. Chemical treated wood data of temperatures and conductivity**

On the other hand in Table 3.9, it is shown the thermal data of the heat-treated sample of Radiata-pine, which was also described previously in section 3.2. In this case, the range of thermal conductivity (λ) varies from 0.1189 to 0.1223, becoming the sample with the least variation of conductivity along tests.

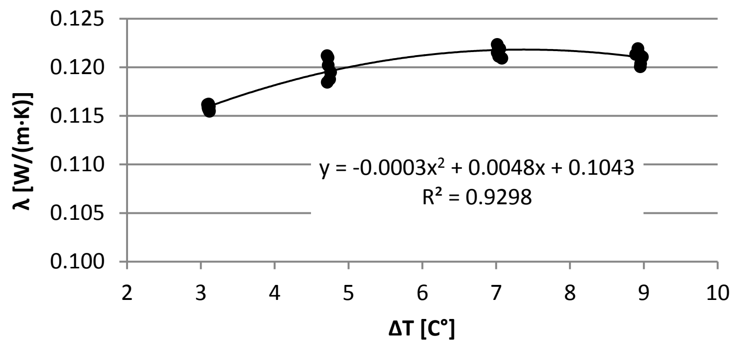
| | | $T_i$ | $T_1$ | $T_2$ | $T_e$ | λ | U | $h_i$ | $h_e$ |
|---|---|---|---|---|---|---|---|---|---|
| | | °C | °C | °C | °C | W/(m·°C) | W/(m$^2$·°C) | W/(m$^2$·°C) | W/(m$^2$·°C) |
| a | $T_{med}$ | 40.7 | 37.2 | 28.4 | 21.4 | 0.1215 | 2.6986 | 14.2616 | 7.4494 |
| | $T_{max}$ | 43.0 | 38.1 | 28.4 | 21.4 | 0.1108 | 2.4573 | 10.7003 | 7.6197 |
| | $T_{min}$ | 38.4 | 36.3 | 28.4 | 21.4 | 0.1356 | 3.1259 | 25.2744 | 7.6148 |
| b | $T_{med}$ | 36.7 | 34.0 | 27.5 | 22.1 | 0.1184 | 2.5924 | 13.6486 | 7.0427 |
| | $T_{max}$ | 38.8 | 34.8 | 27.5 | 22.1 | 0.1070 | 2.3051 | 9.5846 | 7.1056 |
| | $T_{min}$ | 34.7 | 33.1 | 27.5 | 22.1 | 0.1398 | 3.0652 | 24.3241 | 7.1081 |
| c | $T_{med}$ | 32.8 | 30.9 | 26.3 | 22.2 | 0.1163 | 2.5066 | 13.5947 | 6.5932 |
| | $T_{max}$ | 35.0 | 31.7 | 26.2 | 22.2 | 0.0987 | 2.0774 | 8.0011 | 6.5917 |
| | $T_{min}$ | 30.8 | 30.0 | 26.3 | 22.2 | 0.1460 | 3.1228 | 32.9281 | 6.5994 |
| d | $T_{med}$ | 28.5 | 27.4 | 24.6 | 22.0 | 0.1118 | 2.3336 | 12.9676 | 5.8586 |
| | $T_{max}$ | 30.9 | 28.2 | 24.6 | 22.0 | 0.0855 | 1.7298 | 5.7967 | 5.9012 |
| | $T_{min}$ | 26.8 | 26.6 | 24.6 | 22.0 | 0.1614 | 3.2327 | 65.3473 | 5.9214 |

**Table 3.9. Heat-treated wood data of temperatures and conductivity**

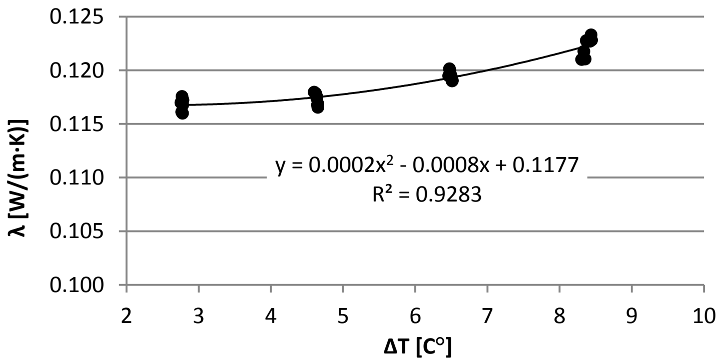
In Graphic 3.4, Graphic 3.5 and Graphic 3.6, they are represented the thermal characterization of natural Radiata-pine in the three modes; natural, chemical treated and heat-treated wood. In this case, thermal conductivity is obtained according to a reference thickness value, which is 2.38 cm for sample 1 and 2, and 2.02 cm for sample 3.




**Graphic 3.4. Thermal conductivity of Radiata-pine**

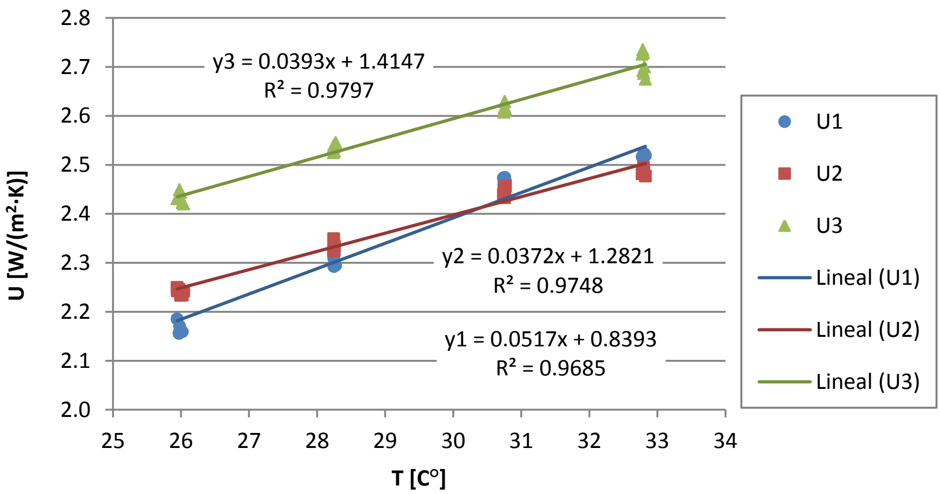



**Graphic 3.5. Thermal conductivity of Radiata-pine treated with chemicals**




**Graphic 3.6. Thermal conductivity of Radiata-pine heat-treated**

In Graphic 3.7, it can be seen the transmittance variation depending on sample, natural (1), chemical treated (2) and heat-treated (3) Radiata-pine. Sample 2 and 3 represent the same increment along time, that is, their increment is proportional. However, in case of Sample 1, it highly increases its thermal transmittance along time, which represents the most variable material.




**Graphic 3.7. Thermal transmittance of sample 1, 2 and 3**

### 3.2.2.4 Transmittance measurements


**Figure 3.9. Multifunctional transmittance detector © TESTO 435-1 with thermocouples and a wireless temperature probe**

In order to analyse the transmittance of the material located in the test box a bench of tests was realized measuring data through a transmittance multifunction detector.

As it is shown in Figure 3.9, the transmittance equipment has three main parts: three thermocouples installed in the outside surface of the sample, the data registration and process equipment where the thermocouples are plugged, and a wireless temperature probe, which is located inside the test box. The technical specifications are shown in Table 3.10.

| Technical specifications | |
|---|---|
| Measuring range | -50 to +150 °C |
| Accuracy | ± 0.2 °C (-25 hasta + 74.9 °C)<br>± 0.4 °C (-50 hasta – 25.1 °C)<br>± 0.4 °C (+75 hasta + 99.9 °C)<br>± 0.5 % of v.m. (Remaining range) |
| Resolution | 0.1 °C |
| Software | Testo Comfort-Software |

**Table 3.10. Technical specifications of Testo 435-1**

In this case, test “a” was realized for each sample; natural (1), chemical treated (2) and heat-treated (3) Radiata pine. This test represents 22°C exterior temperature and 40 °C interior temperature, previously described in section 3.2.2.2.

In Table 3.11 they are represented the transmittance results for each sample (1, 2 and 3). As it can be seen, this method considers the superficial temperature of one of the sample face as a Known convection coefficient for all cases. That is, 7.6923 W/($m^2$·°C) convection coefficient (he) which corresponds to the inverse value of the superficial resistance obtained by the Spanish Building Technical Code (CTE) for interior vertical walls, 0.13 W/($m^2$·°C) [56].

| | 1 | 2 | 3 |
|---|---|---|---|
| Te [°C] | 19.71 | 19.86 | 20.19 |
| Ti [°C] | 42.64 | 42.87 | 42.88 |
| Tse [°C] | 25.29 | 25.69 | 26.26 |
| Tsi [°C] | ---- | ---- | ---- |
| he [W/($m^2$·°C)] | 7.6923 | 7.6923 | 7.6923 |
| hi [W/($m^2$·°C)] | 2.8464 | 22.4191 | 5.6130 |
| U [W/($m^2$·°C)] | 2.0232 | 2.1078 | 2.0643 |

**Table 3.11. Transmittance obtained by TESTO equipment**

However, if the opposite convection coefficient (hi) is obtained by means of the expression (3-4) previously shown in section 3.2.2.1, it can be seen a huge difference between samples, while in case of the transmittance obtained by test box procedure the convection coefficients are similar in all cases, as it can be seen in Table 3.12.

The test box procedure is based on the registration of temperature data every second by thermocouples inside and outside the test box and the development of heat transfer principles, as it was previously described in Chapter 2. In contrast, the transmittance detector does not register data every second, as its data registration range is by minute, which makes difficult the analysis when short heat cycles take place.

| | 1 | 2 | 3 |
|---|---|---|---|
| Te [°C] | 19.61 | 19.62 | 20.29 |
| Ti [°C] | 43.08 | 43.22 | 43.18 |
| Tse [°C] | 25.91 | 26.16 | 27.11 |
| Tsi [°C] | 36.49 | 36.46 | 36.72 |
| he [W/(m$^2$·°C)] | 7.5407 | 7.6094 | 7.6193 |
| hi [W/(m$^2$·°C)] | 7.2104 | 7.3540 | 8.0333 |
| U [W/(m$^2$·°C)] | 1.8708 | 1.9521 | 2.2685 |

**Table 3.12. Transmittance obtained by test box procedure**

The difference of transmittance for natural and chemical treated Radiata-pine (1, 2) is very low in both methods. That is, the thermal behaviour of both samples is quite similar. However, there is a huge difference if heat-treated Radiata pine (3) is analysed, as following the test box procedures its transmittance is higher than the rest of samples (1, 2), while by the transmittance detector it represents the lowest transmittance.

In this case, it is difficult to compare this sample (3) with the others (1, 2) because it is 0.0202 m thickness, while the other two samples are 0.0238 m, which implies that the transmittance is higher.

### 3.2.2.5 Condensation risk

If the previous norm UNE-EN 12664 is analysed, it is explained a calculus process to foreseen if the presence of condensation may take place in the material during a test taking into account the relative humidity relation, in its Annex G [44]. This part of the normative is informative; however, an analysis taking into account the resulted values of conductivity depending on gradient for each sample is assessed.

In this case, the characterized values by conduction method explained in section 3.2.1 are used to foreseen if wood can be suffered by condensation during the characterization of the different samples by test box.

For this checking, the heat flux (q), an acceptable humidity relation value (g) and the relation of the change of humidity content (w) are obtained. The normative, UNE-EN 12664, considers that the admissible humidity content of the sample should be less than 0.01 kg/ ($m^3$·h) in order to avoid condensation.

In Table 3.13, it is represented an estimation value of the water content of each sample, taking into account a gradient of temperature between 5 and 15 °C. As it can be seen, the lower is the difference of temperature the less is the risk of condensation. In this case, due to its thermal conductivity and thickness, the heat-treated Radiata-pine is more likely to have condensation, while natural and chemical treated Radiata-pine are less vulnerable.

| | Natural | | | Chemical treated | | | Heat-treated | | |
|---|---|---|---|---|---|---|---|---|---|
| ΔT [°C] | 5 | 10 | 15 | 5 | 10 | 15 | 5 | 10 | 15 |
| q [W/$m^2$] | 22 | 51 | 81 | 25 | 51 | 82 | 26 | 51 | 86 |
| g [kg/($m^2$·s)] ·$10^{-7}$ | 1.03 | 2.05 | 3.24 | 1.01 | 2.05 | 3.31 | 1.05 | 2.07 | 3.45 |
| w [kg/($m^3$·h)] | 0.013 | 0.030 | 0.048 | 0.015 | 0.031 | 0.050 | 0.015 | 0.036 | 0.060 |

**Table 3.13. Estimation of humidity content for each sample**

In case of the tests permormed by the test box method; “a”, “b”, ”c”, and “d”, which corresponds to 40, 36, 32 and 18 °C interior temperature, while the exterior temperature keeps on 22 °C, the gradient of temperatures are 19, 15, 11 and 7 °C respectively, taking into account the temperature inside and outside the test box. However, if the superficial temperatures are taking into consideration, the gradient of the material corresponds to 3, 5, 7, 9 °C respectively.

As it was mentioned, the less is the gradient of temperature, the less is the risk of condensation. However, the less is the gradient, the higher is the error in the conductivity values as the flux is minor and other effects can become more impact. In case of test box, the convection effect gains importance. This can be appreciated in section 3.2.2.5, by the results shown in Table 3.7, Table 3.8 and Table 3.9, where it can be seen that the difference of interior convection coefficients increases. Due to that, these tests are not recommendable to less than 3 °C gradient of temperature between material surfaces.

## 3.3 Specific heat

It was previously demonstrated that the heat treatment highly alters the resistance to water vapour diffusion of the Radiata-pine, while the alteration produced by chemical treatment is not as relevant. Now, the specific heat of natural, chemical treated and heat-treated Radiata-pine is also obtained, in order to foreseen both thermal mass and inertia.

For the tests, NETZSCH DSC 200 F3 Maia equipment for Differential Scanning Calorimetry is used, as it can be seen in Figure 3.10. In Table 3.14 they are shown the technical specifications of this equipment. In this case, UNE-EN ISO 22007-2 is followed to obtain the specific heat of each sample; natural (1), chemical treated (2) and heat-treated Radiata-pine [60].


**Figure 3.10. NETZSCH DSC 200 F3 Maia equipment**

| Technical specifications | |
|---|---|
| Temperature Range | 150 to 600 °C |
| Heating rates | 0 to 100 K/min |
| Cooling rates | 0 to 70 K/min (depending on Temp.) |
| Sensor | Heat flux System |
| Measurement range | ± 600 mW |

| | |
|---|---|
| Enthalpy accuracy | < 1% |
| Cooling options | Forced air; $LN_2$; Intracooler |
| Atmospheres | Oxid., inert (static, dynamic) |
| Software | Proteus |

**Table 3.14. Technical specifications of NETZSCH DSC 200 F3 Maia**

A bench of samples for natural, chemical treated and heat-treated Radiata-pine were tested. In Figure 3.11, it is shown chemical treated Radiata-pine samples. In this case, they were analysed five samples for each specimen. In Table 3.15, it can be seen the results of specific heat (C) obtained through these tests


**Figure 3.11. Chemical treated Radiata-pine samples**

| | C [J/(kg·K)] | | |
|---|---|---|---|
| | Natural | Chemical treated | Heat-treated |
| 1 | 1485 | 1328* | 1442 |
| 2 | 1528 | 1650 | 1384 |
| 3 | 1434 | 1761 | 1184* |
| 4 | 1629 | 1616 | 1158* |
| 5 | 1597 | 1696 | 1498 |
| Standard deviation | 80 | 63 | 57 |
| Average | **1535** | **1681** | **1441** |

* This value was excluded from the average and standard deviation

**Table 3.15. Specific heat of Radiata pine**

From these values, both thermal mass ($m_t$) and inertia (I) are possible to analysed, as thermal conductivity (λ), apparent volume (V), density (ρ) and specific heat (C) are known.

$$m_t = V \cdot \rho \cdot C \qquad \textbf{(3-9)}$$

$$I = \sqrt{\lambda \cdot \rho \cdot C} \qquad \textbf{(3-10)}$$

*$m_t$: Thermal mass [J/K]*
*I : Thermal inertia [J m $^{-2}$·K $^{-1}$·s $^{-½}$]*
*V : Volume [m$^3$]*
*ρ: Density [kg/m$^3$]*
*C : Specific heat[J/(kg·K)]*
*λ: Thermal conductivity [W/(m·K)]*

In Table 3.16, it is shown the different properties of each sample: natural (1), chemical treated (2) and heat-treated (3) Radiata pine. In this case, the thermal conductivity (λ) in average for each sample presented in Table 3.5 and density (ρ) in Table 3.19, section 3.2.1, are considered. In case of volume apparent (V), it is considered 1 m$^2$ of board, considering that natural and chemical treated wood are 0.0238 m thick and heat-treated is 0.0202 m.

| | V [m$^3$] | ρ [kg/m$^3$] | C [J/(kg·K)] | λ [W/m·K] | $m_t$ [J/K] | I [J m $^{-2}$·K $^{-1}$·s $^{-½}$] |
|---|---|---|---|---|---|---|
| 1 | 0.0238 | 554.7 | 1535 | 0.1275 | 20265 | 329.49 |
| 2 | 0.0238 | 513.4 | 1681 | 0.1250 | 20540 | 328.45 |
| 3 | 0.0202 | 502.5 | 1441 | 0.1088 | 14627 | 280.68 |

**Table 3.16. Thermal mass ($m_t$) and inertia (I) of each sample**

The thermal mass and inertia of natural and chemical treated Radiata-pine are quite similar, with 1.34 and 0.32 % difference respectively, although the first one has 7.45 %

more density (ρ), 1.96 % thermal conductivity (λ), and 8.69 % less specific heat (C) than the second one.

On the other hand, heat-treated wood represents the highest difference with respect to the other samples in terms of thermal mass and inertia, around 28 % and 15 % respectively. This sample has the lowest volume, density, specific heat and thermal conductivity, which implies less thermal mass and inertia.

In terms of Regulation, the Spanish Building Technical Code (CTE) stablishes a value of 1600 J/(kg·K) for solid wood, which is extended to conifer and leafy [19]. This value differs to natural and chemical treated wood 4.06 and 4.82 % respectively. In case of heat-treated wood, the difference is much higher, 9.94 %.

### 3.4 Water vapour diffusion

Thermal behaviour of façades involves not only their thermal resistance but also their permeability. As previously it was mentioned, wood is a hygrothermal material, which means that it absorbs water and releases it when the relative humidity of the air rises and goes down. As it is known, water content in enclosures changes their thermal conductivity. Because of that a bench of tests is assessed in order to know the permeability of the three samples: natural (1), chemical treated (2), and heat-treated Radiata-pine (3).

In this case the international norm UNE-EN ISO 12572 was followed in order to obtain the dimensionless factor of water vapour diffusion (μ) [61]. For that, the samples are put as caps properly sealed with silicon and paraffin, on metal containers. Inside the container there is silica gel, which is a desiccant to force the water vapour flux inside the container.

Then, these mechanisms are placed into a chamber with constant temperature and humidity, 23°C and 50%. The precision of this chamber is ±1°C and ±3% respectively. The vapour flux is forced to cross the sample due to the silica, which absorbs the water content, and the impermeable container, which avoid the entrance of water vapour through its walls. In Figure 3.12, it is shown the test preparation process step by step.

The containers are weighed every 24 hours or more until the relation between the differences of their weigh divided to the differences of duration between them are proportional in the last five measurements at least.

The results are presented in Table 3.17, Table 3.18 and Table 3.19 for each type of sample (1, 2 and 3). In all cases, three pieces of wood were tested, as UNE-EN ISO 12572 stablishes this minimum number of tests in order to characterize this material.

In each case, the transmission speed of water vapour (g), water vapour permeance (W), resistance to water vapour (Z), permeability to water vapour (δ), resistance factor to water vapour diffusion (μ) and equivalent thickness of air resistance to diffusion of water vapour (Sd) are obtained.

If the attention is focused on the resistance factor to water vapour diffusion (μ) for each type of sample, it can be seen that natural and chemical treated Radiata-pine are quite similar, 33.37 and 36.96 respectively. Those values are higher than the water vapour diffusion factor considered by the Spanish Building Technical Code (CTE) [19] for conifer wood, which is 20. In case of Radiata-pine with heat-treatment, this factor increases three times with respect to Regulation and twice respect to characterized natural and chemical treated Radiata-pine, until 69.48.

1. Impermeable container

2. Introduce silica gel

3. Seal with silicon

4. Cover with masking tape

5. Seal with paraffin

6. Place into the climate chamber

**Figure 3.12. Preparation of the permeability test step by step**

| | 1.1 | 1.2 | 1.3 | Average |
|---|---|---|---|---|
| g [kg/(s.m2)] | 3.505E-07 | 3.208E-07 | 3.189E-07 | 3.301E-07 |
| W [kg/(m2.s.Pa)] | 2.628E-10 | 2.405E-10 | 2.391E-10 | 2.475E-10 |
| Z [(m2.s.Pa)/kg] | 3.805E+09 | 4.158E+09 | 4.182E+09 | 4.048E+09 |
| δ [Kg/(m.s.Pa)] | 6.252E-12 | 5.711E-12 | 5.716E-12 | 5.893E-12 |
| μ [-] | 3.140E+01 | 3.438E+01 | 3.435E+01 | 3.337E+01 |
| Sd [m] | 7.470E-01 | 8.163E-01 | 8.209E-01 | 7.947E-01 |

**Table 3.17. Permeability properties of Sample 1, natural Radiata-pine**

| | 2.1 | 2.2 | 2.3 | Average |
|---|---|---|---|---|
| g [kg/(s.m2)] | 3.025E-07 | 3.032E-07 | 2.923E-07 | 2.993E-07 |
| W [kg/(m2.s.Pa)] | 2.268E-10 | 2.274E-10 | 2.192E-10 | 2.244E-10 |
| Z [(m2.s.Pa)/kg] | 4.409E+09 | 4.398E+09 | 4.563E+09 | 4.457E+09 |
| δ [Kg/(m.s.Pa)] | 5.356E-12 | 5.392E-12 | 5.193E-12 | 5.314E-12 |
| μ [-] | 3.665E+01 | 3.641E+01 | 3.781E+01 | 3.696E+01 |
| Sd [m] | 8.657E-01 | 8.635E-01 | 8.957E-01 | 8.750E-01 |

**Table 3.18. Permeability properties of Sample 2, chemical treated Radiata-pine**

| | 3.1 | 3.2 | 3.3 | Average |
|---|---|---|---|---|
| g [kg/(s.m2)] | 1.970E-07 | 1.806E-07 | 1.829E-07 | 1.868E-07 |
| W [kg/(m2.s.Pa)] | 1.477E-10 | 1.354E-10 | 1.371E-10 | 1.401E-10 |
| Z [(m2.s.Pa)/kg] | 6.770E+09 | 7.385E+09 | 7.293E+09 | 7.149E+09 |
| δ [Kg/(m.s.Pa)] | 2.974E-12 | 2.741E-12 | 2.772E-12 | 2.829E-12 |
| μ [-] | 6.601E+01 | 7.162E+01 | 7.082E+01 | 6.948E+01 |
| Sd [m] | 1.329E+00 | 1.450E+00 | 1.432E+00 | 1.404E+00 |

**Table 3.19. Permeability properties of Sample 3, heat-treated Radiata-pine**

After measuring wood humidity in different moments, we realized that both natural and chemical treated wood has similar water content. However, in case of heat-treated wood, this usually differs as it can be seen in Figure 3.13. In this measurement, relative humidity values are 10.5 % and 10.7 % for chemical and natural wood, and 7.3 % for heat-treated wood at the same moment.


a) b)

**Figure 3.13. Relative humidity measures for natural (a) and heat-treated wood (b)**

In Table 3.20, there are shown the thermal conductivity and water vapour diffusion factor for each sample, natural (1), chemical treated (2) and heat-treated (3) wood. As it can be appreciated, the lower is the resistance factor of water diffusion obtained through UNE-EN ISO 12572, the higher is the conductivity error between methods, test box and UNE-EN 12664 tests.

| | BOX | UNE 12664 | ISO 12572 | CTE | | | |
|---|---|---|---|---|---|---|---|
| | λ [W/m·k] | λ [W/m·k] | μ [-] | μ [-] | Δλ [%] | Δμ [%] | ΔT [°C] |
| 1 | 0.1188 | 0.1291 | 33.37 | 20 | 7.96 | 40.07 | 14.89 |
| 2 | 0.1207 | 0.1307 | 36.96 | 20 | 7.64 | 45.88 | 14.65 |
| 3 | 0.1185 | 0.1167 | 69.48 | 20 | -1.53 | 71.22 | 14.68 |

**Table 3.20. Conductivity and diffusion factor results**

The difference of results between methods are not only due to their different heat transfer mode, but also to their resistance to water vapour diffusion, as text box allows humidity flux across sample, while the hot and cold metal plates of the conduction method do not allow it. As it can be seen in Table 3.20, the most resistance to water vapour diffusion the material has, the closer are results between methods.

## 3.5 Conclusions

In general terms, it is appreciated less thermal conductivity fluctuation when Radiata-pine is protected with chemical substances or heat-treatment. However, the lowest conductivity value obtained by test box is registered for the natural wood sample, when gradient between surfaces and material average temperature are the lowest. After conditioning the samples to 23°C temperature and 50% relative humidity, the density of chemical and heat-treated wood is slightly lower than natural wood density, which may imply that they have less cellulose or lignin.

The fluctuation along the tests of the natural wood thermal conductivity is twice higher than the fluctuation of the chemical treated sample and four times the heat-treated one. The heat-treated wood is the most stable, as its conductivity difference is only 0.0034 W/(m·°C), while treated wood with chemical substances has a difference of 0.0065 W/(m·°C) between the highest and the lowest conductivity value, and natural wood has a difference of 0.0143 W/(m·°C).

Test box method based on the thermocouples and UNE-EN 12664 [44] procedure were assessed. In both cases, the conductivity of natural wood (1) increases more drastically than the other samples. In case of chemical treated wood (2), it has less conductivity variation than the previous one. The heat-treated wood (3) represents the sample with the least variation of its thermal properties.

However, the resulted thermal conductivity was different as both method represent different thermal situation. The method stablished by test box represents the material exposed to air and the thermal behaviour of both elements is linked. In case of UNE-EN 12664 procedure, it does not contemplate nor convection coefficient nor its behaviour depending on material surface.

In case of using transmittance detector equipment, this is closer to test box method, as it also uses the test box to produce the necessary temperature gradient between surfaces. However, it considers that the convection coefficients are constant, which it is not as it was demonstrated by thermocouples. Both exterior and interior convection coefficients vary, although the exterior one varies less as the temperature in this side is more constant.

Heat-treated wood represents the least variation in terms of convection, which indicates that it is more insulated. In case of natural wood (1), its superficial resistance is the highest which in principle would indicate that it is the least insulated. However, the temperature cycles inside the test box are as long as the cycles of the heat-treated wood (3), while chemical treated wood (2) has shorter cycles. That means that the temperature inside the box reaches the operational temperature at the same time. That is, both samples (1, 3) requiring the same time duration to heat the inner box until reach the operational temperature, as it was mentioned in section 3.2.2.2.

In order to guarantee the correct use of test box, the risk of Radiata-pine condensation was also estimated for each test (a, b, c, d). By these estimations, it is demonstrated that the lower is the gradient of temperature, the lower is this risk. However, at the same time, the higher is the error in the conductivity values as the flux is minor and other effects can become more impact.

Due to that, it is validated that these tests are not recommendable for less than 3 °C gradient of temperature between material surfaces. That is, for this material, Radiata-pine, both tests “a” and “d”, which corresponds to 40 and 28 °C inside the test box, are more susceptible to have an error, the first one due to the higher influence of transient convection inside the test box, and the second one due to the estimated condensation risk.

On the other hand, there is a relation between transmittance and permeability, as the sample with most resistance to water diffusion (3) has similar results by test box and UNE-EN 12664 procedures, while the other samples (1, 2) have higher error. This implies that the hygrothermal behaviour in natural and chemical treated wood is more evident, because their conductivity highly varies depending on temperature and humidity. However, heat-treated wood is more stable which means that the difference of temperature and humidity do not influence in the same way.

The thermal mass and inertia of natural and chemical treated Radiata-pine are quite similar. Natural wood has more density and less specific heat than chemical treated wood. These values got compensated and the resulted thermal mass and inertia become similar. On the other hand, heat-treated wood represents the lowest volume, density, specific heat and thermal conductivity. As a result, this implies that it has the lowest thermal mass and inertia.

To sum up, in terms of water vapour flux, a further research is required in order to analyse its influence in the material thermal conductivity, as well as the measurement of their porosity.

*"I am among those who think that science has great beauty"*

Marie Curie

1867-1934

# CHAPTER 4

# Energy simulation

# 4 Energy simulation

Currently, tendencies around sustainability linked to building façades make us to develop new systems, which apart from presenting a low environmental impact with relation to both production and waste of material, also allow energy savings during the whole building life cycle. In this regard, wood is characterized for being a renewable and ecological resource whose production helps to mitigate the CO released to the atmosphere, cutting down the carbon footprint.

In this case, different exterior claddings made of joined wood strips will be carefully analyzed, in terms of energy savings. Different shapes and configurations will be addressed. For this purpose, a case study will be carried out by the simulation of different cross-sectional areas through the THERM v 7.3© software, which allows us to study the thermal behavior of the material through its thermal resistance as a whole.

A simulation with WUFI Pro is also performed. This software enables a one-dimensional investigation of the thermal behaviour of façades, depending on the climate data, in this case Bilbao weather data were selected [32].

Apart from the energy performance analysis of material and façade, the test box simulation was also conducted. In this case, the DesignBuilder v. 4 software was used. This tool is based on the EnergyPlus software combined with user-friendly interface [62]. In this case, CFD simulation was realized in order to study the air behaviour inside the test box and energy losses through it.

## 4.1 Energy Simulation with THERM v.7.3

The exterior cladding of timber framed façades is the part that usually differs in section, due to discontinuousness, such as different solutions of joined wood boards. The geometry of the exterior cladding influences the thermal transmittance, as the thickness is not the same along the exterior face. Getting to know the equivalent thermal conductivity of this exterior part makes easier to calculate the thermal resistance of the global façade, as the rest of components are usually continuous vertical layers.

To the thermal resistance estimation, THERM v 7.3© software was used, a two-dimensional finite-element heat-transfer analysis tool. The calculus description of the software by its developers is explained next [63, 64]:

THERM's steady-state conduction algorithm, CONRAD [65], is a derivative of the public-domain computer program TOPAZ2D [66, 67]. THERM's radiation view-factor algorithm, VIEWER, is a derivative of the public-domain computer program FACET [68]. THERM contains an automatic mesh generator that uses the Finite Quadtree algorithm [69]. THERM checks solutions for convergence and automatically adapts the mesh as required using an error-estimation algorithm based on the work of Zienkiewicz and Zhu [70, 71].

THERM's calculation routines evaluate conduction and radiation from first principles. Convective heat transfer is approximated through the use of film coefficients obtained from engineering references [72, 73]."

This program allows estimate the thermal transmittance of different solutions. The inputs are the thermal conductivity of the material and the environment boundary conditions.

For this study, four solutions made of joined wood boards and traditional solutions made of wood strips solution were previously selected. In this case, the total length of each tongue-and-groove board is twelve and fifteen centimetres depending on design, and the total thickness three centimetres.

THERM is used to know the R-value of each solution. From this, form and size will be analysed in order to estimate the thermal resistance of the solutions depending on their geometry.

### 4.1.1 Exterior cladding simulation

The thermal resistance of walls made of a number of different layers is easy to estimate if the layers are homogenous and continuous. In fact, it is easy to calculate with the Spanish Technical Code [45], because it estimates the heat flow goes perpendicular to the different surfaces of the layers which configure the whole façade system. However, when there are layers with different shapes or angles, the calculation is more complex.

The Spanish Building Technical Code, CTE, stablishes 0.15 W/(m·°C) thermal conductivity value (λ) for wooden strips made of medium density conifer [19], as it was previously shown in Table 1.4, in section 1.2.2. The thermal resistance may be obtained through the expression (4-1). In this case, the thermal resistance of a continuous wood layer 3 cm thick made of Radiata-pine is obtained.

$$R = \frac{e}{\lambda} = \frac{0.03}{0.15} = 0.20 \tag{4-1}$$

*R: Thermal resistance [(m²·°C)/W]*
*λ: Thermal conductivity [(m·°C)/W]*
*e: Layer thickness [m]*

The CTE also stablishes the boundary conditions related to both interior and exterior superficial resistances, which correspond to 0.13 and 0.04 $(m^2 \cdot °C)/W$ respectively; as the wall is vertical and the heat flux runs in horizontal direction [45], represented in Table 2.1, section 2.1.

If the configuration of different wood façades is analyzed, it is common to see studs, boards, insulation panels and wood cladding strips, disposed in horizontal and vertical position. Most of them are cube forms, which make easier the estimation of the thermal resistance without turn to specific software. In Figure 4.1 they can be seen two examples of wooden façade, the first one is made of CLT (Cross laminated Timber) and the second one is a timber framed façade.

**Figure 4.1. CLT (left) and timber framed (right) façades**

In both cases, the exterior cladding made of joined wood strips brings a handicap. The strips have chamfers in order to block water when it is raining, so the strips are not totally plain and their sections show forms with different angles. Because of that, it is difficult to estimate the thermal resistance of this layer. That is, the weather influence in cladding design and its geometry. Besides, from the architectural point of view, wood can cover wide variety of geometries, as it is very adaptable, and allows investigating other cladding forms.

In Table 4.1, Table 4.2, Table 4.3, Table 4.4 and Table 4.5, there are represented four designs based on tongue-and-groove wooden boards, named D1, D2, D3 and D4, and a traditional solution made of wood strips rectangular in shape, named D5.

| | | | |
|---|---|---|---|
| | $e_{max}$ | 0.0300 | [m] |
| | $\lambda_{conifer}$ | 0.1500 | [W/(m·C)] |
| | Rsi | 0.1300 | [(m²·C)/W] |
| | Rse | 0.0400 | [(m²·C)/W] |
| | hi | 7.6923 | [W/(m²·C)] |
| | he | 25.0000 | [W/(m²·C)] |
| | R | 0.3464 | [(m²·C)/W] |
| | U | 2.8872 | [W/(m²·C)] |
| D1 | $R_{D1}$ | 0.1764 | [(m²·C)/W] |
| | $U_{D1}$ | 5.6689 | [W/(m²·C)] |

① Finite elements mesh
②③ Isotherm lines
④ Flux vectors
⑤⑥ Constant flux lines

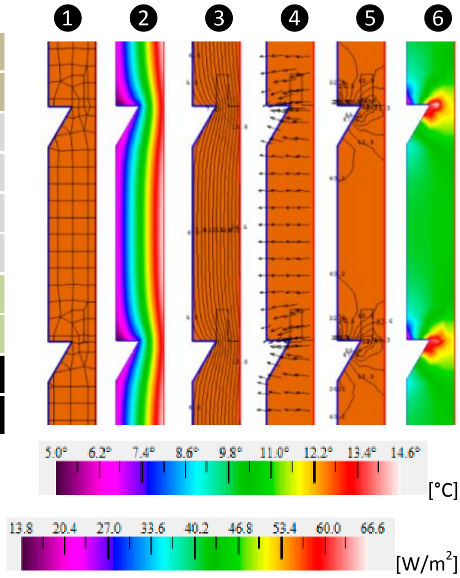



**Table 4.1. Tongue-and-groove wooden boards, design D1**

| | | | |
|---|---|---|---|
| | $e_{max}$ | 0.0300 | [m] |
| | $\lambda_{conifer}$ | 0.1500 | [W/(m·C)] |
| | Rsi | 0.1300 | [(m²·C)/W] |
| | Rse | 0.0400 | [(m²·C)/W] |
| | hi | 7.6923 | [W/(m²·C)] |
| | he | 25.0000 | [W/(m²·C)] |
| | R | 0.3304 | [(m²·C)/W] |
| | U | 3.0269 | [W/(m²·C)] |
| D2 | $R_{D2}$ | 0.1604 | [(m²·C)/W] |
| | $U_{D2}$ | 6.2344 | [W/(m²·C)] |

① Finite elements mesh
②③ Isotherm lines
④ Flux vectors
⑤⑥ Constant flux lines

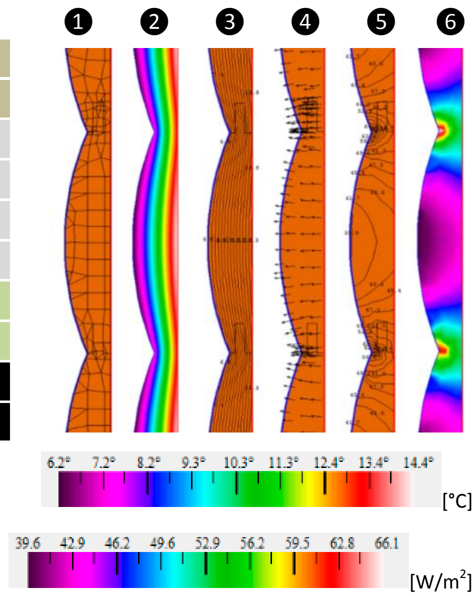
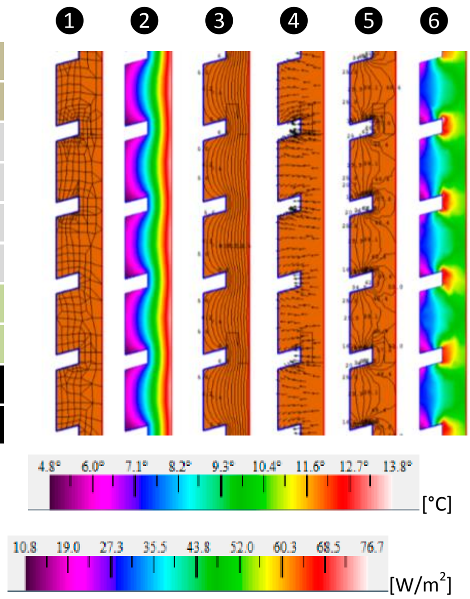



**Table 4.2. Tongue-and-groove wooden boards, design D2**

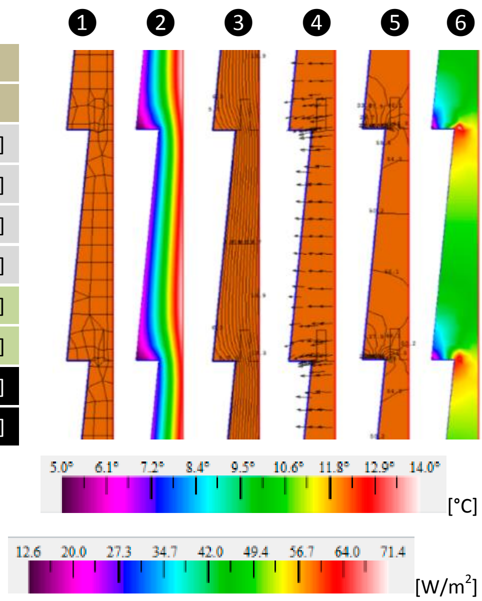
| | | | |
|---|---|---|---|
| | $e_{max}$ | 0.0300 | [m] |
| | $\lambda_{conifer}$ | 0.1500 | [W/(m·C)] |
| | Rsi | 0.1300 | [(m²·C)/W] |
| | Rse | 0.0400 | [(m²·C)/W] |
| | hi | 7.6923 | [W/(m²·C)] |
| | he | 25.0000 | [W/(m²·C)] |
| | R | 0.3034 | [(m²·C)/W] |
| | U | 3.2965 | [W/(m²·C)] |
| D3 | $R_{D3}$ | 0.1334 | [(m²·C)/W] |
| | $U_{D3}$ | 7.4963 | [W/(m²·C)] |




① Finite elements mesh
②③ Isotherm lines
④ Flux vectors
⑤⑥ Constant flux lines

**Table 4.3. Tongue-and-groove wooden boards, design D3**

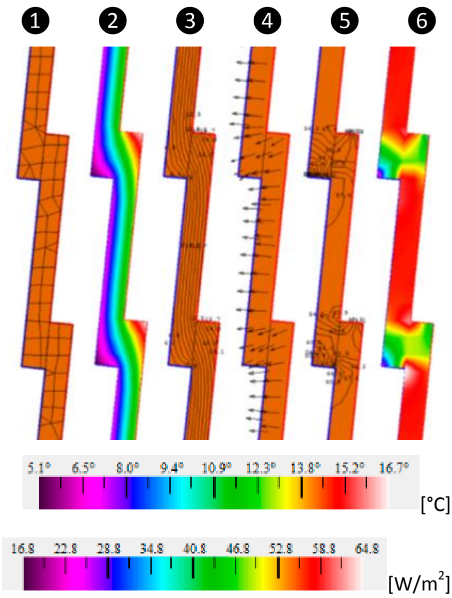
| | | | |
|---|---|---|---|
| | $e_{max}$ | 0.0300 | [m] |
| | $\lambda_{conifer}$ | 0.1500 | [W/(m·C)] |
| | Rsi | 0.1300 | [(m²·C)/W] |
| | Rse | 0.0400 | [(m²·C)/W] |
| | hi | 7.6923 | [W/(m²·C)] |
| | he | 25.0000 | [W/(m²·C)] |
| | R | 0.3104 | [(m²·C)/W] |
| | U | 3.2216 | [W/(m²·C)] |
| D4 | $R_{D4}$ | 0.1404 | [(m²·C)/W] |
| | $U_{D4}$ | 7.1225 | [W/(m²·C)] |




① Finite elements mesh
②③ Isotherm lines
④ Flux vectors
⑤⑥ Constant flux lines

**Table 4.4. Tongue-and-groove wooden boards, design D4**

| | | | |
|---|---|---|---|
| | $e_{max}$ | 0.0300 | [m] |
| | $\lambda_{conifer}$ | 0.1500 | [W/(m·C)] |
| | Rsi | 0.1300 | [(m²·C)/W] |
| | Rse | 0.0400 | [(m²·C)/W] |
| | hi | 7.6923 | [W/(m²·C)] |
| | he | 25.0000 | [W/(m²·C)] |
| | R | 0.2700 | [(m²·C)/W] |
| | U | 3.7031 | [W/(m²·C)] |
| D5 | $R_{D5}$ | 0.1000 | [(m²·C)/W] |
| | $U_{D5}$ | 10.000 | [W/(m²·C)] |




① Finite elements mesh
②③ Isotherm lines
④ Flux vectors
⑤⑥ Constant flux lines

**Table 4.5. Tongue-and-groove wooden boards, design D5**

In all cases, the thermal resistance decreases in relation to a continuous layer, whose value is 0.20 (m²·°C)/W, as it was obtain in expression (4-1). This value is considered the reference one.

The thermal resistance varies from 0.17 to 0.19 (m²·°C)/W, where the solution with the most area in section and the least perimeter exposed to the exterior represents the most insulated, D1.

On the other hand, the least efficiency solution is the traditional one, D5, which is the least industrialized and most used over decades in northern countries. In this case, the strips are joined through nails. However, in terms of material, is the solution with the least use of material. Besides, it is the solution that generates less amount of waste derived from its production, as it is rectangular and it does not required mechanized processes. The thermal bridges originated by nails are less relevant in the other solutions, as the amount is lower, although in this study are not taken into account.

Once the thermal resistance of each solution is obtained, their equivalent thickness with respect to a continuous layer made of the same material, Radiata-pine medium density with 0.15 W/(m·°C) thermal conductivity, is assessed ($e_{eq}$). The results are shown in Table 4.6.

| | $R_{reference}$: 0.2 [(m²·C)/W] | | | $\lambda_{conifer}$: 0.15 [W/(m·°C)] | | |
|---|---|---|---|---|---|---|
| | | | | $e_{eq}$ [m] | $e_{max}$ [m] | $\Delta e_{max}$ |
| **D1** | $R_{D1}$ | 0.1764 | [(m²·C)/W] | 0.0266 | 0.03 | -11,80% |
| **D2** | $R_{D2}$ | 0.1604 | [(m²·C)/W] | 0.0241 | 0.03 | -19,80% |
| **D3** | $R_{D3}$ | 0.1334 | [(m²·C)/W] | 0.0200 | 0.03 | -33,30% |
| **D4** | $R_{D4}$ | 0.1404 | [(m²·C)/W] | 0.0211 | 0.03 | -29,80% |
| **D5** | $R_{m5}$ | 0.1000 | [(m²·C)/W] | 0.0150 | 0.03 | -50,00% |

**Table 4.6. Thermal resistance resulted by each solution, D1, D2, D3, D4 and D5**

As it can be appreciated in this table the first option, D1, has 0.0266 equivalent thickness, close to 0.03 m, which represents the highest thickness in all cases ($e_{max}$). That means that it uses the major amount of thickness to insulate, and it has less thermal bridges. This is the most compact solution and its section area is also larger. At the same time, it presents less discontinuousness than the rest of solutions.

In contrast, the least energy efficiency solution made of tongue-and-groove boards is the third one, D3. In this case its section area is larger than the fourth one, D4, however it has high amount of perimeter in section exposed to exterior climate, which enhance heat losses. Both results of section area and exposed perimeter are shown in Table 4.7.

| | Area [cm²] | Perimeter[cm] |
|---|---|---|
| **D1** | 4305.14 | 169.02 |
| **D2** | 3804.18 | 153.97 |
| **D3** | 4068.75 | 243.17 |
| **D4** | 3375.00 | 165.75 |
| **D5** | 2590.85 | 164.89 |

**Table 4.7. Area and perimeter exposed to exterior for D1, D2, D3, D4 and D5**

The design D2, presents the least exposed perimeter. This means that it is the most compact. However, it has less material than D1, which makes it being slightly less insulated.

On the other hand, the design D3 has large area but at the same time long perimeter. That decreases its thermal resistance. Because of that, it represents one of the worst solutions, after the traditional D5.

In case of D4, it represents a compact solution but its perimeter is long and its area no so large. Because of that, it is one of the worst solutions in terms of insulation. Although having less amount of material, D4 has more thermal resistance than D3.

The last design, D5, is the traditional one made of strips joint through nails and is not a tongue-and-groove solution. It has the least section and its exposed perimeter is large. Because of that, it is the least insulated system.

### 4.1.2 Clearances in tongue-and-groove wooden boards

Thermal behaviour of wooden façades depends not only on the material thermal conductivity but also in its disposition. Tongue-and-groove boards allow executing the enclosure rapidly and clean, because of that its use is being spreading. In section 4.1.1, different designs were studied in order to estimate the geometry importance in the thermal behaviour of this kind of systems. Now clearances are analysed because the tongue of the pieces are not assembly filling all the groove space, as it can be appreciated in Figure 4.2. At the same time, the movements generated due to wood swelling and contraction during weathering also promotes the apparition of these clearances.

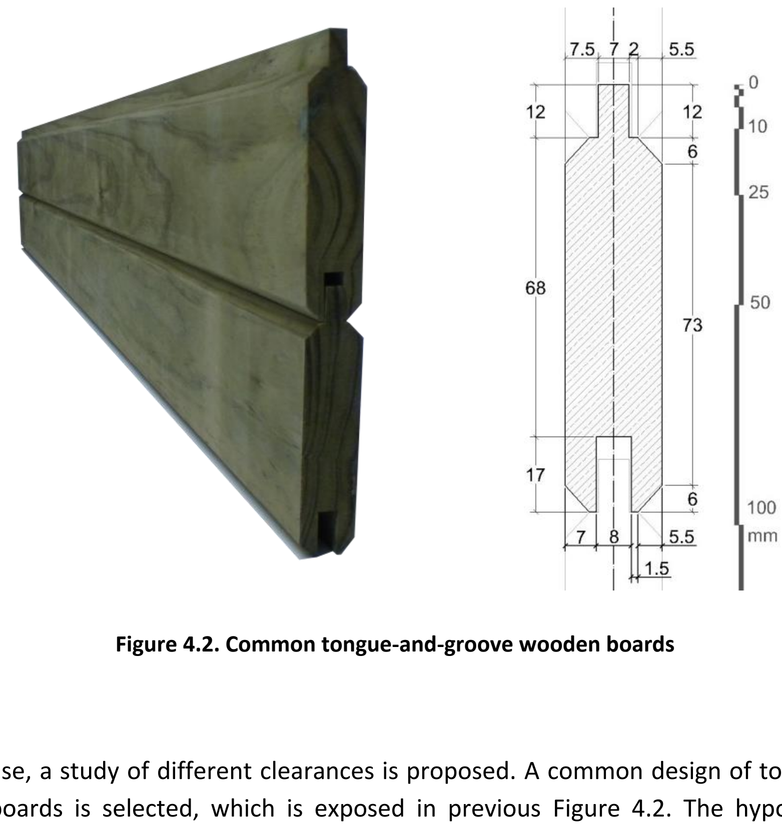



**Figure 4.2. Common tongue-and-groove wooden boards**

In this case, a study of different clearances is proposed. A common design of tongue-and-groove boards is selected, which is exposed in previous Figure 4.2. The hypotheses of clearances are shown in Figure 4.3. As it can be seen, these clearances are related to horizontal and vertical direction. The horizontal one is limited to 1 mm, as it is the free space between the tongue and the groove designed to allow an easier assembly of the pieces. On the other hand, the vertical one is considered until 2 mm. In this case, some pieces were assembly to see the size of these clearances. In this case, the pieces are not totally assembly due to imperfections, letting 2 mm approximately of clearance. The weathering process may influence even more in the apparition of clearances, but it also depends on wood specimen and protection treatment.

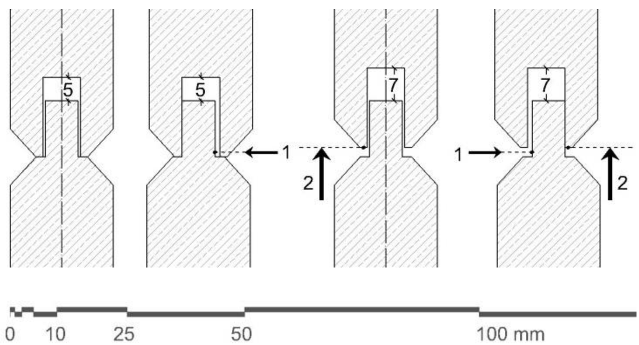



**Figure 4.3. Tongue-and-groove boards: Clearances and movements**

In order to analyse its influence in a wooden façade, insulation behind the wooden cladding is considered, as it is the most representative layer in terms of avoid energy losses. Besides, if insulation is also simulated the interior convection can be presented outside the interior surface of the wooden cladding after the second continuous layer. The most common interior convection takes place along a continuous surface.

In Figure 4.4, it is represented different distributions of clearances. In this study the wooden cladding is made of conifer wood, such as Radiata-pine, whose density is between 480 and 560 kg/m$^3$, 0.15 W/m·K thermal conductivity which corresponds to Regulation estimation [19], and the insulation is glass wool 5 cm thickness and 0.04 W/m·K thermal conductivity, as standard values.

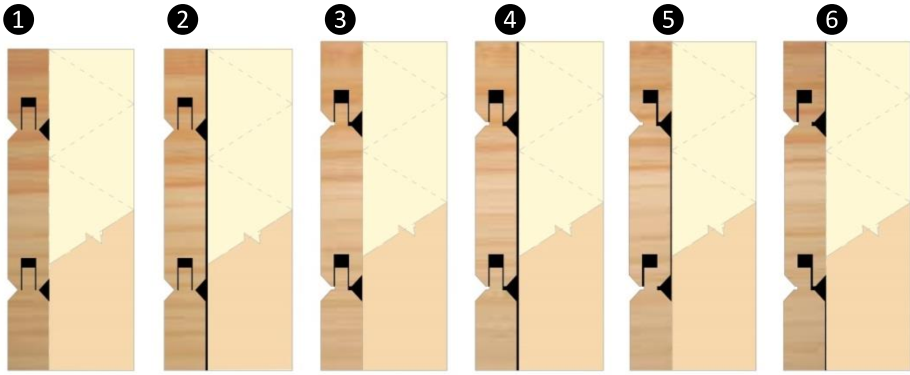



**Figure 4.4. Analysis of different distribution of clearances**

The study of clearances is realized through a bench of simulations by THERM v.7.3. software, which was previously described in section 4.1.

In Figure 4.5 and Figure 4.6 there are shown the simulation results. In this case, the distribution of temperature across each option and their heat flux are obtained. While the distribution of temperatures shown in Figure 4.5 is no representative, in case of the representation of the heat flux some aspects can be analysed.

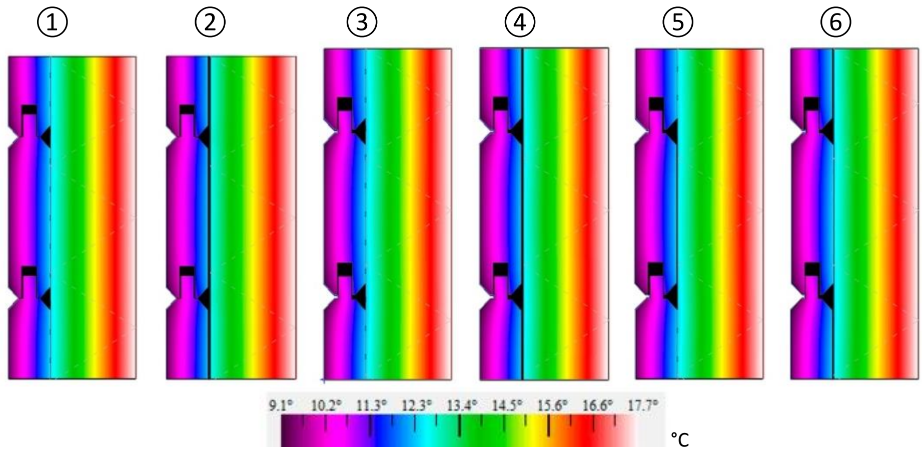



**Figure 4.5. Distribution of temperature**

In Figure 4.6, it is easy to make a difference between groups of two. In the first group, the first and second option, have the fewer amount of energy losses, as the flux is lower than in the rest of options. In this case, there are presented only clearances in horizontal direction. That is, the assembly is perfect and the horizontal clearances are due to design. In the second group, the third and fourth option, the heat losses are similar although the third option is slightly more insulated than the fourth one. In the last group, the fifth and sixth options are intermediate solutions, whose energy losses are in the middle of the rest ones. In this case, the options are the same but the simulation cut is selected in different length which influences the result, due to the position of adiabatic limits.

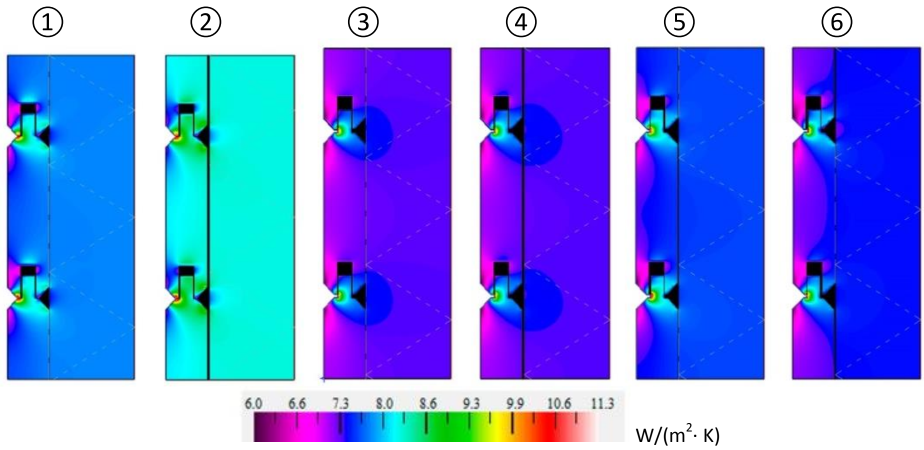



**Figure 4.6. Distribution of heat flux**

The results of energy simulations for each case are shown in Table 4.8. As it can be seen, the most representative aspect which influences energy losses are overall clearances in vertical direction, as the thickness in joint points is narrower and the heat runs easier. The second solution is the most efficient, due to the fact that the clearance between layers improves the thermal behaviour of the system, as a small air cavity between them is created.

The reference value is a continuous cladding 22 mm thickness totally in contact with the same wool insulation as the other cases. As it can be seen, the second option is the only one that improves the thermal resistance 1 % respect the reference value.

The third solution is the worst in terms of energy efficiency. In this case, the cladding is totally in contact with insulation and it has vertical clearances. In case of option five and six, they are the same option and the slightly difference between them in value is due to adiabatic cut, which is 0.04%.

The difference of heat flux between the second option and the fifth option, which are the most and the least energy efficient solutions respectively, is 1.44%. However, the implementation of insulation cuts this difference as it is the most representative insulated material in the system.

| | Reference | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| U [W/(m$^2$ ·K)] | 0.6781 | 0.6798 | 0.6714 | 0.6833 | 0.6783 | 0.6812 | 0.6809 |
| R [(m$^2$ ·K)/ W] | 1.4747 | 1.4711 | 1.4894 | 1.3555 | 1.4742 | 1.4679 | 1.4686 |
| Φ [W/m$^2$] | 7.7306 | 7.7493 | 7.654 | 7.79 | 7.7326 | 7.766 | 7.7626 |
| Q [W] | 1.3142 | 1.3174 | 1.3012 | 1.3555 | 1.3455 | 1.3513 | 1.3507 |
| ΔT [°C] | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 | 11.4 |
| EEN [%] | 0 | 0.44 | 0.53 | 0.68 | 0.69 | 0.69 | 0.71 |
| ΔR [%] | 0 | -0.24 | 1.00 | -8.08 | -0.03 | -0.46 | -0.41 |

**Table 4.8. Energy simulation results for each case**

Now only cladding is analysed in order to compare this part. In this case an air layer or cavity is considered behind wooden cladding. In this case, 0.12 W/(m·K) conductivity for Radiata-pine wood is considered, as it is closer to reality taking into account the worst value obtained through tests in section 3.2.2.3, Chapter 3.

Because of the extraction of insulation layer, the clearances options are reduced to three, which are named as A, B and C. In Figure 4.7, it is shown the heat flux across the cladding depending on clearances.

The results of each option A, B and C, are represented in Table 4.9. In this table Transmittance (U), thermal resistance (R) and heat flux (Φ) are obtained. As it can be seen in the results, the least energy efficiency solution is B, as its heat flux is higher. The option C is quite similar to B. The most efficiency is A, which is very similar to the reference, which is a continuous layer, as its thermal transmittance only differs 3.84 %. The heat flux in B case is 12.76 % higher than the reference flux value, and 8.60 % higher than A, which is the construction solution perfectly assembled.

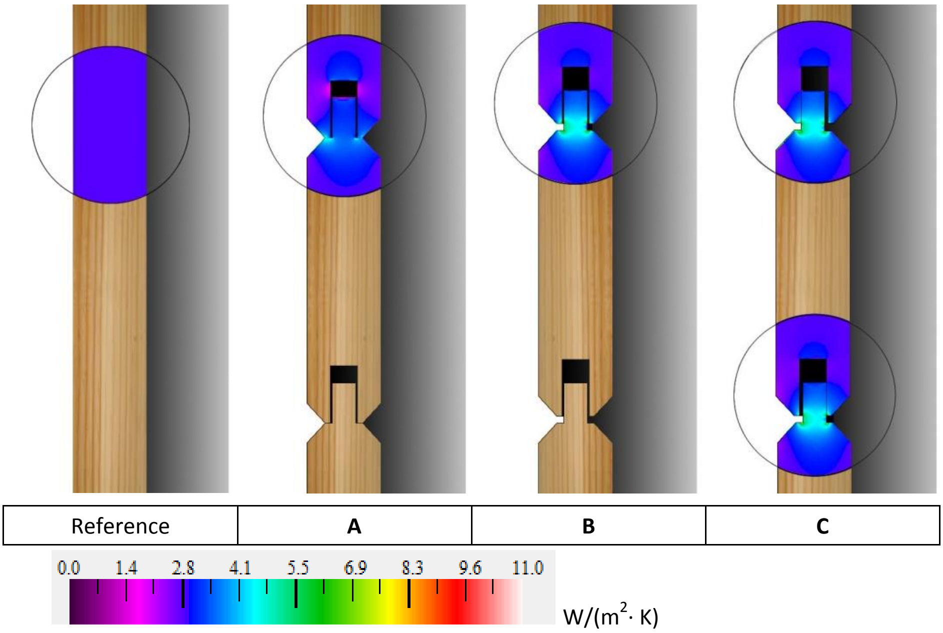



**Figure 4.7. Distribution of heat flux across Radiata-pine cladding**

| | Reference | A | B | C |
|---|---|---|---|---|
| U [W/(m$^2$·K)] | 2.5026 | 2.5986 | 2.7570 | 2.7566 |
| R [(m$^2$·K)/ W] | 0.3996 | 0.3848 | 0.3627 | 0.3628 |
| Φ [W/m$^2$] | 0.4680 | 0.4859 | 0.5277 | 0.5276 |

**Table 4.9. Simulation results for Radiata-pine cladding**

The most unfavourable solution depends mainly on the vertical assembly. When the tongue is separated from the groove, the effective thickness of material in flux direction is shorted. Because of that the thermal bridge in this section increases.

#### 4.1.2.1 Cladding thermography

The material definition in THERM software, described in section 4.1, is overall reduced to conductivity and emissivity properties, which are necessary to simulate the heat transfer. In this case, a further test was performed to estimate the emissivity of a cladding system of tongue-and-groove boards, in which a heat chamber was used to maintain a more constant internal heat, reducing the transitory heat wave [74]. In this case, the wooden boards were made of chemical treated wood, because of its better aesthetic ageing, as it will be demonstrate in Chapter 5. Figure 4.8 represents the test preparation.

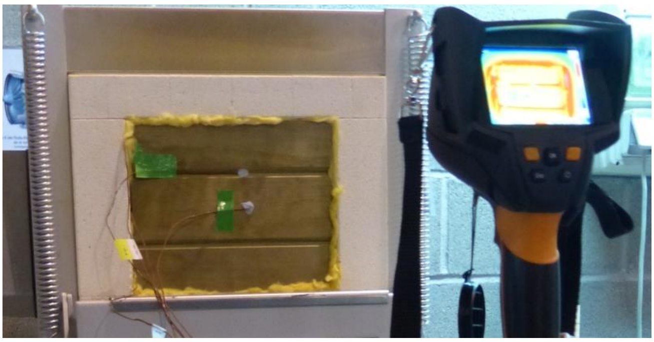


**Figure 4.8. Wood wall test with a heat chamber**

A simulation with THERM and a thermography were performed (Figure 4.9, Table 4.10). The thermography method is commonly used to detect pathologies, analyze the thermal behavior [74], and even can be used to estimate the water content and the density of material [75, 76].

Table 4.11 shows an estimation of the emissivity of the tongue-and-groove wooden boards considering the material surface temperature (T) and the exterior one ($T_e$), which was realized by means of thermocouples and thermography. The material emissivity, which in this case is 0.94, is estimated as the temperatures detected by the thermocouples are the same as those detected by thermocouples.

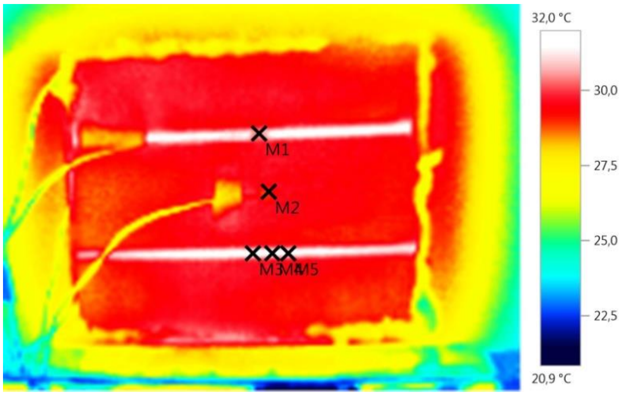



**Figure 4.9. Thermography**

| Property | Technical data: Testo 875i |
|---|---|
| Thermal sensitivity (NETD) | <50 mK to 30°C (86°F) |
| Measurement range (adjustable) | Range 1: -20 to 100°C (-4 to 212°F)<br>Range 2: 0 to 350°C (32 to 212°F)<br>Range 3 (only Testo 875i-2): 350 to 550°C (662 to 1022°F) |
| Accuracy | Range 1: ±2°C (±3.6°F)<br>Range 2: ±2°C (±3.6°F)<br>Range 3: ±3% of the average value |

**Table 4.10. Thermographic camera specifications**

| | T [C°] | $T_{e}$. [C°] | Emissivity |
|---|---|---|---|
| M1 | 30.5 | 20 | 0.94 |
| M2 | 29.0 | 20 | 0.94 |
| M3 | 31.7 | 20 | 0.94 |
| M4 | 31.5 | 20 | 0.94 |
| M5 | 31.5 | 20 | 0.94 |

**Table 4.11. Emissivity estimation of the wooden boards**

## 4.2 Hygrothermal simulation with WUFI Pro v.5.3

WUFI Pro is a specialized tool for the research of the hygrothermal behaviour of façades. It is applied overall to scientific research, such as thermal and moisture simulation, to analyse the hygrothermal behaviour of construction components, allowing the study of properties of hygroscopic material like wood [77-82].

**Figure 4.10. Corporative logotype**

A simulation with WUFI Pro v. 6 was performed to compare the results of wood conductivity previously obtained. WUFI Pro v.6 software enables the one-dimensional investigation of the hygrothermal performance of building components for various effects such as built-in moisture, driving rain, solar radiation, long-wave emissions, capillary transport and summer condensation [83-85]. This tool permits a simulation over a complete year. However, this software presents some limitations relating to modeling, when some layers vary in size along the wall [86, 87].

In order to analyse transmittance, the postprocessor of this software compares the monthly values for the transient thermal transmission with two reference values U1 and U2 which are 0.73 W/(m$^2$·K) and 1. 93 W/(m$^2$·K) respectively. In case of U1, this is the same as the limit transmittance allowed by the Spanish Technical Building Code, CTE [56].

Those values, U1 and U2, are based on the minimum thermal performance which determines that R1 is 1.2 (m$^2$·K)/W, as required by German standard DIN 4108-2:2003-02, and R2 is 0.55 (m$^2$·K)/W, as required by German standard DIN 4108-2:1981-08 [86, 87]. R1 and R2 are the thermal resistances homologous to U1 and U2 respectively.

These minimum R-values have been converted to the maximum permissible U-values U1 and U2 using surface heat transfer resistances of 0.04 (m$^2$·K)/W at the exterior surface and 0.13 (m$^2$·K)/W at the interior surface. These superficial thermal resistances are the same as the values described in CTE in order to estimate the façades transmittance [45]. The tool establishes four grades of results depending on transient transmittance obtained for each month:

- Calculation period is less than one year
- At least one of the evaluated months has a thermal transmission exceeding U2.
- All evaluated months have a thermal transmission below U2.
- All evaluated months have a thermal transmission below U1

Both transient transmittance and thermal resistance are obtained through the expressions (4-2) and (4-3).

$$U = (-Q)/\Delta T_a \qquad \textbf{(4-2)}$$

$$R = \Delta T_s/(-Q) \qquad \textbf{(4-3)}$$

*$U$: Transient transmittance [W/(m²·K)]*
*$Q$: Monthly mean value of heat flux through the interior surface [W/m²]*
*$\Delta T_a$: Monthly mean value of temperature difference between indoor and outdoor air temperature [K]*
*$\Delta T_s$: Monthly mean value of temperature difference between interior and exterior surface [K]*

The Regulation in our territory, CTE, requires a minimum transmittance value for façades depending on climate zone, which in this case corresponds to U1. However, it does not study the influence of moisture in the thermal behaviour of hygrothermal materials, which influences the global enclosure thermal transmittance, due to its hygrothermal absorption, desorption and permeability properties among others [88].

In terms of vapour flux, this software allows to simulate the water content behaviour of wood, which it cannot be obtain through the last software THERM v.7.3 [64]. If health and comfort are analysed, it is important to ensure that there is no risk of condensation. Due to that the Spanish Building Technical Code, CTE, forces to justify that there is no risk [89].

In order to estimate the risk of condensation, water vapour diffusion factor of each material is needed. In case of wood, CTE considers that this value is 20 [19]. However, as it was previously tested and analysed in section 3.4, this value differs depending on treatment. At the same time, this property influences the hygrothermal behaviour of material as conductivity not only varies depending on temperature but also on material water content [90, 91], which is influenced by weather conditions.

To spread knowledge about hygrothermal materials is needed, as well as more accurate estimation of the material response to climate, which is allowed through simulation. A correct interpretation of weather due to orientation and location as well as its effect on enclosures due to material properties, such as its wetting and drying capacity, is also possible through this kind of tools [92].

### 4.2.1 Radiata-pine simulation

In order to study the thermal behaviour of Radiata-pine, a simulation by WUFI software of the characterization of the material with test box is performed. In this case, test "b" for each sample; natural (1), chemical treated (2) and heat-treated (3) Radiata-pine is carried out. In this test the exterior temperature is 21°C, while the interior temperature keeps 36 °C.

In Table 4.12, they are shown the parameters used to define the hygrothermal properties of each sample; 1, 2 and 3. The water diffusion factors (μ) correspond to the values obtained through UNE-EN ISO 12572 tests [61], which were previously described in section 3.4. The specific heat (cp) is considered 1535, 1681 and 1441 J/(Kg·K), as they were also previously obtained in Table 3.15, section 3.3, through UNE-EN ISO 22007-2 [60]. In case of porosity (p), the value of 0.73 is considered for all cases.

| | 1 | 2 | 3 |
|---|---|---|---|
| μ [-] | 33.37 | 36.96 | 69.48 |
| cp [J/(Kg·K)] | 1535 | 1681 | 1441 |
| p [-] | 0.73 | 0.73 | 0.73 |
| e [m] | 0.02 | 0.02 | 0.02 |

**Table 4.12. Definition of sample 1, 2 and 3 properties**

In case of the thermal conductivity, the values obtained through test box tests are introduced, which are represented in Table 4.13. In this case, the conductivity dependence of temperature is introduced in the model, which is 40, 36, 32 and 28°C temperature according to test “a”, “b”, “c” and “d” respectively. These tests were described in section 3.2.2.2.

| [W/(m·K)] | | a | b | c | d |
|---|---|---|---|---|---|
| λ | 1 | 0.1202 | 0.1188 | 0.1122 | 0.1031 |
| | 2 | 0.1205 | 0.1207 | 0.1185 | 0.1123 |
| | 3 | 0.1215 | 0.1185 | 0.1163 | 0.1118 |

**Table 4.13. Sample 1, 2 and 3 conductivity depending on test**

After defining material properties, one of the tests performed with the test box is simulated for each sample; 1, 2 and 3. In this case, test “b” is selected as its gradient of temperature is high and it has no risk of condensation, following the recommendations given in the conclusions of Chapter 3.

In Table 4.14 there are shown the transmittance (U) and superficial thermal resistance (Rs) values obtained by test box procedure for test “b”. On the other hand, in Table 4.15 there are represented the results of transient transmittance ($U_T$) obtained by WUFI Pro software for each sample; 1, 2 and 3. In this case, moisture transport was not taken into account as test box does not analyse this phenomenon.

As it can be seen in Table 4.14, not only the transmittance differs but also the superficial thermal resistance for each case (Rs). These resistances are homologous to the convection coefficients obtained through expression (3-4), section 3.2.2.1.

| [W/(m$^2$·K)] | | e [m] | Rs1 | Rs2 | Rs3 |
|---|---|---|---|---|---|
| **U** | 1 | 0.0238 | 2.2846 | | |
| | 2 | 0.0238 | | 2.2918 | |
| | 3 | 0.0202 | | | 2.5066 |

| [(m$^2$·K)/W] | | Interior | Exterior |
|---|---|---|---|
| **Rs** | 1 | 0.0648 | 0.1419 |
| | 2 | 0.0704 | 0.1429 |
| | 3 | 0.0733 | 0.1420 |

**Table 4.14. Transmittance (U) and superficial resistance (Rs) values obtained by Test Box**

| [W/(m$^2$·K)] | | e | $Rs_0$ | Rs1 | Rs2 | Rs3 | | $\Delta U_T$ |
|---|---|---|---|---|---|---|---|---|
| $U_T$ | 1 | 0.0238 | 2.121 | 2.364 | | | | 0.243 |
| | 2 | 0.0238 | 2.189 | | 2.394 | | | 0.205 |
| | 3 | 0.0202 | 2.340 | | | 2.617 | | 0.277 |
| | | 0.0238 | 2.179 | | | | 2.418 | 0.239 |

**Table 4.15. Transient transmittance results by WUFI Pro ($U_T$)**

If the superficial thermal resistances of test box are analysed, it can be seen that they are different depending on sample (1, 2, 3), although being the same test (b). In case of natural Radiata-pine (1), this has the lowest superficial thermal resistance and transmittance, although in this test it does not represent the lowest conductivity material, 0.1188 W/(m·°C).

Apart from the superficial resistances obtained through test box (Rs), superficial thermal resistances predefined by WUFI Pro software for interior walls ($Rs_0$) are also including in the simulations, in order to compared results.

Heat-treated Radiata-pine (3) represents the highest superficial thermal resistance and the lowest conductivity material, 0.1185 W/(m·°C). In this case, the transmittance is the highest due to the fact that it has less thickness which reduces its thermal resistance. Because of that an analysis with more thickness is also presented, although the convection coefficients should be slightly higher, that is, lower superficial thermal resistance.

Chemical treated radiate-pine (2) represents an intermediate transmittance value. In this case, its conductivity is 0.1207 W/(m·°C). It represents the least transient transmittance variation ($\Delta U_T$), as its superficial thermal resistance is close to the pre-defined superficial thermal resistance value, $Rs_0$.

### 4.2.2 Wooden façade hygrothermal behaviour

In the next example, a wooden façade made of Radiata-pine cladding is analysed. In this case, 5 cm thickness mineral wool insulation for the intermediate layer is selected, which has 0.04 W/(m·K) thermal conductivity. For the interior cladding, a gypsum layer 1.5 cm thickness is introduced, as it is the most used in our territory. The exterior cladding is made of 2 cm thickness Radiata-pine. That is, the solutions are composed by three continuous layers.

In order to compare natural (1), chemical (2) and heat-treated (3) Radiata-pine their different conductivity is considered. In this case the values obtained with UNE 12664 [44] tests are used; whose conductivity in average are 0.1291, 0.1307 and 0.1167 respectively, shown in section 3.2.1. For the definition of the conductivity dependence related to temperature, the values of previous Table 3.4 in section 3.2.1 are considered. In all cases, thermal bridges generated by studs and clearances are not taken into account. The simulations are identified as 1, 2 and 3 according to Radiata-pine sample.

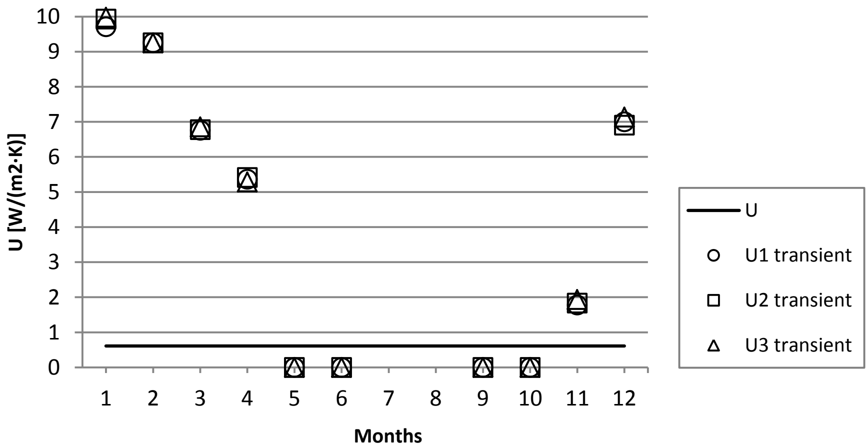
In this case, a year simulation is performed. For the exterior environment Bilbao climate data is selected. WUFI tool allows the implementation of weather base data, which in our territory this is generated by AEMET, Meteorological Agency of Spain [93].

The simulation results are shown in Graphic 4.1 and Table 4.16. As it can be seen the results are quite similar, as the thermal insulation layer gains weight in the global thermal behaviour of each solution, being the most representative material.

However, the third case based on treated Radiata-pine, whose thermal conductivity is the lowest, has the lowest transmittance with respect to the other samples only in December, when its thermal behaviour is better than the other two cases. That means that the conductivity is not the only restrictive property in terms of heat transfer.

For the definition of the different cases, conductivity and resistance factor to water vapour diffusion are different. Their porosity and specific heat are considered the same value, as t was described in the previous section 4.2.1. For natural, chemical treated and heat-treated wood density, 554.7, 513.4 and 502.5 kg/m$^3$ are respectively considered, which were previously shown in, Table 3.4, section 3.2.1. Those values were registered after conditioning the samples to 23°C temperature and 50% relative humidity, and immediately previous to conductivity tests based on UNE-EN 12664 [44]. The conductivity dependence of water content is also considered and predefined by software.

Although the reference transmittance is quite similar, 0.6122, 0.6129 and 0.6061 W/(m$^2$·K) for 1, 2 and 3 solution, being the third one the most insulated, the transient transmittance demonstrates the complex analysis of hygrothermal materials, as in different months the lowest transmittance belong to a different solution.




**Graphic 4.1. Transmittance in case 1 (U1), 2 (U2) and 3 (U3)**

| | 1 | 2 | 3 |
|---|---|---|---|
| 1- January | 9.7115 | 9.9299 | 9.9835 |
| 2- February | 9.2577 | 9.2582 | 9.2507 |
| 3- March | 6.7610 | 6.7794 | 6.8568 |
| 4- April | 5.3675 | 5.4169 | 5.2881 |
| 5- May | 0.0000 | 0.0000 | 0.0000 |
| 6- June | 0.0000 | 0.0000 | 0.0000 |
| 7- July | ---- | ---- | ---- |
| 8- August | ---- | ---- | ---- |
| 9- September | 0.0000 | 0.0000 | 0.0000 |
| 10- October | 0.0000 | 0.0000 | 0.0000 |
| 11- November | 1.7822 | 1.8328 | 1.9361 |
| 12- December | 7.0047 | 6.9095 | 7.1370 |

**Table 4.16. Transmittance in case 1 (U1), 2 (U2) and 3 (U3)**

January is the coldest month in Bilbao, as it can be seen in Table 1.6 of section 1.4.1. It is also the rainiest one and its relative humidity is around 80%. In case of transient transmission, the most insulated solution is the first one (1), whose cladding is made of natural Radiata-pine.

On the other hand, in December and February, the second (2) and third (3) solutions are the most insulated respectively. The solution with heat-treated wood cladding has the lowest design conductivity; however, when this material is simulated in transient mode by weather data it does not translate the same concept, as it does not represent the most insulated solution.

WUFI Pro software allows a video representation of hygrothermal behaviour of façades. This representation allows the correct interpretation of results as it is possible to see the water content, relative humidity and temperature development across the different layers, which compound the enclosure solutions. The condensation limit, represented by a purple line, is also represented along time in order to ensure there is no risk. In Figure 4.11, it is represented the hygrothermal behaviour of the studied solution made of heat-treated wood cladding (3).

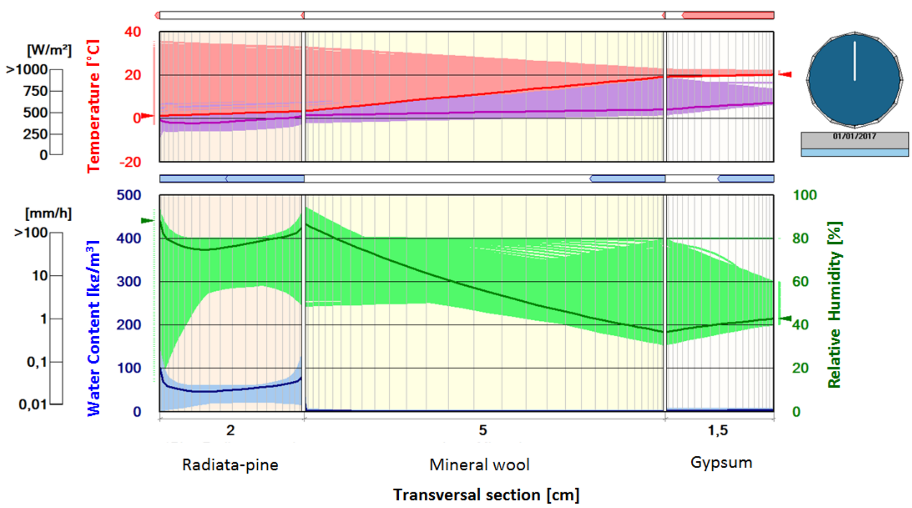



**Figure 4.11. Hygrothermal behaviour of case 1 during a year**

## 4.3 Computational fluid dynamics with Design Builder

In order simulate the test box, described in section 2.1, a simulation with Design Builder software is performed. Design Builder is a simulation tool which combines various energy modules in order to estimate heating and cooling energy demand into a room, using different systems and energy sources. This software combines different advanced tools based on the ENERGY PLUS engine [94, 95].

Through the CFD module (Computational fluid dynamics) it is able to analyse the energy losses of the test box, which were previously estimated and shown in Chapter 2, section 2.1. It also allows to foreseen how the air flows inside the box.

The Design Builder software analyse both moisture and heat transfer through a combined Heat and Moisture Finite Element, defined in the Heat Balance Algorithm. Because of that, the superficial air coefficients vary along time and depend on both temperature and mass transfer. However, it does not simulate the hygrothermal behaviour of walls between rooms.

In this example, the first test which corresponds to 21°C exterior temperature and 28°C inside temperature is simulated for natural Radiata-pine. In this case 0.103 W/(m·K) of thermal conductivity for this material is introduced. This is the value obtained through this test and method, which corresponds to a relative thermal conductivity derived from its hygrothermal properties in this moment.

Due to the limits of the software, the box is scaled 100 times bigger. The simulation was performed for a year. It is also needed to select the weather data in order to estimate the necessary consumption to heat the inner space of the test box. Because of that, a time selection was done, that is, the days and hours when the exterior temperature (Te) is close to the laboratory one are considered. In this case Bilbao climate data is introduced, where the laboratory is located. The interior temperature average is 28 °C (Ti). The simulation results are shown in the Table 4.17.

| Walls | Ceiling | Floor (ext) | Lost | Heating | Ti | Te |
|---|---|---|---|---|---|---|
| -0.3386 | -0.0115 | -0.0087 | -0.3588 | 0.3555 | 28,00 | 20,49 |
| **95.2%** | **3.2%** | **2.4%** | **0.9% error** | | | |
| **Lost percentage** | | | | | | |

**Table 4.17. Design Builder results for sample S1, to 28°C Test**

As it can be seen in the results there is an error between lost and heating results. That is because there have been chosen 287 days which temperature is similar to the laboratory one, in order to simulate the closest model. If total year data is taken the lost and heating value is just the opposite, as the system is presented in balanced.

If the results obtained are compared with the losses obtained through test box resistances, which were previously seen in Chapter 2, section 2.1, it can be appreciated a slight difference, as it is shown in Table 4.18.

| Walls | Ceiling | Floor (ext) | Lost | Heating | Ti | Te |
|---|---|---|---|---|---|---|
| -0.3358 | -0.0115 | -0.0115 | -0.3588 | 0.3555 | 28,00 | 20,49 |
| **93.6%** | **3.2%** | **3.2%** | **0.9% error** | | | |
| **Thermal resistance distribution** | | | | | | |

**Table 4.18. Design Builder results and lost in relation with box thermal resistance**

In this case, the Design Builder shows that the lost through ceiling is bigger than floor. That represents the behaviour of the air as it changes its density depending on temperature, so it produces a movement getting the hottest air in the upper level. Because of that the lost thought walls is increased and the percentage in Design Builder results is slightly higher than results related to the thermal resistance of the test box.

The convection inside the test box is supposed to be instable, due to the range of temperatures, while the exterior coefficient is more constant, as the temperature in the laboratory stay constant. In the hypothesis, the interior convective coefficient is estimated from the exterior one, taking into account the superficial temperatures registered in the test and the expression (6-3), section 3.2.2.1.

The Figure 4.12 illustrates the inner air behaviour thought a CFD simulation in Design Builder software.

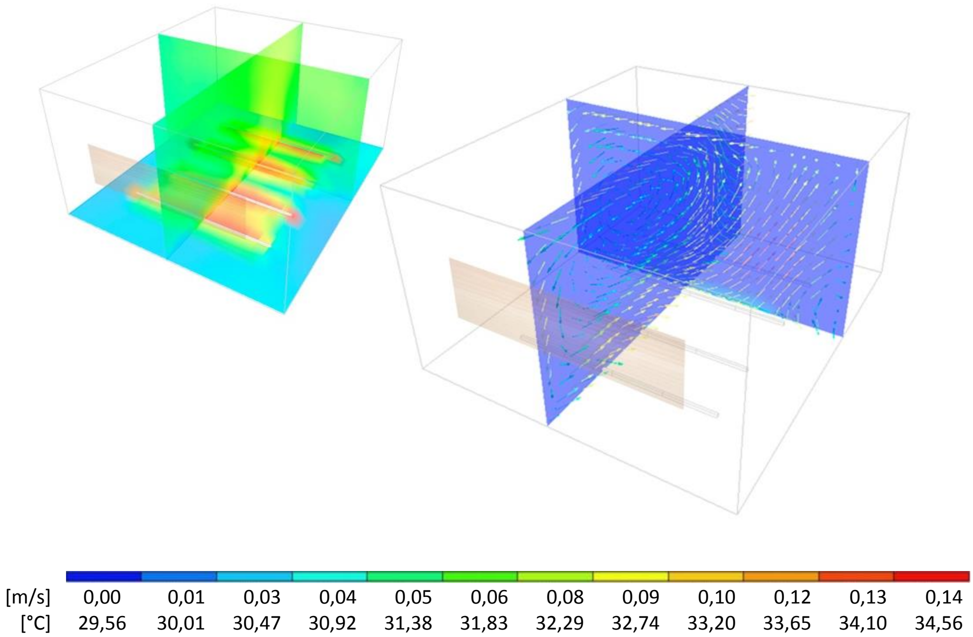



**Figure 4.12. CFD simulation of the test box**

The Design Builder software analyse both moisture and heat transfer through a combined Heat and Moisture Finite Element, defined in the Heat Balance Algorithm. Because of that, the superficial air coefficients vary along time and depend on both temperature and mass transfer.

In order to analyse the thermal behaviour of the material it is necessary these properties: thickness, conductivity, density and specific heat. In this case, 2 cm thickness, 0.103 W/(m·K) thermal conductivity tested by test box, 560 kg/m$^3$ density, and 1600 J/(kg·K) specific heat were introduced in the model. This last value was taken from the Spanish normative, the Building Technical code (CTE)[19], which apart from being an standard value, it is similar to the values obtained in section 3.3, chapter 3.

## 4.4 Conclusions

From the modelling it is concluded that the higher is the perimeter exposed to exterior; the lower is its thermal resistance, when the total thickness is the same in two cases. In this chapter a comparison between five solutions is made (D1, D2, D3, D4, D5), shown in section 4.1.

According to their simulation through THERM sv.73 software, the third solution (D3) is the least efficient in comparison with the rest of solutions, taking into account the same total thickness. In contrast, the most efficient is the first one (D1), which has more material and less discontinuousness.

On the other hand, the fourth solution (D4) has less material than the third one but it is more efficient, because its thermal resistance is slightly higher. That proves that the design influences directly in energy efficiency during its use phase, even considering the same total thickness. In this study, moisture flux was not considered, as this software does not allow this kind of assessment.

In terms of global sustainability, the mechanized processes also represent energy consumption, which derives in less sustainable solutions if the whole life cycle of the product is considered. Due to that, although being the least energy efficient solution during the use phase, in case of production phase, solutions such as D5 represent the least environmental impact as it is less mechanized. Besides, this solution has less costs and raw material consumption, which also interferes in sustainable development.

In order to analyse the hygrothermal behaviour of construction materials WUFI Pro software is commonly used. It also allows simulate heat transfer along time, which is not possible with THERM tool. In contrast, it does not allow study complex geometries as those simulated by THERM.

In order to simulate the heat transfer of the Radiata-pine samples by test box, WUFI Pro is used. In this case, the transient transmittance is obtained and compared. For that, generic properties and tested ones are introduced in the model. The boundary conditions are based on test “b”, which corresponds to 22 °C and 36 °C for exterior and interior temperatures respectively.

As a result, although heat-treated wood has lower thermal conductivity than natural and chemical treated one, depending on the boundary condition it does not have to be the solution with the lowest transmittance. That is, the lowest is the thermal conductivity of material, the lower is the superficial thermal resistance. In case of low thickness solutions, that implies more relevance, as both material resistance (Rm) and superficial thermal resistance (Rs) are closer. The material resistance is obtained by the development of expression (4-1), which directly depends on material thickness and thermal conductivity.

For the hygrothermal study a basic wooden façade solution is simulated. In this case, a comparison between claddings made of natural (1), chemical treated (2) and heat-treated (3) Radiata-pine is assessed in case 1, 2 and 3 respectively. UNE-EN 12664 conductivity values obtained for each sample in Chapter 3 were considered, as well as, resistance to water vapour diffusion, specific heat and emissivity properties obtained through tests.

It is demonstrated that the transient transmittance analysis for hygrothermal materials is complex, as in different months the lowest transmittance belong to a different solution. The hygrothermal behaviour plays an important role when its response to weather data is assessed, because the temperature and humidity are changing constantly along time. However, analysing the months with the most energy consumption, an optimization of the most suitable hygrothermal materials for specific façade systems could be possible.

Finally, in order to understand both convection coefficients and test box behaviour, its Computational Fluid Dynamics simulation is performed by Design Builder software. In this case, the attention is paid to the inside behaviour of the air, as it influences the global transmittance. It is demonstrated that the test works correctly as the main amount of heat passes across the sample. It also shows that there is an important air movement inside. Because of that, the convective laminar flux is only produced in the outside face of the sample, as it was contemplate in the principles described in section 3.2.2, Chapter 3.

*"Do not spend time beating on a wall, hoping to transform it into a door"*

Coco Chanel

1879-1909

# CHAPTER 5
# Durability

# 5 Durability

The Radiata-pine thermal conductivity varies depending on both water content and temperature gradient, as it is a hygrothermal material. In this thesis, the main interest is focused on the conductivity analysis compared with the material temperature gradient.

However, it is known that the degradation alters material properties, not only in terms of physical properties such as conductivity or mechanical strength [21, 96], but also its colour and appearance [22, 23, 97]. When other sustainable aspects like social sustainability are assessed, social awareness, culture and traditions play an important role. In this case, the aesthetic variation of wood depending on if it is treated or not is analysed, as it was included in the sustainable development seen in section 1.4, Chapter 1.

The samples described in section 3.2; natural, chemical treated and heat-treated Radiata-pine is tested. For the test, a previous analysis of weather conditions in Bilbao is studied in order to place the samples in the most harmful orientation and inclination, in order to degrade the material faster. The samples are 30 x 10 x 2 cm size.

The aim in this section is getting to know the grade of ageing in wood, as the both treatments mentioned protect wood against biotic agents and they were not specially create for keeping wood appearance, such as colour or roughness, although there are light stabilisers and films to protect wood against decolouration and superficial degradation [29, 30].

In Figure 5.1, the appearance of Radiata-pine is shown, in the three modes; natural, chemical treated and heat-treated wood. At first sight, they are completely different and easy to distinguish.

1) 2) 3)

**Figure 5.1. Natural wood (1), chemical treated (2) and heat-treated (3) Radiata-pine**

Natural wood is less dark than the other samples and it has the most ecological appearance, as it is natural.

In this case, the chemical treated wood is green coloured. This coloration can be produced due to the copper oxidation of the product, as it contains this element. This product is used to protect wood which is exposed to the *Class of Use* 3.2 and 4, previously explained in section 3.2.

On the other hand, the heat-treated wood is brown coloured. This coloration is produced due to burn of material at high temperature, 210 °C. This treatment allows wood to the *Class of Use* 3.2, which is the corresponding class for façades without contact with ground or fresh water.

## 5.1 Test preparation

In order to place the samples, UNE-CEN/TS 15397 EX is followed. In this case, the samples are separated and inclined facing the sun. The support is built according to the specifications of this norm [98].

In this test, the most harmful orientation and inclination for wood ageing is considered [99]. For that, the sample main surface to test is placed perpendicular to the sun in order to suffer the most amount of solar radiation, which implies 45° inclination respect to the horizontal plane. In case of orientation, the *Climate Consultant* software is used [100], in order to analyse the most harmful.

The tests are placed in the roof of the School of Engineering in Bilbao. The samples are elevated from the floor in order to avoid water splashes and the direct contact with ground, as the samples are analysed for their ageing in the *Class of Use* 3.2, previously mentioned.

The solar charts allow us to understand the solar path and light period depending on the season. There are two types; cylindrical and stereographic. In Figure 5.2, there are shown the cylindrical chart of Bilbao, from June to December, which representation is done by *Climate Consultant* software under the title of “Sun Shading Chart”. In this case, the software includes the different temperatures during the day. At the same time, it is represented the solar chart of Bilbao from December to June, in Figure 5.3.

In this case, the southwest is the most harmful orientation in relation with superficial deterioration as the gradient of temperatures varies more than in the other orientation. In both Figure 5.2 and Figure 5.3 it is marked the interval of direct solar radiance and temperature according to south-southwest (SSW) orientation, which is 30° turned from the south to the west.

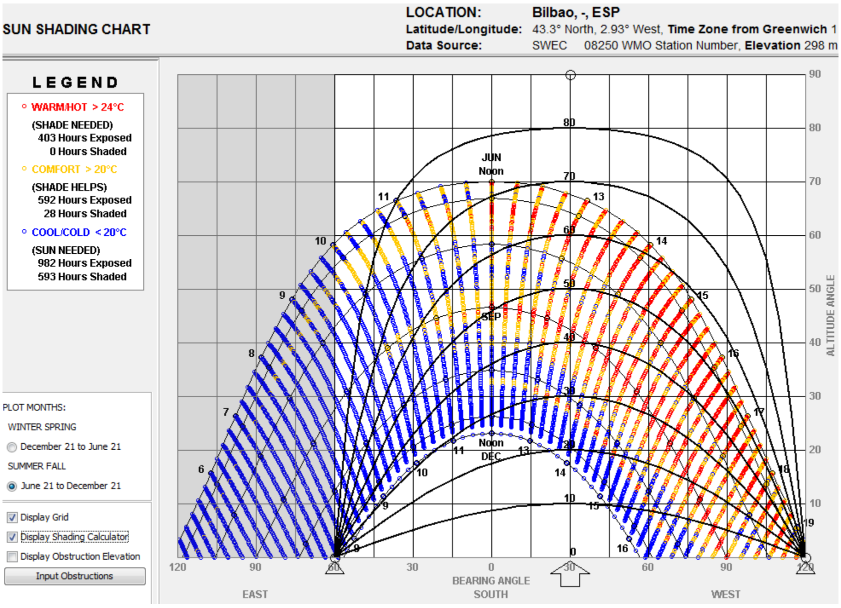



**Figure 5.2. Cylindrical solar chart, from June to December**

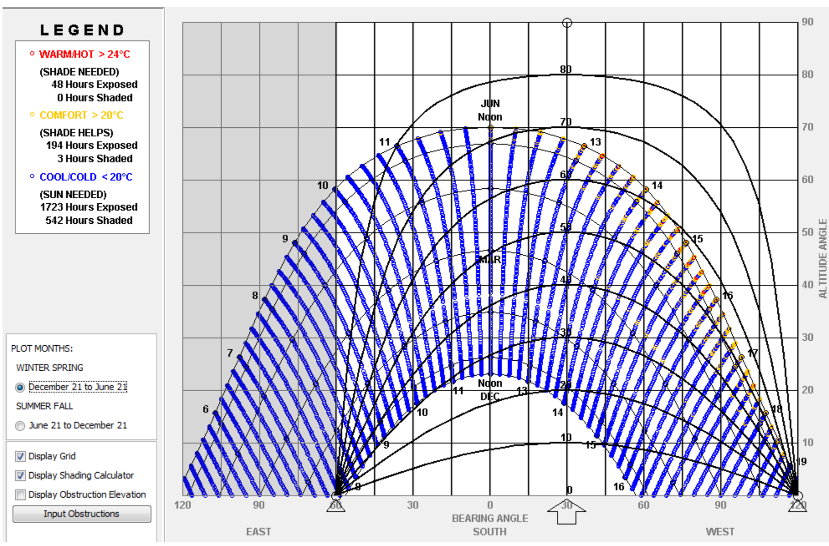



**Figure 5.3. Cylindrical solar chart, from December to June**

The samples are placed and tied on a plastic net, in order to evacuate water when it is raining and allow the wind pass due to safety. The system is similar to norm [98], where they can be seen different configurations. The main support is anchored to the floor.

Previously, it was done a shading study, in order to avoid sun interferences during test. Because of that samples are separated to each other, and there are no barriers or buildings closer to them that may interfere in protecting the samples against the abiotic agents; rain, wind, sun or snow.

In Figure 5.4, an example of shading simulation is shown. In this case, the sun path during 21th of January is represented. This kind of representation allows us to ensure that the test is placed properly and the sun points on the element, as it can be seen three-dimensional by the shading projection on the simulated ground.

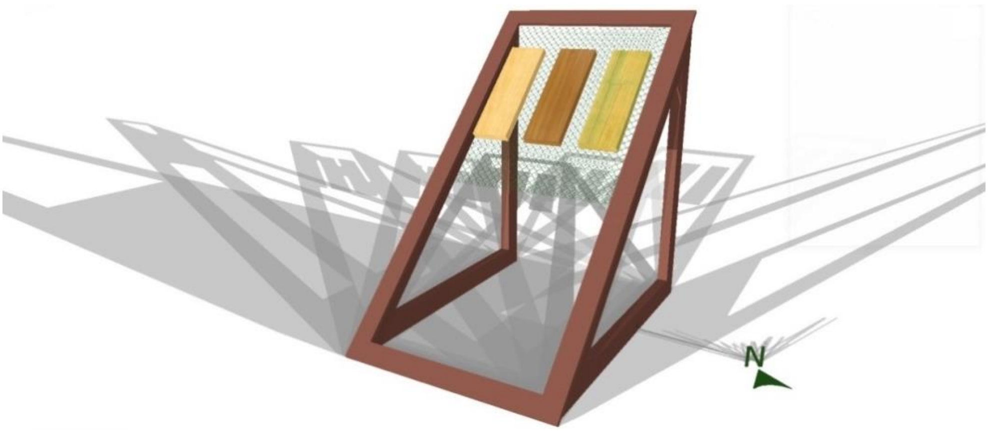



**Figure 5.4. Shading simulation of the test in January**

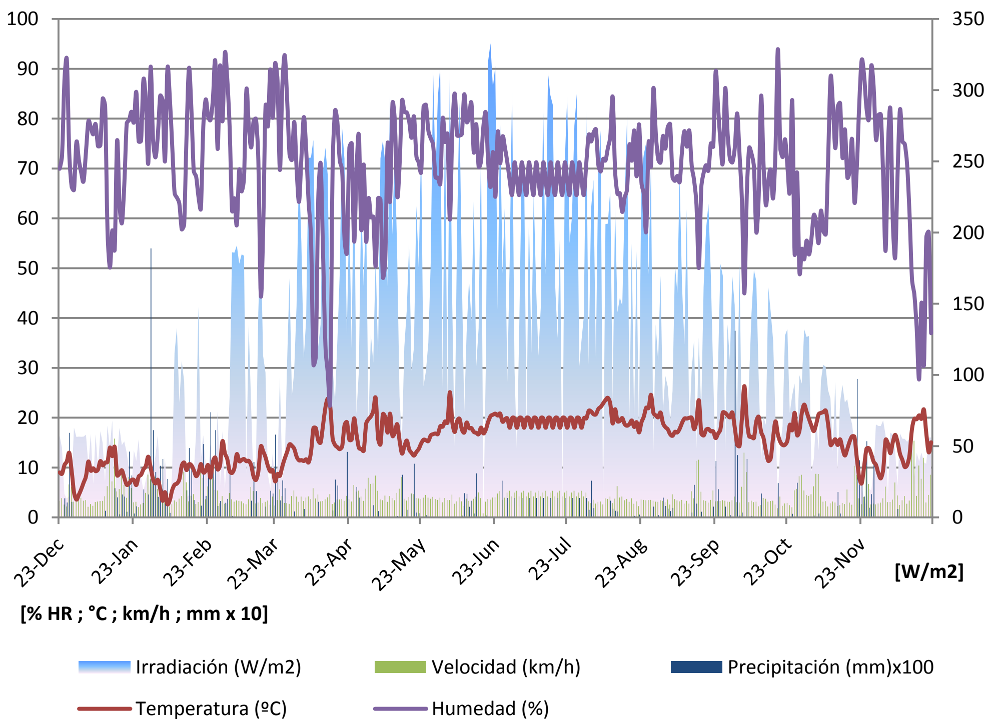
Once the support of the test is installed, the samples are placed. Those are separated each other at least 5 cm. In Figure 5.5, it is shown the test with the different samples. In this case, these photographs correspond to 23th of December 2014. This is the first day in test, which means that those are the original appearance of the samples. The photographs were taken at 12:50 am and it was a cloudless day.

**Figure 5.5. The samples placement**

## 5.2 Registration of climate data

All climate data are registered, in order link the material deterioration to weather data. In this case, the data registration started 23th December 2014. During two years, the samples keep in the same orientation and inclination, which were assessed in the previous section 5.1.

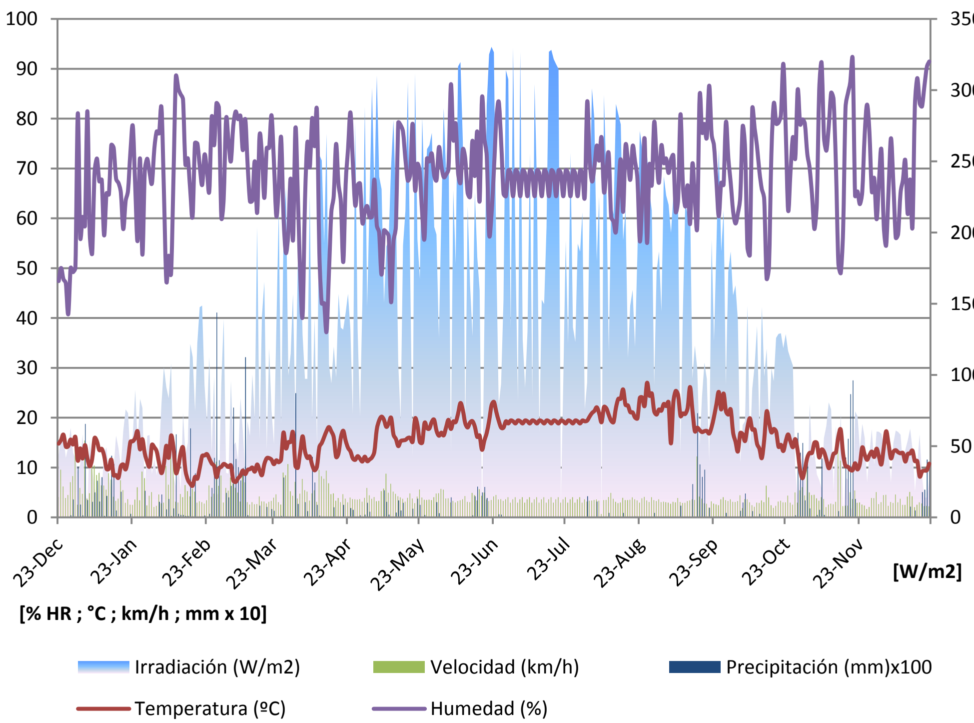
In Graphic 5.1, it is represented the climate data along 2015, in Bilbao. As it can be seen, the months with more solar irradiation are in May, June and July. In terms of rain, the rainiest months are January, February, March and November, although the second most rainy day was registered in October. If humidity is studied, it can be seen that in April and December it was lower than the rest of the year. On the other hand, June and July were the most regular months in terms of humidity and temperature, around 68 % and 20 °C average. The humidity registered in the rest of months was very irregular. In general terms, the temperature falls gradually from October and starts increase from March. The wind velocity goes from 0.3 to 15.8 km/h. If the average of all the year is calculated the value is 4.4 km/h. This agent influences the superficial rugosity of material due to friction deterioration.




**Graphic 5.1. Climate data during 2015 in Bilbao**

It is also detected that both July and August represent the months with less variability, in general terms, not only humidity and temperature values but also precipitation and wind velocity. In case of humidity and temperature, in Graphic 5.1 it can be seen a low variation due to day and night development along these months. In fact, the amplitude of their cycles is constant.

If climate data along 2016 is also analysed, it can be seen in Graphic 5.2 that the pattern is more or less the same as the previous year. In this year, its summer also represents the least variation in terms of both temperature and humidity. In fact, it was more dried and temperature constant than the previous one and there were less rainy days. In general terms, the humidity variations along 2016 were less pronounced than in 2015. In this case, the lowest relative humidity in average was 37.25 % and it took place 14th April.




**Graphic 5.2. Climate data during 2016 in Bilbao**

In Table 5.1, they are shown the most representative data during the first period of test which corresponds to the first three months, until 23th March. In this table is pointed the highest and lowest value of temperature and humidity registered. The maximum value of irradiation, wind velocity and precipitation are also registered as highly influence in ageing.

In this case, the lowest temperature registered was 0°C in the last day of December, while the highest temperature was 22.82 and it took place on 7th March. On the other hand, the maximum and minimum relative humidity took place on 26th February and 9th March respectively. The maximum irradiation, wind velocity and precipitation were 700 W/m$^2$ in March, 10.95 m/s and 3.1 mm in January, respectively.

| Date [dd/mm/yy] | Temperature [°C] | Humidity [%] | Irradiation [$W/m^2$] | Velocity [m/s] | Precipitation [mm] |
|---|---|---|---|---|---|
| 31/12/14 | MIN 0.305 | 82.7 | 0.658 | 1.152 | 0 |
| 07/03/15 | MAX 22.82 | 26.64 | 609.2 | 0.778 | 0 |
| 09/03/15 | 18 | MIN 24.09 | 316.6 | 1.594 | 0 |
| 26/02/15 | 11.29 | MAX 98.5 | 0.016 | 1.773 | 0.3 |
| 17/03/15 | 19.77 | 28.68 | MAX 700 | 1.713 | 0 |
| 15/01/15 | 14.6 | 44.36 | 16.4 | MAX 10.95 | 0 |
| 30/01/15 | 9.79 | 92.6 | 0.275 | 2.732 | MAX 3.1 |

**Table 5.1. Climate data from 23/12/2014 to 23/03/2015**

In Table 5.2, they are shown the most representative data during the second period of test, from 23th March to 23th June. In this period, the temperatures increased respect to the previous period, in case of the minimum and maximum temperature registered, which were 6th April and 4th June. In case of humidity, the maximum value obtained on 27th March is similar to the maximum value obtained a month ago. However, the minimum value registered on 14th April has decreased respect to the first period, from 24.09 to 14.15 %. The maximum irradiation is also higher, 1108 $W/m^2$. In terms of wind velocity, the highest one has also increased until 8.67 m/s, 5th May. The maximum precipitation registered keeps similar, 3.7 mm, on 26th April.

| Date [dd/mm/yy] | Temperature [°C] | Humidity [%] | Irradiation [$W/m^2$] | Velocity [m/s] | Precipitation [mm] |
|---|---|---|---|---|---|
| 06/04/15 | MIN 5.162 | 86.7 | 8.79 | 0.954 | 0 |
| 04/06/15 | MAX 36.92 | 21.55 | 752 | 1.068 | 0 |
| 14/04/15 | 30.15 | MIN 14.15 | 647.3 | 1.792 | 0 |
| 27/03/15 | 9.69 | MAX 98 | 2.381 | 0.482 | 0.1 |
| 28/05/15 | 20.25 | 64.19 | MAX 1108 | 1.362 | 0 |
| 05/05/15 | 22.08 | 33.74 | 0.66 | MAX 8.67 | 0 |
| 26/04/15 | 14.74 | 90.5 | 30.52 | 1.706 | MAX 3.7 |

**Table 5.2. Climate data from 23/03/2015 to 23/06/2015**

In Table 5.3, they are shown the most representative data during the third period of test, from 23$^{th}$ June to 23$^{th}$ September. As it can be seen, the maximum temperature registered 16$^{th}$ July is similar to the maximum temperature registered in June. However, the minimum temperature increases more than 5 °C until 11.65 °C, on 8$^{th}$ September. In case of humidity values, the minimum value is more similar to one registered in the first period instead of the second period value, which corresponds to 26.41 %, on 16$^{th}$ July. The maximum value decreases slightly until 96.7 %, on 28$^{th}$ August. In terms of wind velocity, the highest value registered is between the first and second period values, 9.9 m/s, on 15$^{th}$ September. The maximum precipitation value registered is considerably higher than the ones registered in previous periods, which correspond to 6 mm, on 26$^{th}$ June.

| **Date [dd/mm/yy]** | **Temperature [°C]** | **Humidity [%]** | **Irradiation [W/m$^2$]** | **Velocity [m/s]** | **Precipitation [mm]** |
|---|---|---|---|---|---|
| 08/09/15 | MIN 11.65 | 84.4 | 9.36 | 0.763 | 0 |
| 16/07/15 | MAX 36.57 | MIN 26.41 | 769 | 1.506 | 0 |
| 28/08/15 | 18.05 | MAX 96.7 | 0.002 | 0.505 | 0.2 |
| 13/07/15 | 22.75 | 65.31 | MAX 1005 | 1.542 | 0 |
| 15/09/15 | 24.19 | 52.8 | 991 | MAX 9.9 | 0.3 |
| 26/06/15 | 18.09 | 91.5 | 0.01 | 1.769 | MAX 6 |

**Table 5.3. Climate data from 23/06/2015 to 23/09/2015**

In Table 5.4, they are shown the most representative data during the fourth period of test, from 23$^{th}$ September to 23$^{th}$ December. In this period, the minimum and maximum temperature decreases precipitously until 3.5 and 28.5 °C respectively. The highest value was registered on 4$^{th}$ October and the lowest on 30$^{th}$ November. In case of humidity values, the maximum value increases 1 %, until 97.7 %, on 3$^{rd}$ December. However, the minimum humidity value falls 8% approximately respect to the previous period of time until 18.8 %, on 18$^{th}$ December. The highest irradiation decreases until 797 W/m$^2$, registered on 25$^{th}$ December. The wind velocity highest value is similar to the value obtained in the first period, 10.59 m/s. In case of precipitation, the maximum registered value is 7.5 mm on 30$^{th}$ September.

| Date [dd/mm/yy] | Temperature [°C] | Humidity [%] | Irradiation [W/m²] | Velocity [m/s] | Precipitation [mm] |
|---|---|---|---|---|---|
| 30/11/15 | MIN 3.50 | 95.4 | 1.057 | 0.903 | 0 |
| 04/10/15 | MAX 28.48 | 35.42 | 195.2 | 1.859 | 0 |
| 18/12/15 | 24.28 | MIN 18.18 | 0.663 | 4.322 | 0 |
| 03/12/15 | 10.45 | MAX 97.7 | 0.031 | 0.762 | 0 |
| 25/09/15 | 22.87 | 59.09 | MAX 797 | 0.844 | 0 |
| 13/12/15 | 24.19 | 52.8 | 991 | MAX 10.59 | 0 |
| 30/09/15 | 15.83 | 96 | 0.002 | 1.057 | MAX 7.5 |

**Table 5.4. Climate data from 23/09/2015 to 23/12/2015**

In Table 5.5, they are shown the most representative data during the fifth period of test which corresponds to the first three months of 2016, until 23th March. In this case, the lowest temperature registered was 1.06 °C in February, while the highest temperature was 22.45 and it took place on 25th January. On the other hand, the maximum and minimum relative humidity took place on 13rd and 22nd February respectively. The maximum irradiation and precipitation were 1012 W/m² and 25.5 mm in March, respectively. The maximum registration of wind velocity was 10.23 m/s in December.

| Date [dd/mm/yy] | Temperature [°C] | Humidity [%] | Irradiation [W/m²] | Velocity [m/s] | Precipitation [mm] |
|---|---|---|---|---|---|
| 18/02/16 | MIN 1.06 | 83.6 | 0.648 | 1.173 | 0 |
| 25/01/16 | MAX 22.45 | 41.86 | 368.1 | 0.26 | 0 |
| 22/02/16 | 20.63 | MIN 24.34 | 482.9 | 1.39 | 0 |
| 13/02/16 | 11.99 | MAX 97 | 0.004 | 0.398 | 0 |
| 20/03/16 | 15.12 | 41.67 | MAX 798 | 1.012 | 0 |
| 31/12/16 | 17.23 | 44.34 | 349.8 | MAX 10.23 | 0 |
| 15/03/16 | 8.57 | 56 | 506.3 | 2.93 | MAX 25.5 |

**Table 5.5. Climate data from 23/12/2015 to 23/03/2016**

In Table 5.6, they are shown the most representative data during the sixth period of test, from 23th March to 23th June. In this period, the minimum temperature registered was 4.22 °C in April, while the minimum one was 32.29 °C in June. In case of humidity, the maximum value obtained on 27th March is similar to the maximum value obtained a month ago. The minimum humidity value registered on 11st April has decreased respect to the previous period, from 24.34 to 22.45 %. The maximum irradiation is also higher, 1371 W/m$^2$. In terms of wind velocity, the highest one has decreased until 8.33 m/s, 9th April. The maximum precipitation registered was 4.6 mm, on 20th May.

| Date [dd/mm/yy] | Temperature [°C] | Humidity [%] | Irradiation [W/m$^2$] | Velocity [m/s] | Precipitation [mm] |
|---|---|---|---|---|---|
| 02/04/16 | MIN 4.22 | 79.7 | 0.518 | 0.893 | 0 |
| 23/06/16 | MAX 32.29 | 28.13 | 711 | 0.527 | 0 |
| 11/04/16 | 21.06 | MIN 22.45 | 503.7 | 2.466 | 0 |
| 01/04/16 | 10.80 | MAX 96.29 | 0 | 1.5182 | 0.4 |
| 27/05/16 | 26.74 | 31.84 | MAX 1102 | 1.371 | 0 |
| 09/04/16 | 15.71 | 47.01 | 371 | MAX 8.33 | 0 |
| 20/05/16 | 15.58 | 88.6 | 0.001 | 2.475 | MAX 4.6 |

**Table 5.6. Climate data from 23/03/2016 to 23/06/2016**

In Table 5.7, they are shown the most representative data during the seventh period of test, from 23th June to 23th September. As it can be seen, the maximum temperature registered 16th July is similar to the maximum temperature registered in June. However, the minimum temperature increases more than 5 °C until 11.65 °C, on 8th September. In case of humidity values, the minimum value is more similar to one registered in the first period instead of the second period value, which corresponds to 26.41 %, on 16th July. The maximum value decreases slightly until 96.7 %, on 28th August. In terms of wind velocity, the highest value registered is between the first and second period values, 9.9 m/s, on 15th September. The maximum precipitation value registered is considerably higher than the ones registered in previous periods, which correspond to 6 mm, on 26th June.

| Date [dd/mm/yy] | Temperature [°C] | Humidity [%] | Irradiation [W/m$^2$] | Velocity [m/s] | Precipitation [mm] |
|---|---|---|---|---|---|
| 18/07/16 | MIN 12.69 | 83.5 | 28.63 | 0.642 | 0 |
| 21/07/16 | MAX 40.3 | 14.91 | 603 | 0.981 | 0 |
| 27/08/16 | 39.32 | MIN 10.96 | 600.5 | 0.428 | 0 |
| 03/08/16 | 18.28 | MAX 97.1 | 3.218 | 1.01 | 0.2 |
| 12/08/16 | 22.76 | 62.74 | MAX 1078 | 2.009 | 0 |
| 18/09/16 | 18.43 | 45.78 | 458.7 | MAX 6.92 | 0 |
| 15/09/16 | 21.62 | 84.8 | 6.485 | 2.736 | MAX 5 |

**Table 5.7. Climate data from 23/06/2016 to 23/09/2016**

In Table 5.8, they are shown the most representative data during the last period of test, from 23$^{th}$ September to 23$^{th}$ December. In this period, the minimum and maximum temperature decreases precipitously until 3.5 and 28.5 °C respectively. The highest value was registered on 4$^{th}$ October and the lowest on 30$^{th}$ November. In case of humidity values, the maximum value increases 1 %, until 97.7 %, on 3$^{rd}$ December. However, the minimum humidity value falls 8% approximately respect to the previous period of time until 18.8 %, on 18$^{th}$ December. The highest irradiation decreases until 797 W/m$^2$, registered on 25$^{th}$ December. The wind velocity highest value is similar to the value obtained in the first period, 10.59 m/s. In case of precipitation, the maximum registered value is 7.5 mm on 30$^{th}$ September.

| Date [dd/mm/yy] | Temperature [°C] | Humidity [%] | Irradiation [W/m$^2$] | Velocity [m/s] | Precipitation [mm] |
|---|---|---|---|---|---|
| 10/12/16 | MIN 3.629 | 88.4 | 0.638 | 0.902 | 0 |
| 24/09/16 | MAX 29.08 | 42.89 | 502.4 | 0.637 | 0 |
| 14/10/16 | 23.63 | MIN 28.86 | 55.28 | 2.313 | 0 |
| 21/10/16 | 12.37 | MAX 100.2 | 0 | 0.648 | 0 |
| 27/09/16 | 20.44 | 64.42 | MAX 799 | 1.05 | 0 |
| 13/11/16 | 15.63 | 49.53 | 0 | MAX 9.07 | 0 |
| 27/10/16 | 14.56 | 93 | 0.002 | 1.594 | MAX 3 |

**Table 5.8. Climate data from 23/09/2016 to 23/12/2016**

To sum up, the minimum temperature in 2015 was registered in December and the maximum in June, while in 2016 these were registered in February and July respectively. In terms of humidity, the minimum values were registered in April 2015 and August 2016. The maximum relative humidity values in all periods keep similar, between 95 and 100 %. The maximum value of irradiation was registered in April for both years. The maximum wind velocity took place in January 2015 and December 2016. In case of precipitation, the maximum value was registered in March 2016.

## 5.3 Weathering analysis

The samples were installed in December, on the roof of the School of Engineering in Bilbao (University of the Basque Country). In order to evaluate the visual degradation of Radiata-pine, photographs were taken every month. The samples were named as Sample 1, 2 and 3, which corresponds to natural, chemical treated and heat-treated Radiata-pine, respectively.

In Table 5.9, there are shown the different photographs of the samples with a brief description, during the deterioration process. In this case, the period goes from January to March 2015. In this season the climate variation is normal, having sunny days, rain or even snow in short period of time. These data can be seen in Table 1.6, which is described in section 1.4.1, and Graphic 5.1, described in the previous section 5.2.

In case of the natural wood (1), it can be seen that after three months it begins to have some spots. This is characteristic of fungi, as this sample is not protected against biotic agents. In contrast, the treated samples (2, 3) do not present spots as they are treated wood. In terms of cracks, the natural sample does not present them, while chemical and heat-treated samples start to shown some of them. However, cracks are sharper in the third sample than in the second one, which can be defined as small fissures.

In Table 5.10, it can be seen the photographs of the different samples from April to June 2015. In this case, the three samples colour keeps stable. Sample 2 is more coloured than he others in this period of time. In terms of cracks, Sample 1 presents them sharper during May, which can be due to the fast drying of the material after wetting, as the samples are placed facing sun, in order to capture the most amount of solar radiation. In June the cracks are less sharp because of material swelling. In case of Sample 2 and 3, the cracks are also wider in May than in June, although in Sample 2 those are very small.

In this case, both irradiation and temperature arises notably respect to the data registered in previous months. On the other hand, precipitations were cut down significantly.

In Table 5.11 and Table 5.12, there is represented the samples deterioration from July to December 2015. In both tables the coloration and cracks of the three samples keep constant, where is difficult to see large differentiation, as the sun light interferes in the colour perception.

From July to September, the temperatures and irradiation are higher than from October to December. On the other hand, the precipitations in both periods also differ, having more rainy days in November. Although the most intense rain day in this period was registered in September, as it can be seen in section 5.2, the amount of precipitation registered per month was higher, as it is usual according to historic data.

In Table 5.13, Table 5.14, Table 5.15 and Table 5.16, there are shown the different photographs of the samples with a brief description during the deterioration process after a year ageing, that is, in 2016. The deterioration of the samples runs more slowly and the difference between seasons is getting less significant. If the photographs in Table 5.13 are compared to Table 5.16 photographs both colour and cracks keep quite similar. In general terms, the most harmful deterioration of the samples takes place the first year exposed to weather.

| January | February | March | Description |
|---|---|---|---|
|  |  |  | **Sample 1**<br>It is appreciated the apparition of some spots which are visible on the surface. There are no cracks. |
|  |  |  | **Sample 2**<br>It is appreciated the apparition of some fissures along the surface. The colour keeps green. |
|  |  |  | **Sample 3**<br>It is appreciated the apparition of some longitudinal cracks along the surface, parallel to fibres. |

**Table 5.9. Visual assessment of the samples ageing, from January to March, 2015**

| April | May | June | Description |
|---|---|---|---|
|  |  |  | **Sample 1**<br>Both colour and spots keep stables. Some fissures appear and they are more pronounced in May, due to the retraction of the material.<br>Respect to the previous months it has lost its colour turning grey. |
|  |  |  | **Sample 2**<br>The colour keeps stable and there are no spots. The fissures are more pronounced in May and less in June.<br>Respect to the previous semester, the colour is turned into bright brown. |
|  |  |  | **Sample 3**<br>The colour keeps stable and there are no spots. The fissures are more pronounced in May and slightly less pronounced in June.<br>Respect to the previous semester, wood has turned grey. There is a huge difference in colour. |

**Table 5.10. Visual assessment of the samples ageing, from April to June, 2015**

| July | August | September | Description |
|---|---|---|---|
|  |  |  | **Sample 1**<br>Both colour and spots keep stable. There are no new fissures.<br>Respect to the previous semester, its colour has turned more grey and dark. |
|  |  |  | **Sample 2**<br>Colour keeps stable without spots. There are no new fissures.<br>Respect to the previous semester, the colour is turned into brown and it has lost intensity. |
|  |  |  | **Sample 3**<br>Colour keeps stable without spots. There are no new fissures.<br>Respect to the previous semester, wood is even greyer and its fibres are better distinguished. |

**Table 5.11. Visual assessment of the samples ageing, from July to September, 2015**

| October | November | December | Description |
|---|---|---|---|
|  |  |  | **Sample 1**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, its colour has lost intensity. |
|  |  |  | **Sample 2**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, its colour has lost intensity. |
|  |  |  | **Sample 3**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, its colour has lost intensity. |

**Table 5.12. Visual assessment of the samples ageing, from October to December, 2015**

| January | February | March | Description |
| --- | --- | --- | --- |
|  |  |  | **Sample 1**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, it keeps similar. |
|  |  |  | **Sample 2**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, it keeps similar. |
|  |  |  | **Sample 3**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, it keeps similar. |

**Table 5.13. Visual assessment of the samples ageing, from January to March, 2016**

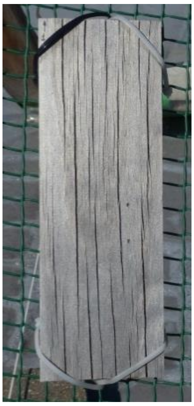
| April | May | June | Description |
|---|---|---|---|
|  |  |  | **Sample 1**<br>Colour keeps stable and the fissures are strongly pronounced in April.<br>Respect to the previous semester, its colour keeps similar. |
|  |  |  | **Sample 2**<br>Colour keeps stable and the fissures are strongly pronounced in April.<br>Respect to the previous semester, its colour keeps similar. |
|  |  |  | **Sample 3**<br>Colour keeps stable and the fissures are strongly pronounced in April.<br>Respect to the previous semester, its colour keeps similar. |

**Table 5.14. Visual assessment of the samples ageing, from April to June, 2016**

| July | August | September | Description |
|---|---|---|---|
|  |  |  | **Sample 1**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, it keeps similar. |
|  |  |  | **Sample 2**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, it keeps similar. |
|  |  |  | **Sample 3**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, it keeps similar. |

**Table 5.15. Visual assessment of the samples ageing, from July to September, 2016**

| October | November | December | Description |
|---|---|---|---|
|  |  |  | **Sample 1**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, it keeps similar. |
|  |  |  | **Sample 2**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, its colour has slightly lost its intensity. |
|  |  |  | **Sample 3**<br>Colour keeps stable and there are no new fissures.<br>Respect to the previous semester, it keeps similar. |

**Table 5.16. Visual assessment of the samples ageing, from October to December, 2016**

In Figure 5.6, Figure 5.7 and Figure 5.8, it is represented the Sample 1, 2 and 3 appearance before the test, after a testing year and after two testing years. As it can be seen, after a year the deterioration speed falls in the three cases, as it is difficult to analyse the change of colour and the apparition of new cracks in each sample. The appearance is relatively constant.

a b c

**Figure 5.6. Sample 1, before (a), after a year (b), after two years (c)**

a b c

**Figure 5.7. Sample 2, before (a), after a year (b), after two years (c)**

a b c

**Figure 5.8. Sample 3, before (a), after a year (b), after two years (c)**

In terms of water content, it is also detected that Sample 1 absorbs more water than Sample 2 and much more than 3, as it can be appreciated in Figure 5.9. That means that the protect process alters the water absorbance of the material, which is necessary in order to keep wood in lower percentage of humidity and avoid fungi growing.

1 2 3

**Figure 5.9. Samples after rainy days, 04/09/2015**

### 5.3.1 Emissivity

In Figure 5.10 it is shown the ageing samples after 2 years, both photograph and thermography, which was taken considering the unit as emissivity value of reference. After obtaining the temperatures along a line of points (P1, P2, P3), which corresponds to natural (1), chemical treated (2) and heat-treated (3) Radiata-pine, it is possible to estimate wood emissivity because the black plastic material has a known value, 0.95 of emissivity as it was previously explained in section 3.2.2.1.2, Chapter 3. These lines (P1, P2, P3) are proportionally divided into 18 points of temperature

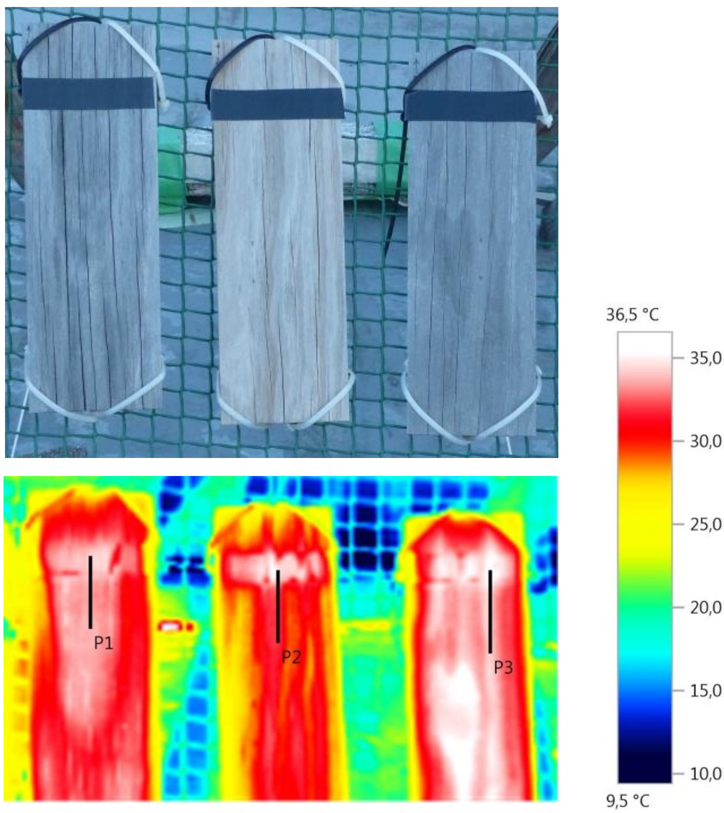



**Figure 5.10. Reference termography (ε = 1)**

In Table 5.17 they are shown the different values of temperature (T) and emissivity (ϵ) obtained through thermography. At first, the reference thermography is realized taking into account the unit as the reference value of emissivity, which corresponds to a black body, obtaining a reference temperature ($T_0$) along the lines P1, P2 and P3. Then the real emissivity of wood is obtained, as the emissivity of the reference black plastic material is known, which is 0.95, and the temperature of both wood and black plastic has to be the same. That is, the temperature of the natural (1), chemical treated (2) and heat-treated (3) wood samples is 36.21, 36.63 and 37.68 °C, respectively.

| | P1 | | | P2 | | | P3 | | |
|---|---|---|---|---|---|---|---|---|---|
| Points | $T_0$ [°C] | ϵ [-] | T [°C] | $T_0$ [°C] | ϵ [-] | T [°C] | $T_0$ [°C] | ϵ [-] | T [°C] |
| 1-7 | 34.30 | 0.95 | 36.21 | 34.80 | 0.95 | 36.63 | 35.8 | 0.95 | 37.68 |
| 8-9 | 33.7 | 0.93 | 36.21 | 32.4 | 0.88 | 36.63 | 34.9 | 0.93 | 37.68 |
| 10-18 | 33.4 | 0.92 | 36.21 | 31.9 | 0.87 | 36.63 | 34.3 | 0.91 | 37.68 |

| Reference: Black material | Boundary | Wood |
|---|---|---|

**Table 5.17. Reference temperature ($T_0$), material temperature (T) and emissivity (ϵ) of P1, P2 and P3**

If the results are analysed, natural wood has 0.92 of emissivity, chemical treated wood has 0.87, and heat-treated wood has 0.91, after 2 years. As it can be appreciated, the hottest sample corresponds to heat-treated wood (3) with 37.68 °C temperature, while natural wood (1) represents the lowest heat with 36.21 °C and chemical treated wood (2) an intermediate value of 36.63 °C temperature, in that instance. However, in terms of emissivity the sample with the highest value of emissivity is not the hottest. That is, although natural wood represents the least reflective material, it does not absorb as heat as the others.

If material emissivity before ageing and after one and two years is assessed, it can be seen that this varies, as it is shown in Table 5.18. Although, the variation of material morphology among samples makes impossible to stablish an exact differentiation of deterioration influence, in general terms, it is possible to affirm that ageing cuts down emissivity.

| | Origin | 1 year | 2 years |
|---|---|---|---|
| 1 | 0.93 | 0.83 | 0.92 |
| 2 | 0.93 | 0.89 | 0.87 |
| 3 | 0.93 | 0.88 | 0.90 |

**Table 5.18. Emissivity variation in sample 1, 2 and 3 before and after ageing**

## 5.4 Thermal conductivity

The thermal characterization of natural (1), chemical treated (2) and heat-treated (3) Radiata-pine is assessed. For that, the test box procedure previously described in Chapter 2 is followed. In this case, a correlation between their characterization results presented in Chapter 3, section 3.2.2.3, is realized.

The deteriorated samples were tested though test "a", previously described in section 3.2.2.2, which corresponds to a gradient of temperature between 9 and 11 °C among sample faces, with 40°C temperature inside the test box and 21°C outside. In this case, both original and ageing samples were tested at the same time in order to compare them with similar boundary conditions, as both temperature and humidity influence the wood thermal behavior, as it was previously studied in section 4.2. In this case, the relative thermal conductivity is obtained.

In Table 5.19, there are shown the results obtained by the three samples. A difference between the original samples conductivity (λ) and those after deterioration (λ´) is realized.

| | λ | λ´ | Δλ |
|---|---|---|---|
| | [W/(m·K)] | | [%] |
| **1** | 0.1202 | 0.0821 | -31.65 |
| **2** | 0.1205 | 0.0898 | -25.44 |
| **3** | 0.1215 | 0.1006 | -17.18 |

**Table 5.19. Thermal conductivity variation between original (λ) and elder samples (λ´)**

If the results presented in Table 5.19 are analysed, a decrement of the thermal conductivity after the deterioration is obtained. This fact makes the material more insulated than previously. That is, it is demonstrated that deteriorated Radiata-pine has lower thermal conductivity than original one.

## 5.5 Conclusions

As it was previously mention, during the first period of time, from January to March 2015, there were sunny cloudless days, rain and even snow during some days. The sharp and fast variation of those elements makes deterioration of the samples growing up faster. The most remarkable appearance changes take place from March to April, when the material is not adaptable to environment yet. In fact, there is a huge difference in colour between these months. While during March the colour is similar to original one, in April both natural (1) and heat-treated (3) sample become grey. However, chemical-treated one (2) changes from green to pale brown colour, turning its appearance to more natural colour.

After April, both natural (1) and heat-treated (3) Radiata-pine samples appear to be the same, which makes difficult to distinguish them. In terms of cracks they are also similar, which are wider than the fissures of the chemical treated sample. If rugosity is analysed, natural and heat-treated Radiata-pine also presents the most variation, while chemical treated Radiata-pine keeps less deteriorated after two year.

However, in terms of thermal behaviour, the least variation of thermal conductivity after a year weathering is presented by the heat-treated wood (3), while the natural wood (1) presents a variation more than two times higher. In case of chemical treated wood (2), its difference respect to Sample 3 is lower than Sample 1.

Although the third sample (3) is the most stable material, in terms of thermal conductivity, the conductivity variation of the first sample (1) is the most beneficial in terms of energy efficiency.

*“Education is the powerful weapon which you can use to change the world”*

Nelson mandela

1918-2013

# CHAPTER 6
# Sustainability

# 6 Sustainability

The environmental factor is of key importance in terms of the outlook for global sustainability. The actual environmental crisis on the planet, where resources are becoming scarcer every day [101], implies environmental degradation due to problems linked to global warming, acid rain, and ozone depletion of the stratosphere, among others. Many of these effects are attributed to continuous industrial development on our planet. Thanks to sustainable development, there is today a greater awareness in society across all sectors and many actions are underway to reduce the impacts generated in the environment. As Jain and Jain noted [102], in the final analysis, development and the environment are in all probability not independent dimensions.

In this sense, the construction sector has a lot to answer for, as it is one of the principal drains on natural resources and energy. As an example, during their 'lifecycle' (including building, maintenance and demolition), buildings are 'responsible' for 50% of total energy consumption and for 50% of total CO2 atmospheric emissions [103].

Many of the actions in this sector concentrate on the use of materials with higher sustainable rates, in the widest sense; in other words, materials that are recyclable, reusable or naturally renewable, as in the case of timber [104-108], As switching over to certain materials may not be globally achieved immediately, because of the disruption to present-day industry that such changes would cause, this process should be gradually developed. So, firms should continue to adapt to demand in society through product development, while striving to incorporate these new environmental requirements in their products [109].

Over recent decades, different procedures and methodologies to analyse the sustainability of buildings have been developed [110-114]. Some of these tools assess economic and social components, as well as their environmental impact, which are the 3 basic pillars of sustainability [115, 116]. Moreover, the governments of various countries have participated in this process and have been introducing directives and standards that generalize this process of improvement. In the case of Spain, the regulations currently in force - the Technical Building Code [6] has introduced measures related to the minimization of water and energy consumption as well as other materials in the building process [117].

Moreover, the characteristics of wood as a building material, in terms of both strength and the environment, make it an ideal material for the construction of buildings. Even so, it is important to take into account that, as with all materials, wood has to comply with a series of standards, so that it is used as efficiently as possible from an environmental standpoint.

Hence, the main purpose of the present chapter is to develop a methodology to address the degree of "environmental sustainability of wood cladding", by assigning a numeric value, on a scale between 0 (minimum) and 1 (maximum), to different enclosure solutions (scenarios) [118]. Those scenarios will be proposed at a project design stage for a particular wooden enclosure, making it possible to select the most environmentally sustainable option to execute the project.

## 6.1 Assessment model for environmentally friendly cladding

### 6.1.1 Analytical Framework

There are a wide range of methodologies for sustainability analysis [117]. However, sufficient research on rigorous and global evaluation models (quantitative objectives) is as yet unavailable to form an overview of sustainability, consisting at the very least of: environmental (EcoProfile, GBA), economic (BEES) and social factors [119, 120]. Additionally, it may be underlined that most of the methodologies that have been developed refer to environmental issues and not, for example, to Health and Safety [121].

Besides, some of the existing methodologies are intended to evaluate the impacts that are very precisely generated when using life-cycle analysis, based on identifying and quantifying resource flows (inputs: energy. raw materials and water) and environmental emissions (outputs: to the air. water and soil), associated with all stages of their life cycle. These types of tools demand expert knowledge of the source and transformation of the materials used in the building, involving an immense amount of work for data processing [122]. Moreover, their application is dependent on the data that is gathered. As in all countries, the building techniques, the extraction of raw materials, and the generation of energy are not the same for each building, which implies a very significant amount of data collection (in each country), to amass all the necessary information for the analysis [123].

Other building assessment methodologies [124] have established easier models, require less information, and their application is therefore simpler. In other cases, they are based on confirming compliance with a series of requirements that improve building characteristics, such as the US Green Building Council 2010, the Institutional Initiative for a Sustainable Built Environment (iiSBE), and the Building and the Sustainable Rehabilitation Guide for Housing in the Autonomous Region of the Basque Country [125].

Finally, others are based on impact assessment using ‘‘eco-points’’ (number of eco-points obtained acting as a comparative element and reflecting improved environmental design) such as ENVEST (BRE-UK) or based on eco-efficiency concepts such as CASBEE in Japan. All of the above tools have their own calculation methodologies, which are easy to manage in some cases and in others, are based on complex algorithms.

In the case of the Spanish code for concrete and steel [126, 127] an index of environmental sustainability was obtained using an adaptation of the MIVES methodology, which addresses the complex issue of sustainability assessment in a straightforward manner. Thus, the analysis is not excessively time consuming and is easy to understand for practitioners.

### 6.1.2 Evaluation methodology

Whatever evaluation methodology is used, different aspects are evaluated in all existing models (often referred to as criteria and indicators), which are related to the different components of the building (such as façades. roofs and installations), which might require different units of measurement (surface, energy, weight, etc.) based on weighted scoring systems for different parameters [128]. Hence, the sustainability evaluation process will probably use multi-criteria evaluation techniques, where the final result is linked to the evaluation of different criteria, by grouping measurable aspects with heterogeneous units.

These types of decision-making methodologies were previously employed as tools to assist with decision-making in the construction industry: productivity and worker motivation [129], building sector technologies [130], health and safety (H&S) issues [130], social problems [131], costs and quality [132]. Also, in the business world, certain authors [133] have considered the effect on financial aspects of the construction sector. In this last case, business conditions are continually changing and depend on a large number of criteria, which may include either quantitative or qualitative variables or a mixture of both types.

Therefore, the need may be established to carry out preference assignation of some criteria in relation to others, based on attributes where complete information is lacking [134]. The method for this weighting process develops the "Analytic Hierarchy Process (AHP)" decision method proposed by Thomas L. Saaty in 1971. AHP [135] takes into account the relative importance of various aspects (criteria, indicators, etc.) in a project assessment by means of a logical and structured working method, which optimizes complex decision-making problems, through the reformulation of a problem in a hierarchical structure [113, 136-139].

Thus, as shown in Figure 6.1, a particular problem, in this case the evaluation of environmental sustainability, may be subdivided into a set of simpler criteria to be separately evaluated and to determine the influence of each one on the final objective. This is the result of the MIVES methodology [140], based on the following elements. First, an initial evaluation tree that represents the components to measure and the relationships between them. Second, the final elements (the indicators) of the tree that are quantifiable parameters in specific units. Third, the value functions, which transform the quantifications of the sustainability indicators into a similar standard unit. And, finally, the fourth consists of the weighting system (either direct or using various techniques. such as AHP), which defines the importance of each element in the tree and generates a single value.

The aforementioned models based on the MIVES methodology are described in the works and drawing of various authors [121, 141-148].

### 6.1.3 Development of the tree

The scheme (hierarchical decision tree) in Figure 6.1 represents an analytical framework of sustainable criteria referring to different types of environmental information on, in this example, a timber building with wooden façade and roof. A criterion may be broken down into a series of assessment ‘‘indicators’’ that constitute the lowest hierarchical level of the requirement tree.

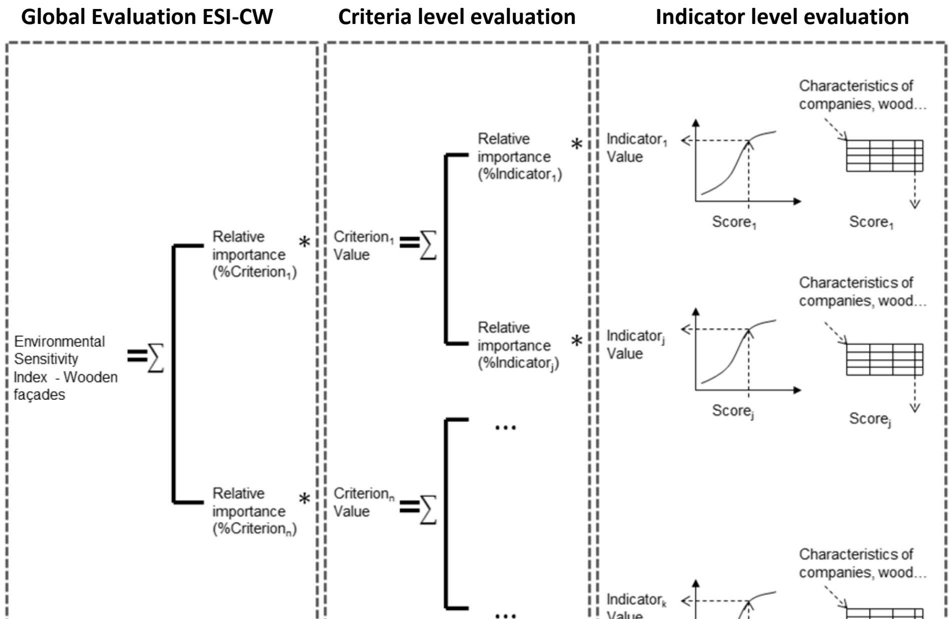



**Figure 6.1. General Hierarchy Diagram of the Evaluation**

The organization of the decision tree will depend on the use to which the indicators are put, in relation to their set objectives, and the selected criteria are the key parameters, which help specify the indicators, constituting the situation status of each study scope. Therefore, the criteria enable the formulation of multi-dimensional objectives necessary to further the design of the environmental sustainability index of wooden façades.

However, the selection of appropriate criteria is a complex task given its significant influence over the final results [149]. For example, the UNE-EN ISO 14031 Environmental Management, Environmental Performance Evaluation, Guidelines [150] lay down the following general criteria for obtaining environmental information and selecting indicators: “Coherence with the environmental policies of each particular country, adaption to the managerial policies, relevance and meaning to internal and external parties with an interest, inclusion of the most pertinent aspects that might imply an impact on the environment and society, adaption to the envisaged use, as per type, quality and quantity of data. representative of company environmental behaviour”, among others. So the degree of compliance with all of these requirements should be reflected in each of the selected indicators.

All of the selected assessment criteria will, of course, be different, as will the indicators defined for their assessment, having two main typologies: direct and indirect, as clearly stated by Garrucho [144]. Thus, the proposed assessment model shown in Figure 1 has a set of different hierarchical levels, ranging from the criteria to the indicators. In figure 1, a series of values (weightings or weights) is assigned to each criteria and indicator. The AHP method approves the values that are assigned by means of a paired comparison of each criterion, which facilitates the objectivity of the process and substantially curtails purely intuitive decision-making [136].

### 6.1.4 Value functions

The assignation of an environmental sustainability index begins with the on-site actions in the building, according to each of the defined indicators, which are valued through a value function. This score is obtained with the mathematical expression defined by Alarcón [146]. The value functions ($Vi$) vary from 0 to 1 (respectively, the minimum and the maximum score of each indicator) and depend on several parameters related with the function shape and the way in which that indicator value corresponds to an adimensional scale (“value”). The selected value function (mathematical expression) is as follows.

$$Vi = A + \frac{1}{B} \cdot \left[ 1 - e^{-ki \cdot \left( \frac{x_{alt} - x_{min}}{C_i} \right)^{P_i}} \right] \tag{6-1}$$

Where;

$$B = \frac{1}{1 - e^{-ki\cdot\left(\frac{|x_{max}-x_{min}|}{C_i}\right)^{P_i}}} \quad \textbf{(6-2)}$$

*$C_i$ : Abscissa value at the inflection point on curves with $P_i > 1$*
*$x_{min}$ : The minimum reference point on the indicator scale. Indicator response generated = 0*
*$x_{max}$ : Maximum reference point on the indicator scale. Indicator response generated = 1*
*$x_{alt}$ : Response to the assessed alternative regarding the respective indicator. value between $x_{min}$ and $x_{max}$. Indicator response generated = $Vi(x_{alt})$*
*$P_i$: Form factor defining whether the curve is: concave. convex. straight or "S" shaped. Concave curves imply $P_i < 1$. Convex or "S" shaped curves imply $P_i > 1$. Straight lines $P_i > 1$*
*$D_i$ : Abscissa value at the inflection point (curves $P_i > 1$)*
*$K_i$ : Ordinate value of point $C_i$*
*$A$ : Value of response "$x_{min}$". $A = 0$ or $A = 1$ (usually $A = 0$).*
*$B$ : Factor for maintaining value function in range [0-1] and the best response equal to 1 (see factor B below)*

### 6.1.5 Weighting factors

The final objective of the proposed methodology is to establish a means of evaluating the environmental sustainability of a wooden façade, in the design project. Therefore, the process is applied to all of the indicators until the entire sublevel of indicators is defined and, afterwards, having defined the respective values and weights at the indicator sublevel, the additive value function is applied. Subsequently, the valuation process at the lowest level (indicators) yields a sustainability value (scale [0–1]), and so on until the highest hierarchical level is reached: firstly criteria and. finally the ESI-CW. as shown in Figure 1 (general overview) and in Figure 2 (specific case study).

In this respect, Figure 2 represents the particular hierarchy tree of the assessment model with all the assigned weighting factors, specifically designed for evaluating the Environmental Sustainability of Cladding made of Wood (ESI-CW). The different hierarchical levels are traced from the criteria (2) down to the indicators (5).

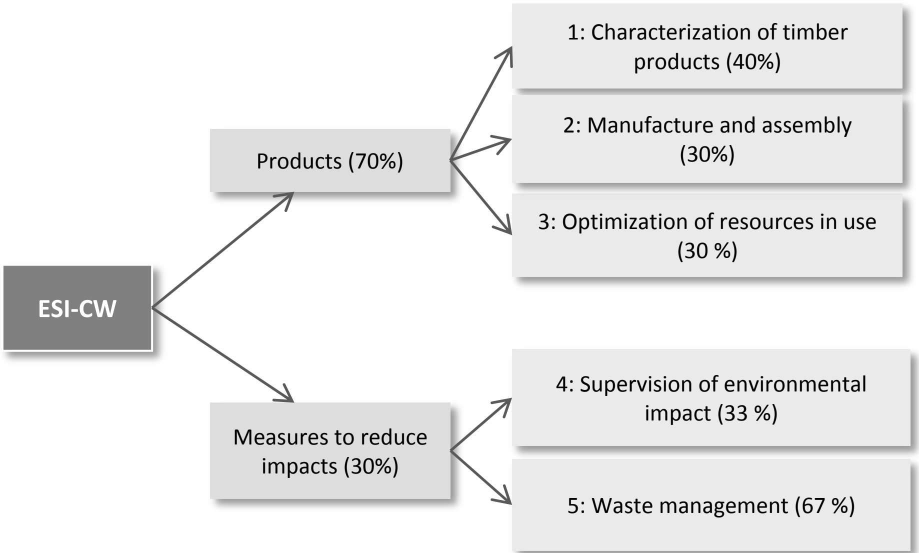



**Figure 6.2. Evaluation tree of the environmental sustainability index**

As previously stated, in the systematic approach for building this hierarchical decision tree, the first task is to estimate sustainability priorities, by assigning weights (AHP) at the respective hierarchical levels (from indicator to criteria and global index ESI-CW). This process enables quantification of the relative priority (weights in figure 2) of each alternative on a scale that emphasizes the importance of criteria to the decision-makers and the consistency of their judgment when drawing comparisons between the various alternatives: a sustainability analysis of specific wood cladding (as in this study) or a comparison of different structural alternatives.

The Delphi method assists a group of individuals (Panel of Experts), who in this case assigned weights to each hierarchical level, to address a complex problem [151]. The members of the panel were chosen for their skills. knowledge and independence, in order to complete this process successfully.

For this study, the Panel of Experts was formed by professionals from the construction sector (engineering and architecture studios. construction companies. raw materials. construction products, research centres and universities) and the selection was based on the guidelines defined by Hallowell and Gambatesse [152]. These authors suggest that the ideal Panel of Experts should be formed of a highly qualified and diverse group of people, ranging between 8 and 16 individuals. In this case, a database of 72 professionals in the construction sector from 30 different organisations (private enterprises. research centres and universities) was used for the selection of the experts and finally 11 experts were selected.

The environmental sustainability index is proposed on the basis of two criteria for a wood cladding, which are the products used and the measures to reduce the generation of impacts. As in other cases, (Annex 11 of the EAE-11 or Annex 13 of the EHE-08) [126, 153], in this study, greater prominence was given to the material used, in this case wood (70%). rather than possible measures to reduce impacts (30%), such as waste reduction.

The proposed assessment model (tree) seeks to quantify those actions that lead to an improvement in the environmental sustainability of the adopted solution. So, the actions to be strengthened from the point of view of the sustainability of wood claddings are as follows:

- Aspects related with materials: use of smaller quantities of raw materials (timber), compliant with façade standards use of local wood resources and traceability of timber source associated with proper forestry management.
- Aspects referring to processes: selection of lower $CO_2$ emissions and lower energy consumption, use of sources from renewable energy and reuse and recycling of possible by-products (waste management systems).
- Aspects focused on timber structure: involvement of manufacturing firms that comply with current environmental regulations (voluntarily certification) and better quality improving the useful life of the building (durability).
- Aspects centred on the timber building stage: procedures for erecting wooden façades in accordance with environmental regulations (certified on a voluntary basis) and procedural and material innovations that increase the productivity and the efficiency of constructions.

In general, there are certain limitations when measuring some aspects that affect the environmental sustainability index of a wooden façade. For example, measurement of the most suitable cladding typology is not always straightforward, because it is evident that some typologies are more efficient that others. if we consider their specific strengths.

### 6.1.6 Definition of criteria and indicators

The evaluation process was broken down into two levels. At the first level, two criteria were defined: the product to be used and measures to reduce environmental impact to a minimum [153].

In the following part, only the methodology for the evaluation of the different proposed indicators in the “Products” criterion will be described, because this is the set of indicators with the highest weight and due to limitations on the length of the paper. In the second level, the “Products” criterion was divided into three indicators, related to the characterization of wood products, their manufacture and the optimization of the resources that are used.

**1. Indicator: “Characterization of timber products”**

This indicator consists of an environmental sustainability assessment associated with the correct management of the material that is used, such that it is economically viable and socially beneficial for society, and compliant at all times with responsible environmental management. In this way, it is possible to supervise the source of the material to be used, contributing a series of guarantees in favour of sustainability (focused on environmentally sensitive issues in this research).

Given that the timbers of a cladding may be of a different origin, the percentages of each source have to be established, as their environmental impact is represented in different ways. The easiest method of confirming the origin of wood is to request its product certification from an international certification body such as the Forestry Stewardship Council (FSC), the Programme for the Endorsement of Forest Certification (PEFC), or other international bodies. Responsible management is encouraged through the use of these labels, which are intended to ensure a degree of ecosystem protection and conservation from the environmental standpoint, while respecting the rights of workers and communities at a social level, and generating economic value and markets in regions with forestry resources.

In Spain, only 7% of the forest area is certified although in the Basque country there is a tendency towards its increment as 100% of its forest area is pretended to be certified, and the use of this type of wood is unevenly distributed across sectors at low levels. The maximum value of total wood consumption (25%) corresponds to the do-it-yourself sector [154]. From the structural point of view, the wood used in construction may have been separated at source and therefore certified as pure material. If there is no such source separation, associated seals are given to a percentage by volume or weight of certified wood. It is important to note that below levels of 70%, the product may not be certified [154] and is treated as non-certified material.

The use of non-certified wood has a low valuation, corresponding to 0 points, a value that quickly rises as soon as certified wood is used. This rate of increase is reduced when the percentage of certified wood is between 50 and 100%, between which a point of maximum value is reached.

| **Product Characterisation** | **$P_{prod}$** |
|---|---|
| Volume of laminated timber with FSC, PEFC or other certifications | $V_{lam}$ |
| Volume of sawn timber with FSC, PEFC or other certifications | $V_{sawn}$ |
| Total volume of wood used in the façade | $V_T$ |

**Table 6.1. Scoring of the "Product Characterization" indicator**

$$P_{product} = \frac{V_{sawn} + V_{lam}}{V_T} \cdot 100 \tag{6-3}$$

Where;

$$P1 = \frac{P_{product}}{100} \tag{6-4}$$

$P1$ = *Score of the "Product Characterisation" indicator for the project*
$P_{product}$ = *Score obtained on the basis of the percentage of certified material (Table 6.1)*

Thus, with expression (6-3), the percentage of certified wood used in the cladding of the building is obtained, relative to the total.

This value (P1) is introduced into the value function that was defined for the indicator, to produce a value between 0 and 1. The index value represents the quantification of the indicator and in this case follows the strategy of enhancing the use of certified wood that encourages forest management that is both environmentally and socially responsible.

In the case of Spain, as previously stated, due to the reduced consumption of wood certified structures, the curve gives a higher score as greater effort is made to introduce this material; insofar as the environmental sensitivity of the project is greater. In this case, a concave upward function is suggested, as shown in Figure 6.3 and expresses in (6-5), to incentivize the greater effort involved in the use of higher percentages of timber with an environmental certification.

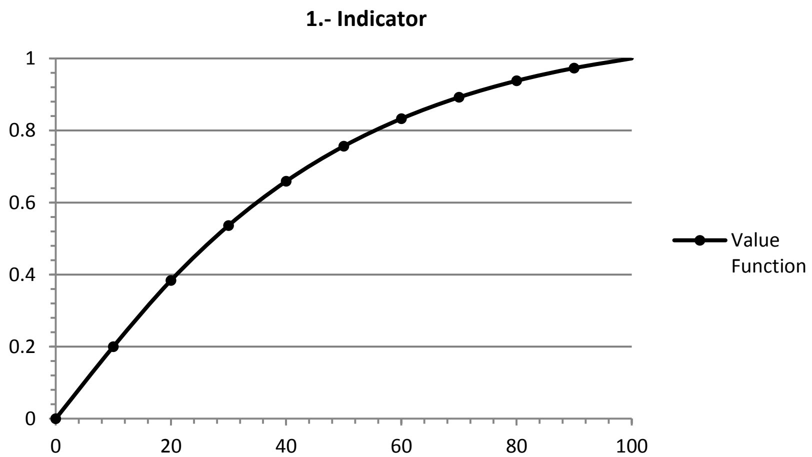



**Figure 6.3. Value function associated with the "Product Characterization" indicator**

$$V_{i1} = 1.083 \cdot \left(1 - e^{\left(-1.6 \cdot \left(\frac{P}{65}\right)^{1.1}\right)}\right) \qquad \textbf{(6-5)}$$

A similar scheme is proposed for the entire set of indicators, in all cases establishing the proposed objectives, the approach to the indicator valuation, as well as the proposed strategy, through different value functions.

### 2. Indicator: "Manufacturing and assembly"

The second indicator attempts to value the environmental sustainability of factory manufacturing processes and on-site assembly. Its valuation should be done through the environmental accreditations of the different participating firms. This decision represented the easiest way of assessing the environmental commitment of the companies involved in the construction process. 3 types of companies were identified: the company responsible for the manufacture of the wooden claddings (Factory), the company responsible for their on-site assembly (not necessarily the Factory) and the construction company (General Contractor) responsible for all other necessary activities to complete the construction project. Thus, companies are encouraged to take steps to obtain environmental management certifications.

This indicator also accounts for the distance from the factory to the site, as the minimization of transport is another objective. Companies in the industry have quoted a maximum distance of 300 km. that acts as a restraint on competition with rival companies that are closer to the construction site.

Table 6.2 sets out the scores for this indicator, in which scores for the manufacturing firm, the installation firm, and the construction firm should be noted in relation to the complete building. In case 1, the maximum value that can be obtained from Pi is 100, where the distance is less than 300 km and the participating companies have environmental accreditations.

| Manufacturing and Assembly: valuation scheme | | Distance ≤ 300 km | | Distance ≥ 300 km | |
|---|---|---|---|---|---|
| | | Case 1 factory $P_{factory}$ | Case 2 on-site $P_{on\text{-}site}$ | Case 1 factory $P_{factory}$ | Case 2 on-site $P_{on\text{-}site}$ |
| **Manufacture and assembly in the factory** | (A) with environmental accreditation | 80 | 0 | 75 | 0 |
| | (B) with environmental commitment | 60 | 0 | 55 | 0 |
| | (C) others | 30 | 0 | 25 | 0 |
| **On-site assembly** | (A) with environmental accreditation | 0 | 70 | 0 | 70 |
| | (B) with environmental commitment | 0 | 30 | 0 | 30 |
| | (C)others | 0 | 0 | 0 | 0 |
| **Construction firm** | (A) with environmental accreditation | 20 | 30 | 25 | 30 |
| | (B) with environmental commitment | 10 | 15 | 15 | 15 |
| | (C) others | 0 | 0 | 0 | 0 |

**Table 6.2. Scoring of the "Manufacturing and assembly" indicator**

It can be seen that the greatest reduction of the impact is related to manufacturing in the workshop and on-site installation. In this way, the waste generated on site can be reduced or re-evaluated in the plant.

In this case, the score is obtained by expression (6-6). Then the value function ($V_{i2}$) takes the "S" form, once again incentivizing the greater effort made by firms to obtain environmental accreditations, above all if that environmental sensitivity is shared by all the firms participating in the constructive process, as may be appreciated in Figure 6.4.

$$P2 = \frac{1}{100} \cdot \sum \left[ P_{factory} \text{ } or \text{ } P_{site} \right] \quad \textbf{(6-6)}$$

*$P2 =$ Score of the "Manufacture and Assembly" indicator for the project*
*$P_{factory}$ and $P_{site}$ = Score placed in the corresponding column that reflects wether the cladding is principally made in the factory or whether the timber has also to be assembled on site. These values are also a function of the distance between the timber works and the location of the site (Table 6.2).*

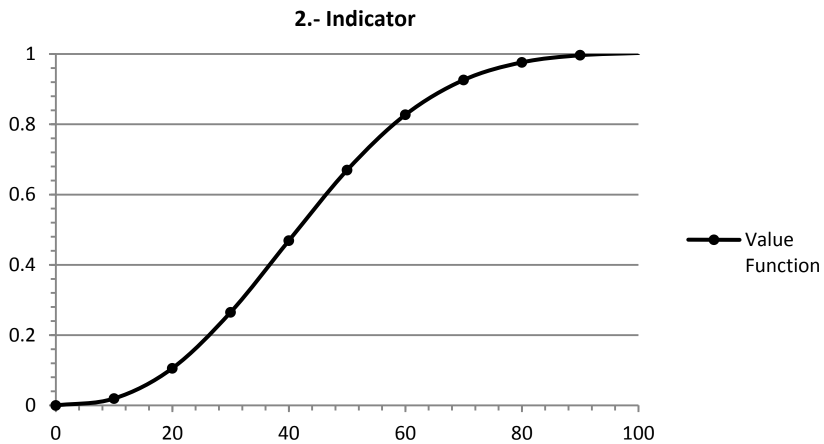



**Figure 6.4. Value function of "Manufacture and Assembly" indicator**

$$V_{i2} = 1.005 \cdot \left(1 - e^{\left(-0.45\cdot\left(\frac{P}{35}\right)^{2.5}\right)}\right) \quad \textbf{(6-7)}$$

### 3. Indicator: "Optimization of resources"

The third indicator accounts for the contribution associated with the reduction of the amount of timber used for the preparation of the external cladding.

This same indicator also accounts for the source of the timber, such that local timber receives a higher score than timber from forests that are at a greater distance, as its transport generates, on the one hand, a greater environmental impact and, in other cases, it is of no benefit to the local economy and its growth in this sector.

| Origin of the material | $P_{origin}$ |
|---|---|
| Origin of the timber with regard to its consumption ≤ 300 km | 55 |
| Origin of the timber with regard to its consumption between 300 and1000 km | 35 |
| Origin of the timber with regard to its consumption ≥ 1000 km | 10 |

**Table 6.3. Score of "Optimization of resources" indicator**

Expression (6-8), based on Table 6.3, gives a score to assign to the value function ($V_{i3}$), which is a growing function in this case represented in (6-9), as may be appreciated in Figure 6.5, in such a way that a high value may be obtained with a relatively low score. In this way, the use of local timber is strengthened, stimulating greater activity for this sector in the area.

$$P3 = \frac{1}{200} \cdot \sum \left[ \%Vol_{origin} \cdot P_{origin} \right] \quad \textbf{(6-8)}$$

$P3 =$ *Score of the "Optimization of resources" indicator for the project*
$\%Vol_{origin} =$ *Percentage of volume of wood according to its origin*
$P_{origin} =$ *Score corresponding to the origin of the wood (Table 6.3). expressed in (6-3)*

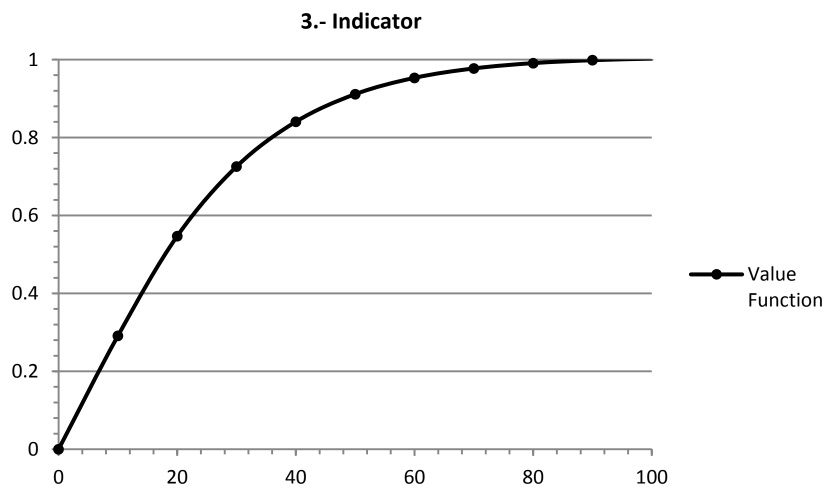



**Figure 6.5. Value function of "Optimization of resources" indicator**

$$V_{i3} = 1.007 \cdot \left(1 - e^{\left(-1.8 \cdot \left(\frac{P}{40}\right)^{1.2}\right)}\right) \quad \textbf{(6-9)}$$

### 4. Indicator: "Impact Control"

This indicator, labelled "Impact Control", values the environmental contribution associated with types of protective substances that are applied to the timber, in order to improve natural durability and to guarantee its useful life in accordance with its (interior or exterior) use, as well as its degree of dampness.

In this case, a class of use 1 assumes that the timber is placed inside the building with a degree of dampness lower than 20%, and a class of use 5 corresponds to a timber that is permanently in contact with seawater, which is the classification that is followed in Spain by the Technical Building Code (CTE) [58]. The score for "class of use 1" is the highest, as the timber requires no treatment, whereas in all other cases the greater aggressivity of the treatment lowers this value.

| Class of use | Type of protection | $P_{protec}$ |
|---|---|---|
| 1 | superficial | 100 |
| 2 | superficial | 95 |
| 3.1 | average 3mm | 65 |
| 3.2 | average 6mm | 55 |
| 4 | deep | 25 |
| 5 | deep | 10 |

**Table 6.4. Scoring of "Impact Control" indicator**

Expression (6-10) yields the score corresponding to the type of protection, in accordance with the percentage of the material that should be treated in view of the different conditions in which the structure may be found.

$$P4 = \frac{1}{100} * \sum \%_{protec} * P_{protec} \tag{6-10}$$

Where:

$P4$ = Score of the "Impact Control" indicator in the project.
$\%_{protec}$ = Percentage of timber treated for protection.
$P_{protec}$ = Score associated with the type of treatment to complete for the improvement of natural durability (Table 6.4).

In this case, the value function ($V_{i4}$) associated with this indicator has a linear form, as it can be seen in Figure 6.6 and expression (6-11), associated with greater protection because the treatment generates greater environmental impact, due in part to the products that it uses and the necessary energetic consumption.

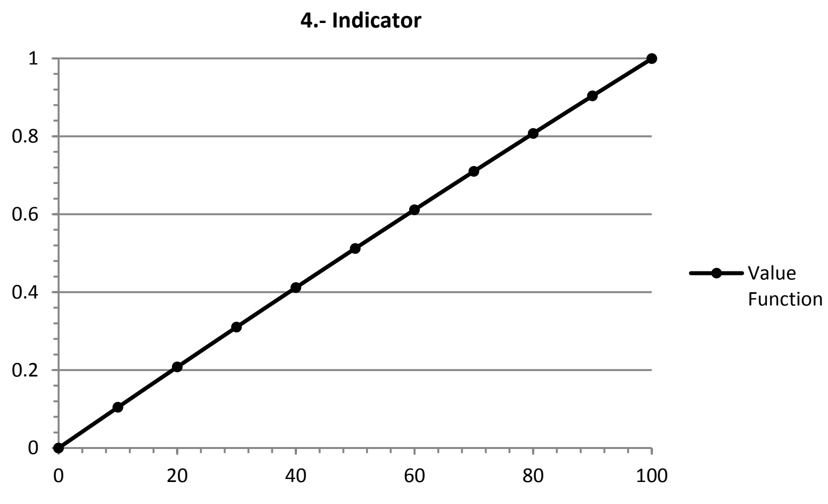



**Figure 6.6. Value function of "Impact Control" indicator**

$$V_{i4} = 10.5 * \left(1 - e^{-0.001*\left(\frac{P}{1}\right)}\right) \tag{6-11}$$

### 5. Indicator: “Waste Management”

Indicator 5, “Waste Management” accounts for environmental sensitivity in the execution phase of the structure, in such a way that the waste generated by the process is minimized, taking into account the existence of a construction and demolition waste management plan.

The score to be included in the value function ($V_{i5}$) through expression (6-12), which has a slight “S” form in this case, may be seen in Figure 6.7.

$$P5 = \frac{1}{100} * \sum \left[P_{mng}\right] \tag{6-12}$$

$P5 =$ *Waste management indicator score in the project*
$P_{mng} =$ *Score associated with the waste reduction measures in the development of the works (table 6)*

| **Waste management** | $\boldsymbol{P_{mng}}$ |
|---|---|
| No specific action in either the Project or the budget | 0 |
| The use of waste containers for stony fractions is proposed in the project and appears in the budget | 30 |
| The firm supplying the structure is responsible for possible waste generated in the assembly of the structure | 60 |
| The supplier collects the waste and proposes an agreement for its valuation | 100 |

**Table 6.5. Scoring of “Waste Management” indicator**

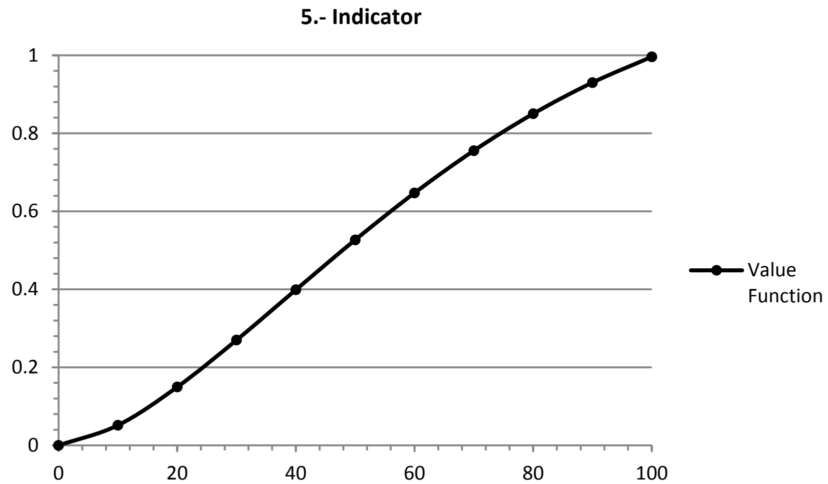



**Figure 6.7. Value function of “Waste Management” indicator**

$$V_{i5} = 1.21 * \left(1 - e^{-0.4*\left(\frac{P}{40}\right)^{1.60}}\right) \quad \textbf{(6-13)}$$

### 6.1.7 Evaluation of alternatives through the environmental sustainability index (ESI-CW)

The final value for the “environmental sustainability” index is obtained from the proposed hierarchy tree (assessment model), where three levels are presented: indicators, criteria, and sensitivity index (ESI-CW). Initially, the information has to be introduced to obtain the indicator values. The criteria values are calculated from the degree of importance of each indicator in its corresponding criterion. Then, multiplying these values by their relative weighting yields the relevant value of the sustainability index.

The final value of the indicators, criteria and indices of sensitivity in all of the scales is a number between zero and one (a minimum value of zero and a maximum of one).

The proposed ESI-CW index follows the scheme presented in Figure 6.1 and, as previously stated in 5.1.1, attempts to follow a similar format to those used in the corresponding annexes of the Spanish codes EHE-08 [126] and EAE [127].

## 6.2 Case study and sensitivity analysis

Application of the model to the timber façade of a detached house is proposed. In this case, the façade is made of CLT (Cross Laminated Timber) 10 cm thickness and the exterior cladding is made of stone stuck to the CLT wall by a mortar layer. Figure 6.8 represents the project.

**Figure 6.8. Case study © A. Buruaga**

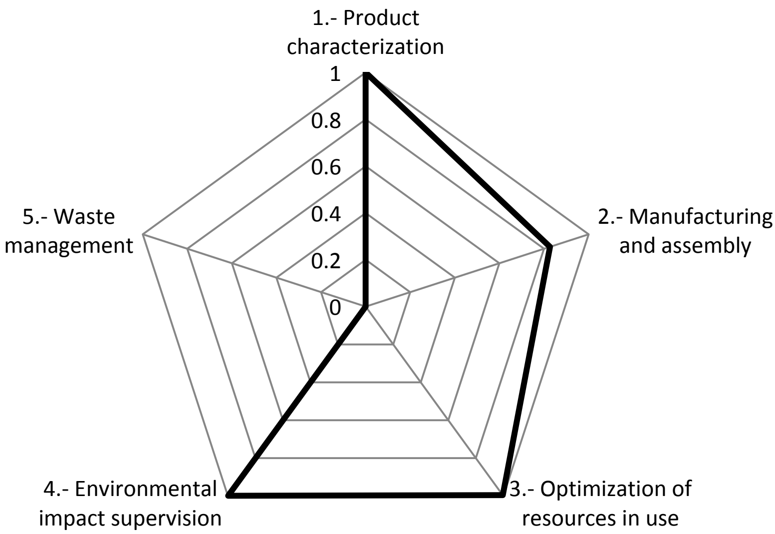
This façade was built was Radiata-pine, a timber that is certified by the PEFC (Programme for the Endorsement of Forest Certification), and that is the predominate species of pine in the surrounding area. The walls were entirely prepared in the factory, and the pieces were transported to the site for assembly. The factory was at a distance of 54 km from the location of the house and the materials in use were from at a distance of less than 100 km.

The timber factory has ISO-9.001 and OHSAS-18.001 accreditation, while the construction firm in charge of carrying out the necessary civil works, has no type of environmental accreditation although it has an environmental commitment.

In this case, the CLT (Cross Laminated Timber) has a class of use set at 1. During the execution of the works this part, which corresponded to wooden façade, generated no waste, so no action was contemplated in that regard. In case of the manufacturer, it was a small company without Research and Development (R&D) department. The results of this case study (Case 1), are shown in Table 6.6 and Graphic 6.1.

| Indicator | Indicator score | Indicator value | % Indicator | Value of criterion | % Indicator | Value of Index |
|---|---|---|---|---|---|---|
| 1: $P_{product}$ | 100 | 1.00 | 40 | 0.95 | 70 | 0.76 |
| 2: $P_{factory}/P_{site}$ | 60 | 0.83 | 30 | | | |
| 3: $P_{use}$ | 54 | 0.99 | 30 | | | |
| 5: $P_{protect.}$ | 100 | 1.00 | 33 | 0.33 | 30 | |
| 6: $P_{mng}$ | 0 | 0 | 67 | | | |

**Table 6.6. Practical valuation, Case 1**

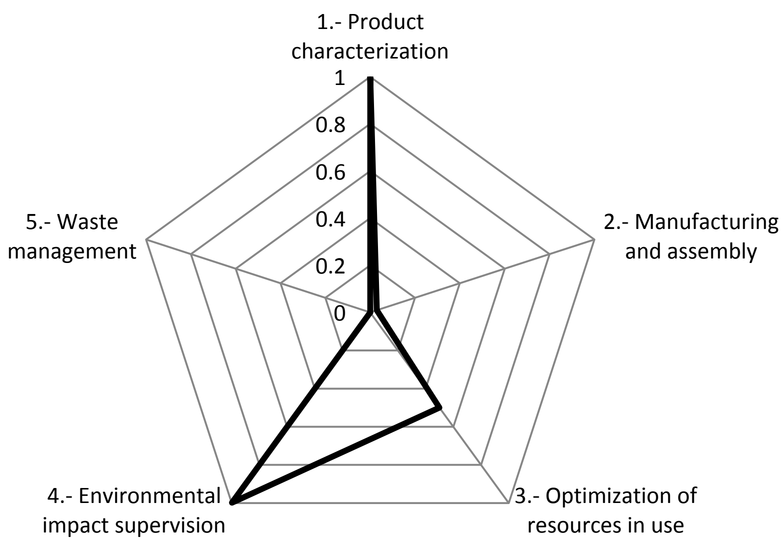



**Graphic 6.1. Results of Case 1**

In this case, although the origin of wood was the Basque Country, the constructor did not have ISO 14.001 accreditation. If wood is brought from Austria, and the CLT manufacturer had ISO 14.000 accreditation, the Index of this second option (Case 2) would be 0.49, as it can be seen in Table 6.7 and Graphic 6.2.

| Indicator | Indicator score | Indicator value | % Indicator | Value of criterion | % Indicator | Value of Index |
|---|---|---|---|---|---|---|
| 1: $P_{product}$ | 100 | 1.00 | 40 | 0.56 | 70 | 0.49 |
| 2: $P_{factory}/P_{site}$ | 12 | 0.03 | 30 | | | |
| 3: $P_{use}$ | 29 | 0.50 | 30 | | | |
| 5: $P_{protect.}$ | 100 | 1.00 | 33 | 0.33 | 30 | |
| 6: $P_{mng}$ | 0 | 0 | 67 | | | |

**Table 6.7. Practical valuation, Case 2**

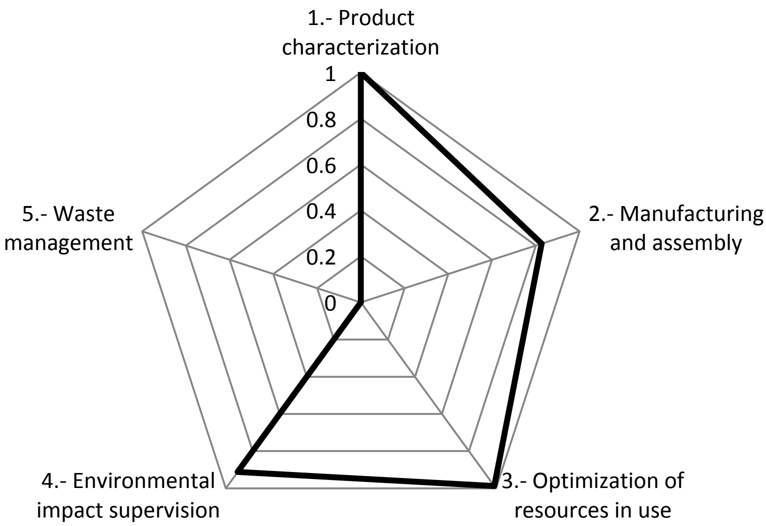



**Graphic 6.2. Results of Case 2**

In both cases, the external cladding is based on a stone layer stuck to the CLT. If this part is changed to a wooden external cladding 2 cm thickness made of joined boards which are joined to the CLT by means of wood studs, the amount of wood would be increased and its index would be 0.75, as it is represented in the third case (Case 3), whose results are shown in Table 6.8 and Graphic 6.3. In this case, both wood origin and manufacturer is the same as the first reference case (Case 1).

| Indicator | Indicator score | Indicator value | % Indicator | Value of criterion | % Indicator | Value of Index |
|---|---|---|---|---|---|---|
| 1: $P_{product}$ | 100 | 1.00 | 40 | 0.94 | 70 | 0.75 |
| 2: $P_{factory}/P_{site}$ | 60 | 0.83 | 30 | | | |
| 3: $P_{use}$ | 48 | 0.99 | 30 | | | |
| 5: $P_{protect.}$ | 91 | 0.91 | 33 | 0.30 | 30 | |
| 6: $P_{mng}$ | 0 | 0 | 67 | | | |

**Table 6.8. Practical valuation, Case 3**




**Graphic 6.3. Results of Case 3**

In comparison with the first case, the increment of wood in the façade when stone external cladding is changed to joined boards does not represent a significant index variation, 1 %., while in terms of global sustainability represents the no consumption of stone raw material, which does not come from renewable resources.

In all cases, it was considered that wood is certified by the PEFC. However, if this is not considered the index goes down. In the first case, this reduction would be from 0.75 to 0.47, which supposes more than 37 % of worsening in the valuation.

On the other hand, if wood waste during construction works is collected separately from the rest of waste, the index improves 7 %, from 0.76 to 0.82.

## 6.3 Conclusions

The range of stakeholders (developers, designers, contractors, end-users, etc.) involved in the construction industry often generates conflicting interests. The present chapter has developed a decision-making methodology that unifies the criteria in relation to the environmental sustainability of timber façades.

This methodology is based on the MIVES concept and, like the Spanish Structural Concrete Code (EHE-08) [126] and the Spanish Structural Steel Code (EAE-11) [127], aims to establish a quick indicator for quantifying the degree of “environmental sustainability” that may be assigned on the basis of information from the agents that intervene in the design of a timber façade. It implies uniformity of the different measurement units, it supplies global (aggregated) results and partial indexes, and it quantifies each indicator, criteria and result; it can be used to enhance the environmental sustainability of timber façades and to reduce the impacts that are generated, in those areas where it has been awarded a lower score.

In addition, it is easy and quick to apply both for technicians who are developing the project and for those who assess such information in a tendering (bidding) process. In fact, the simplicity of the example given in this study has made it easy to see that changes in the material, such as its background and environmental certification, generate significant changes in the overall result.

The proposed methodology includes lines of action that improve the sustainability of wooden façades, considering the economic situation and the particular characteristics of each country, thereby enhancing such initiatives. It is flexible enough for use in other parts of the world, although it would have to be adapted to the reality of each country.

*"Architecture is not just a tree, should grow in agreement with its surroundings"*

Toyo Ito

1941

# CHAPTER 7
# Catalogue of façades

# 7 Wooden façades catalogue

In this chapter a group of timber façades are analysed. In this case, their environmental impact and material costs are assessed. The study pretends to make emphasis in the different factors that influence the optimization of enclosures in terms of economic and environmental issues, taking their transmittance value similar in all cases. For the transmittance value, around 0.40 W/($m^2$·K) is considered. In Spain the least limit is 0.57 W/($m^2$·K) for the coldest regions. In this example, 30% less transmittance is assumed in order to cut down the distance respect to passive house standards [155].

In terms of environmental impact, Eco-indicator 99 is used from Ecoinvent data base [156, 157] through Eco-it software [158]. On the other side, for the costs analysis the Basque Government data base for construction works is used [159].

The present study pretends to show different alternatives of wooden façades with their thermal, economic and environmental characteristics, in order to provide to designers and construction professionals a pre-selection guide. In terms of transmittance, most of them are including in PIME software, which is a dimensional tool for timber structures, in terms of mechanical resistance, and façades, in terms of transmittance. This software allows professionals to calculate their works and justify the Spanish Technical Code requirements, CTE, which corresponds to the basic documents: DB-SE-M and DB-HE [45, 58].

## 7.1 Analysis of façades

Very often, wooden façades are configured as a load wall. That implies that both structural and protection functions are required. Because of that, he catalogue distinguished between façades made of traditional timber frame (A) and CLT (B), Cross Laminated Timber, in order to compare different structural composition. In terms of mechanical response to lateral movement and static loads, they could be considered as the same class of building [160]. In both cases, their beneficial mechanical behaviour or response against earthquakes is gaining more interest in research [161, 162]. For each type, six configurations are realized:

1. **External wood layer made of joined strips:** In this case the external layer, the protection layer against weather agents, is based on a wall of joined strips made of Radiata-pine.

2. **External thermal insulation composite systems (ETICS):** As it is getting more and more used overall in building energy retrofitting, in this case, the external layer is based on an external thermal insulation composite system (ETICS), whose cladding is made of mortar.

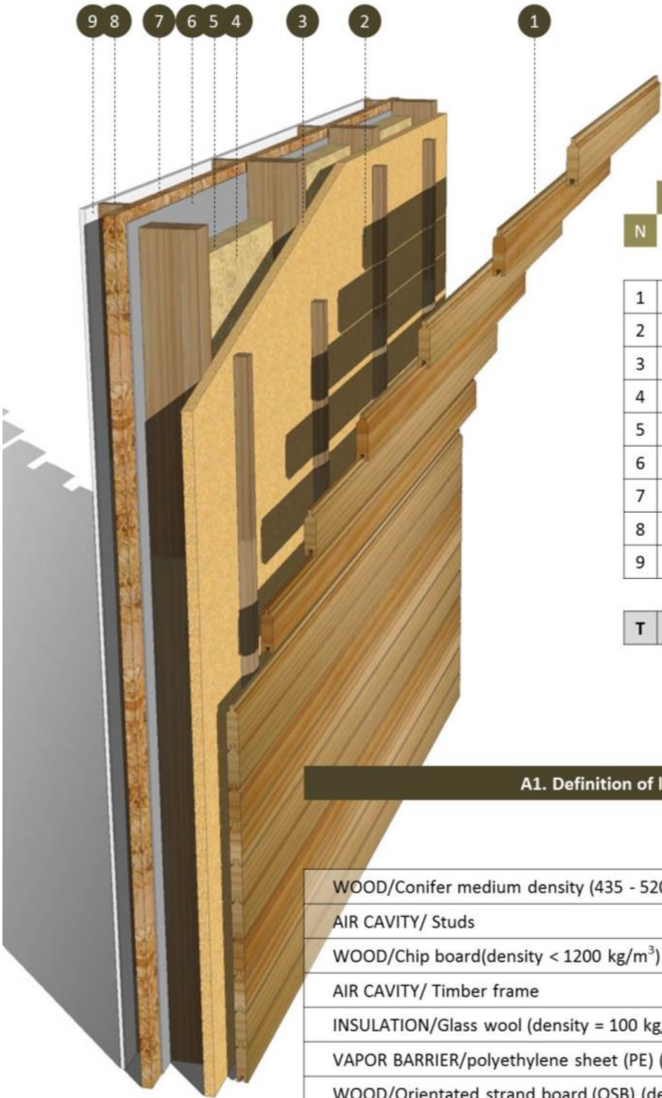
3. **External metal cladding:** As it is used in both roofs and façades, metal sheet cladding is analysed. In this case, the sheets are made of zinc alloy.

4. **External stone cladding:** The aesthetic plays an important role in architecture, because of that, wooden façades with limestone cladding are also realized.

5. **External wood slats cladding:** The difference of this solution and the first one is that, in this case, the slats are not completely joined. That implies that both solutions differ in their thermal behaviour, as this last one has a ventilated air cavity behind.

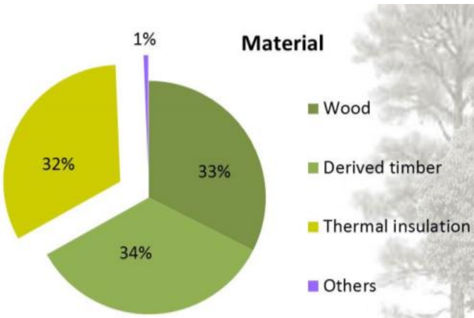
6. **ECO solution:** This solution tries to introduce more ecological materials such as wood fiber composite insulation instead of glass wool, which is more extended, in order to compare them.

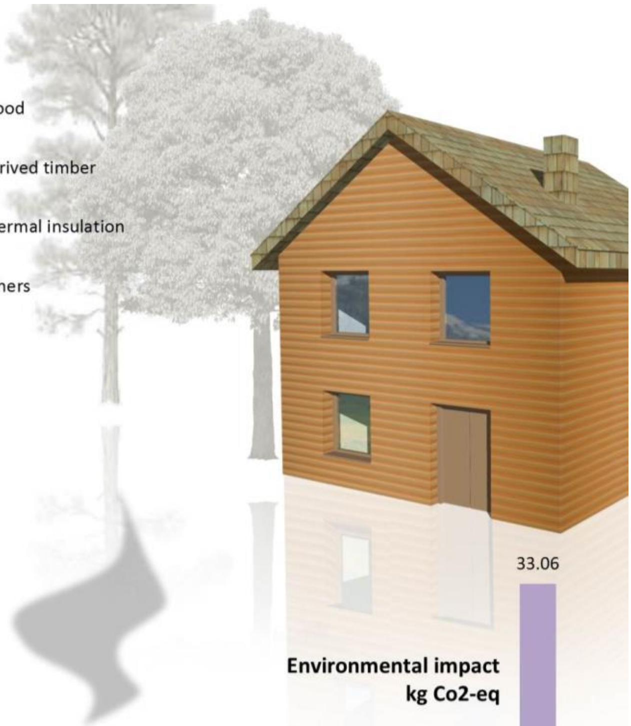
## A1. Timber frame with external wood layer made of joined strips



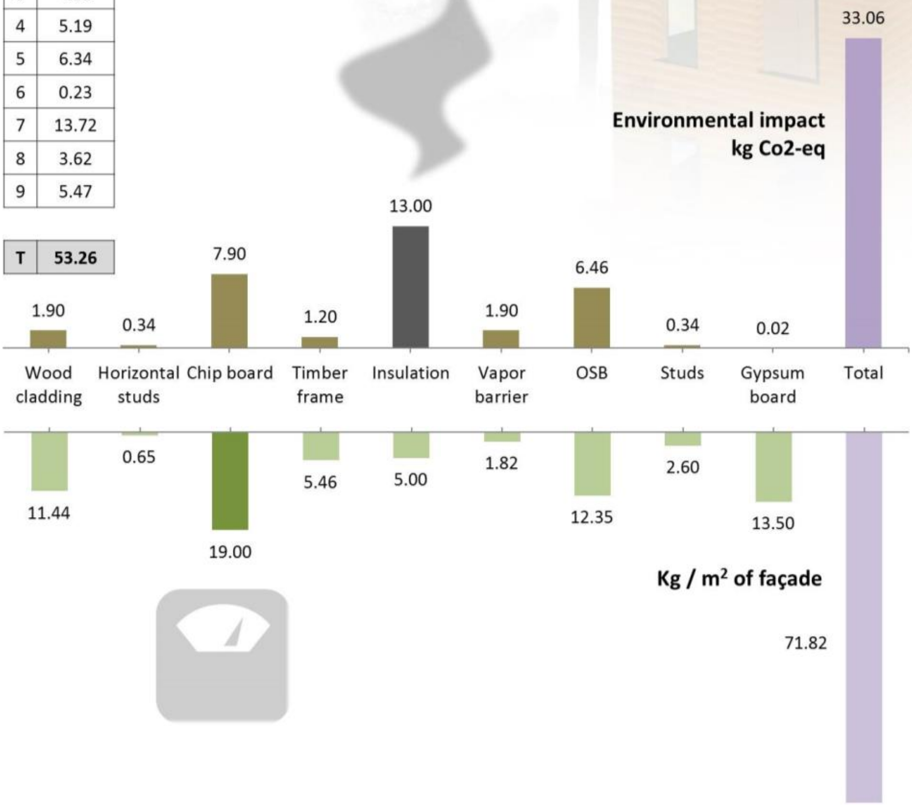

| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | m²°C/W |
| | | | Rse | 0.04 |
| 1 | 0.022 | 0.15 | R1 | 0.15 |
| 2 | 0.025 | ---- | R2 | 0.18 |
| 3 | 0.019 | 0.23 | R3 | 0.08 |
| 4 | 0.05 | ---- | R4 | 0.18 |
| 5 | 0.05 | 0.04 | R5 | 1.25 |
| 6 | 0.001 | ---- | R6 | ---- |
| 7 | 0.019 | 0.13 | R7 | 0.15 |
| 8 | 0.05 | ---- | R8 | 0.18 |
| 9 | 0.015 | 0.25 | R9 | 0.06 |
| | | | Rsi | 0.13 |
| **T** | **0.251** | | **RT** | **2.395** |
| | | | **U= 1/Rt** | **0.417** |

| A1. Definition of layers | N |
|---|---|
| WOOD/Conifer medium density (435 - 520 kg/m$^3$) | 1 |
| AIR CAVITY/ Studs | 2 |
| WOOD/Chip board(density < 1200 kg/m$^3$) | 3 |
| AIR CAVITY/ Timber frame | 4 |
| INSULATION/Glass wool (density = 100 kg/m$^3$) | 5 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/m$^3$) | 6 |
| WOOD/Orientated strand board (OSB) (density < 650 kg/m$^3$) | 7 |
| AIR CAVITY/ Studs | 8 |
| GYPSUM BOARD (density: 750 - 900 kg/m$^3$) | 9 |



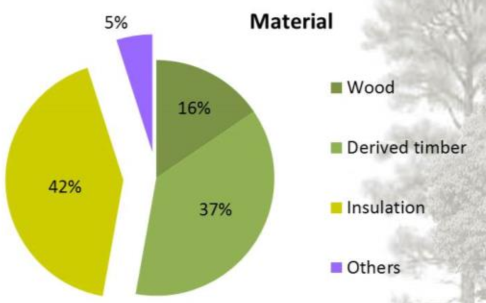
| N | Price €/m² |
|---|---|
| 1 | 12.62 |
| 2 | 1.44 |
| 3 | 4.63 |
| 4 | 5.19 |
| 5 | 6.34 |
| 6 | 0.23 |
| 7 | 13.72 |
| 8 | 3.62 |
| 9 | 5.47 |
| T | **53.26** |



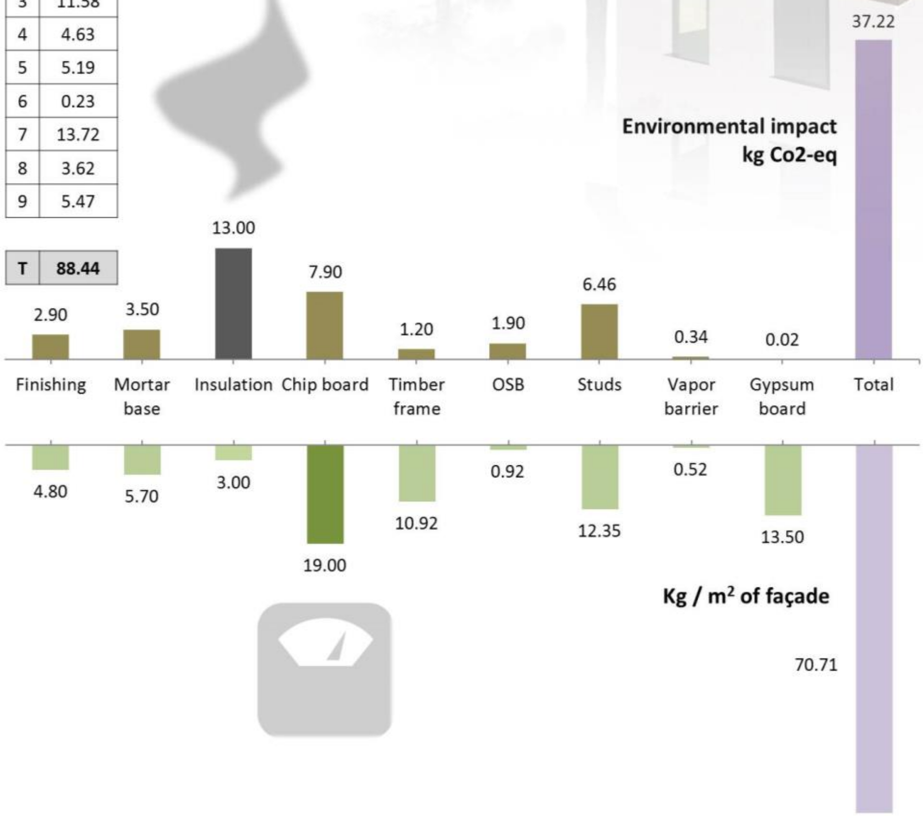
## A2. Timber frame with external thermal insulation composite systems (ETICS)


| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | m²°C/W |
| | | | Rse | 0.04 |
| 1 | 0.003 | 0.2 | R1 | 0.02 |
| 2 | 0.003 | 0.15 | R2 | 0.02 |
| 3 | 0.06 | 0.04 | R3 | 1.50 |
| 4 | 0.019 | 0.23 | R4 | 0.08 |
| 5 | 0.1 | ---- | R5 | 0.18 |
| 6 | 0.001 | ---- | R6 | ---- |
| 7 | 0.019 | 0.13 | R7 | 0.15 |
| 8 | 0.01 | ---- | R8 | 0.18 |
| 9 | 0.015 | 0.25 | R9 | 0.06 |
| | | | Rsi | 0.13 |
| **T** | **0.23** | | **RT** | **2.354** |
| | | | **U= 1/Rt** | **0.425** |

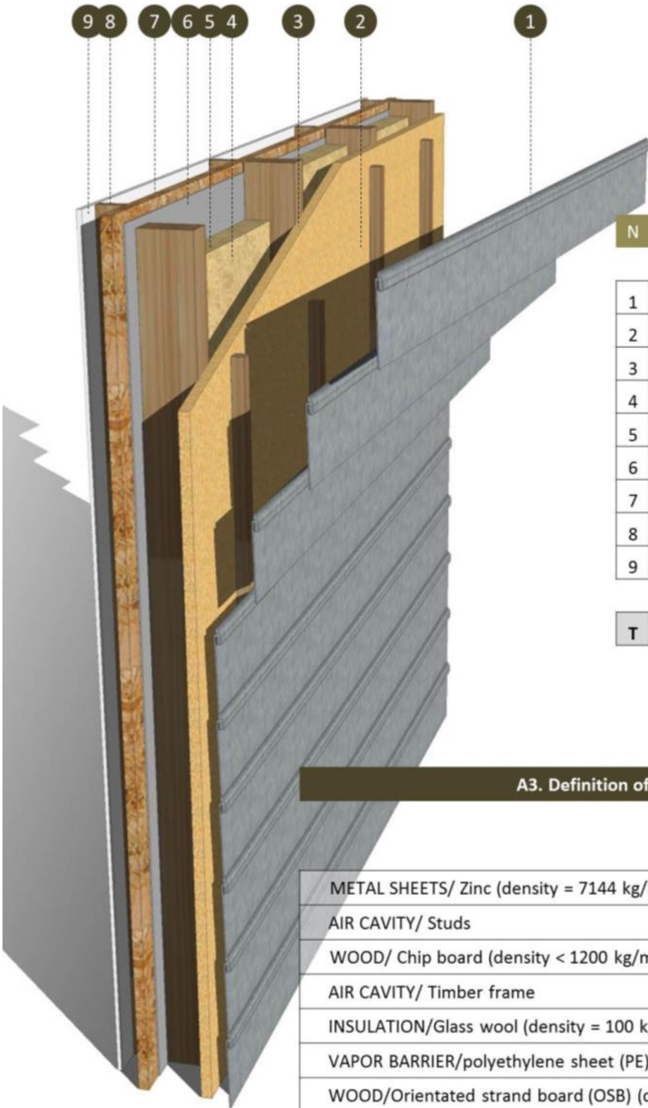
| A2. Definition of layers | N |
|---|---|
| SURFACE FINISHING/ Mortar (density: 1500 - 1600 kg/m³) | 1 |
| BASE LAYER/ Mortar with intermediate frame (density = 1900 kg/m³) | 2 |
| INSULATION/ Expanded polystyrene, EPS (density: 10 - 50 kg/m³) | 3 |
| WOOD/ Chip board (density < 1200 kg/m³) | 4 |
| AIR CAVITY/ Timber frame | 5 |
| WOOD/Orientated strand board (OSB) (density < 650 kg/m³) | 6 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/m³) | 7 |
| AIR CAVITY/ Studs | 8 |
| GYPSUM BOARD (density: 750 - 900 kg/m³) | 9 |




| N | Price (€/m²) |
|---|---|
| 1 | 44.00 |
| 2 | |
| 3 | 11.58 |
| 4 | 4.63 |
| 5 | 5.19 |
| 6 | 0.23 |
| 7 | 13.72 |
| 8 | 3.62 |
| 9 | 5.47 |
| **T** | **88.44** |

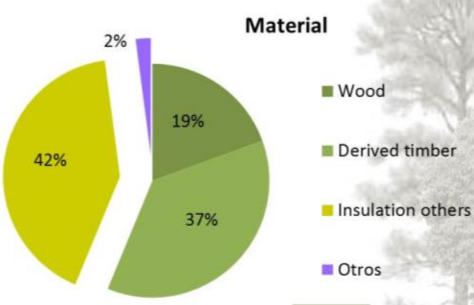


## A3. Timber frame with external metal cladding

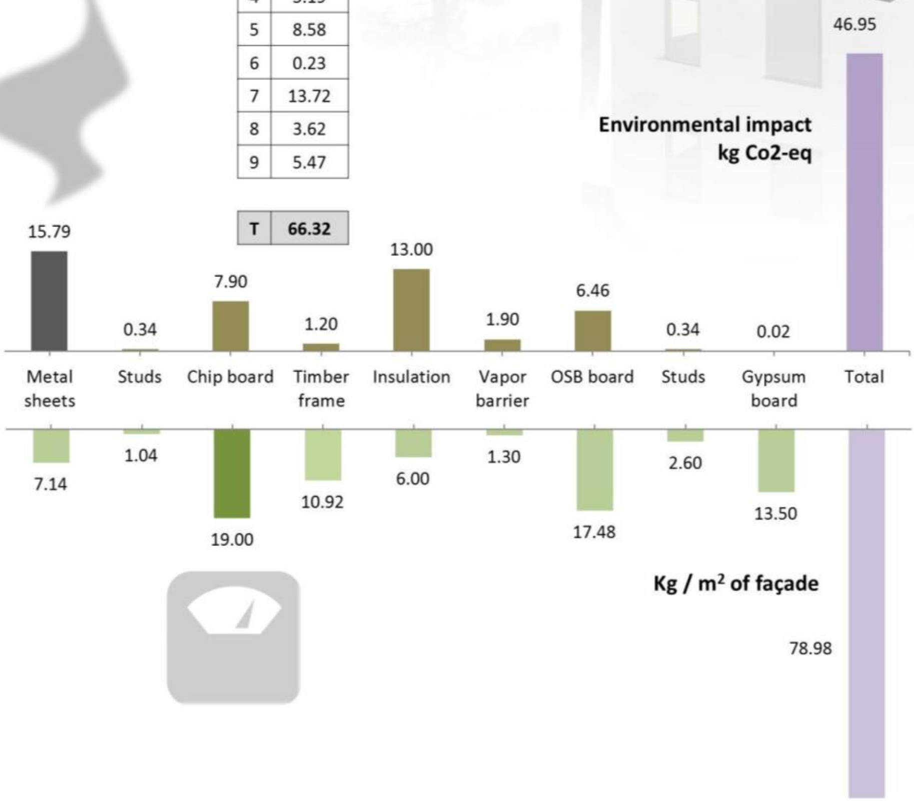



| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | $m^2$°C/W |
| | | | Rse | 0.04 |
| 1 | 0.001 | 112.2 | R1 | 0.00 |
| 2 | 0.025 | ---- | R2 | 0.18 |
| 3 | 0.019 | 0.23 | R3 | 0.08 |
| 4 | 0.04 | ---- | R4 | 0.18 |
| 5 | 0.06 | 0.04 | R5 | 1.50 |
| 6 | 0.001 | ---- | R6 | ---- |
| 7 | 0.019 | 0.13 | R7 | 0.15 |
| 8 | 0.05 | ---- | R8 | 0.18 |
| 9 | 0.015 | 0.25 | R9 | 0.06 |
| | | | Rsi | 0.13 |
| T | 0.231 | | RT | 2.499 |
| | | | U= 1/Rt | 0.400 |

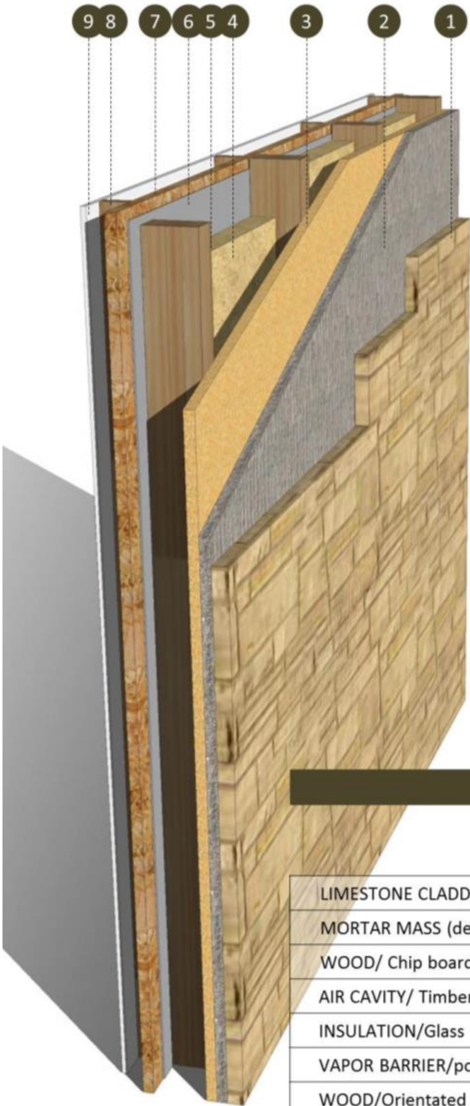
| A3. Definition of layers | N |
|---|---|
| METAL SHEETS/ Zinc (density = 7144 kg/$m^3$) | 1 |
| AIR CAVITY/ Studs | 2 |
| WOOD/ Chip board (density < 1200 kg/$m^3$) | 3 |
| AIR CAVITY/ Timber frame | 4 |
| INSULATION/Glass wool (density = 100 kg/$m^3$) | 5 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/$m^3$) | 6 |
| WOOD/Orientated strand board (OSB) (density < 650 kg/$m^3$) | 7 |
| AIR CAVITY/ Studs | 8 |
| GYPSUM BOARD (density: 750 - 900 kg/$m^3$) | 9 |




| N | Price (€/m²) |
|---|---|
| 1 | 23.44 |
| 2 | 1.44 |
| 3 | 4.63 |
| 4 | 5.19 |
| 5 | 8.58 |
| 6 | 0.23 |
| 7 | 13.72 |
| 8 | 3.62 |
| 9 | 5.47 |
| T | 66.32 |

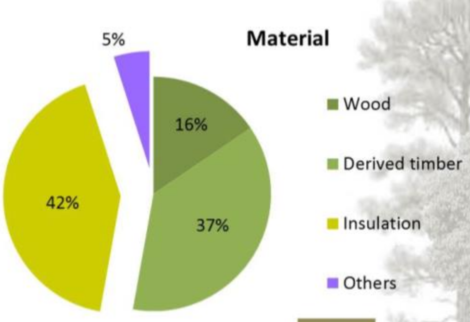


## A4. Timber frame with external stone cladding

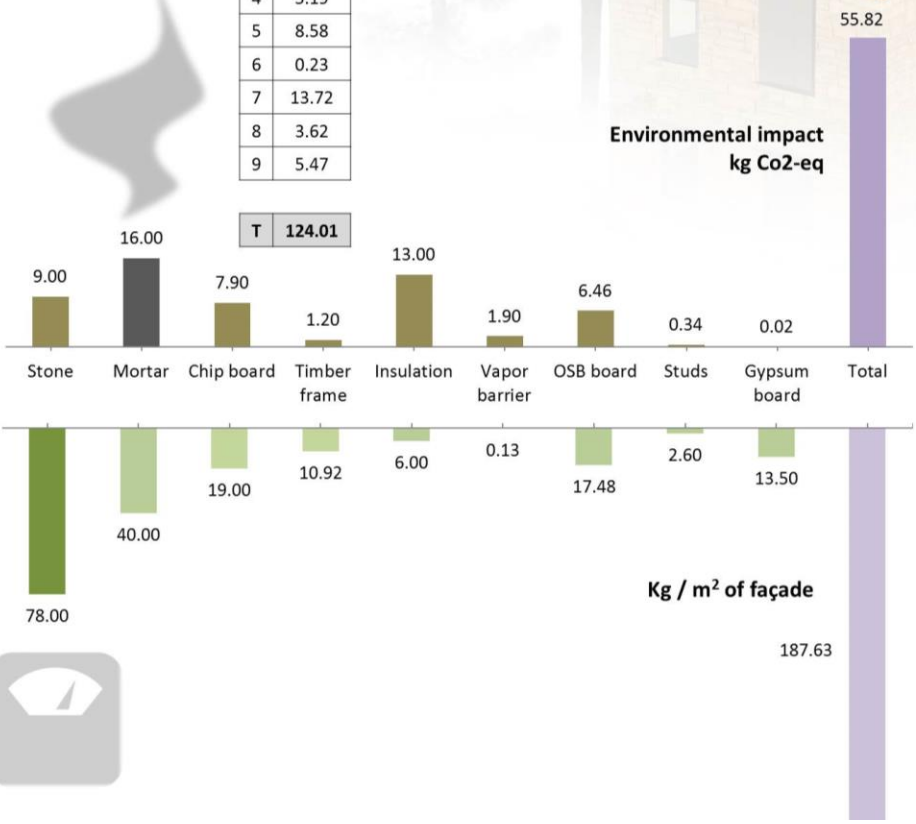



| N | e (m) | λ (W/m°C) | | R ($m^2$°C/W) |
|---|---|---|---|---|
| | | | Rse | 0.04 |
| 1 | 0.03 | 3.5 | R1 | 0.01 |
| 2 | 0.02 | 0.4 | R2 | 0.05 |
| 3 | 0.019 | 0.23 | R3 | 0.08 |
| 4 | 0.04 | ---- | R4 | 0.18 |
| 5 | 0.06 | 0.04 | R5 | 1.50 |
| 6 | 0.001 | ---- | R6 | ---- |
| 7 | 0.019 | 0.13 | R7 | 0.15 |
| 8 | 0.05 | ---- | R8 | 0.18 |
| 9 | 0.015 | 0.25 | R9 | 0.06 |
| | | | Rsi | 0.13 |
| **T** | **0.254** | | **RT** | **2.377** |
| | | | **U= 1/Rt** | **0.421** |

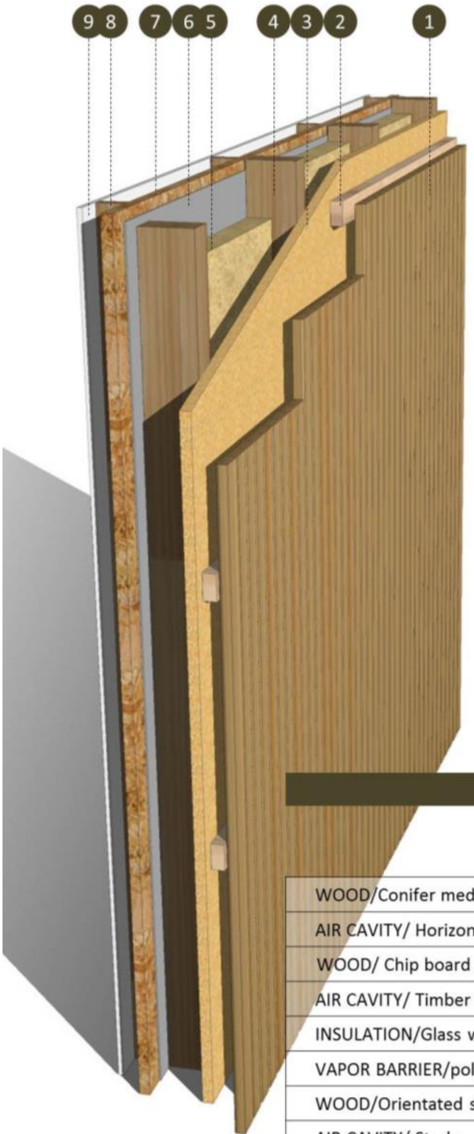
| A4. Definition of layers | N |
|---|---|
| LIMESTONE CLADDING (density = 2600 kg/m3) | 1 |
| MORTAR MASS (density: 250 - 2000 kg/m3) | 2 |
| WOOD/ Chip board (density < 1200 kg/$m^3$) | 3 |
| AIR CAVITY/ Timber frame | 4 |
| INSULATION/Glass wool (density = 100 kg/$m^3$) | 5 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/$m^3$) | 6 |
| WOOD/Orientated strand board (OSB) (density < 650 kg/$m^3$) | 7 |
| AIR CAVITY/ Studs | 8 |
| GYPSUM BOARD (density: 750 - 900 kg/$m^3$) | 9 |




| N | Price (€/m²) |
|---|---|
| 1 | 49.21 |
| 2 | 33.36 |
| 3 | 4.63 |
| 4 | 5.19 |
| 5 | 8.58 |
| 6 | 0.23 |
| 7 | 13.72 |
| 8 | 3.62 |
| 9 | 5.47 |
| **T** | **124.01** |

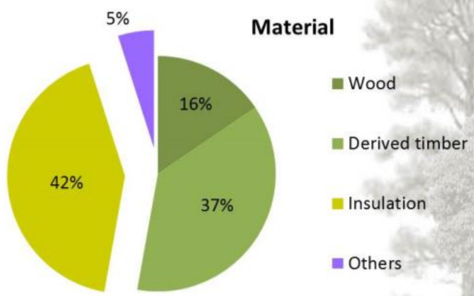


## A5. Timber frame with external wood slats

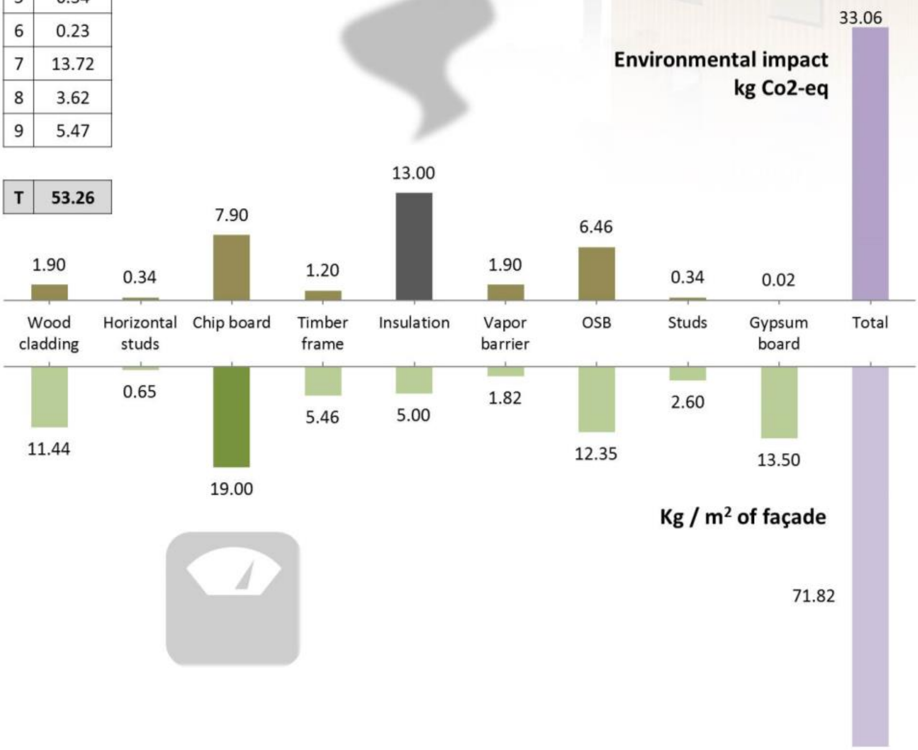



| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | m²°C/W |
| | | | Rse | 0.04 |
| 1 | 0.022 | 0.15 | R1 | ---- |
| 2 | 0.025 | 0.18 | R2 | ---- |
| 3 | 0.019 | 0.23 | R3 | 0.08 |
| 4 | 0.05 | 0.18 | R4 | 0.18 |
| 5 | 0.05 | 0.04 | R5 | 1.50 |
| 6 | 0.001 | 0.17 | R6 | ---- |
| 7 | 0.019 | 0.13 | R7 | 0.15 |
| 8 | 0.05 | 0.18 | R8 | 0.18 |
| 9 | 0.015 | 0.25 | R9 | 0.06 |
| | | | Rsi | 0.13 |
| **T** | **0.251** | | **RT** | **2.319** |
| | | | **U= 1/Rt** | **0.431** |

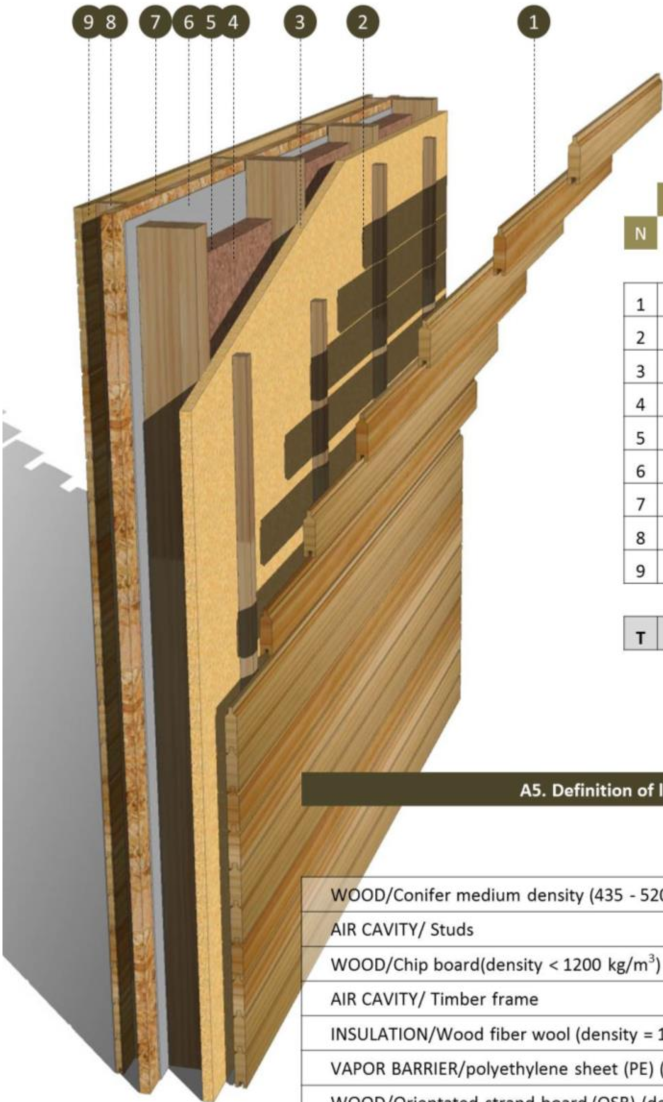
| A5. Definition of layers | N |
|---|---|
| WOOD/Conifer medium density (435 - 520 kg/m$^3$) | 1 |
| AIR CAVITY/ Horizontal studs | 2 |
| WOOD/ Chip board (density < 1200 kg/m$^3$) | 3 |
| AIR CAVITY/ Timber frame | 4 |
| INSULATION/Glass wool (density = 100 kg/m$^3$) | 5 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/m$^3$) | 6 |
| WOOD/Orientated strand board (OSB) (density < 650 kg/m$^3$) | 7 |
| AIR CAVITY/ Studs | 8 |
| GYPSUM BOARD (density: 750 - 900 kg/m$^3$) | 9 |




| N | Price (€/m²) |
|---|---|
| 1 | 12.62 |
| 2 | 1.44 |
| 3 | 4.63 |
| 4 | 5.19 |
| 5 | 6.34 |
| 6 | 0.23 |
| 7 | 13.72 |
| 8 | 3.62 |
| 9 | 5.47 |
| T | **53.26** |

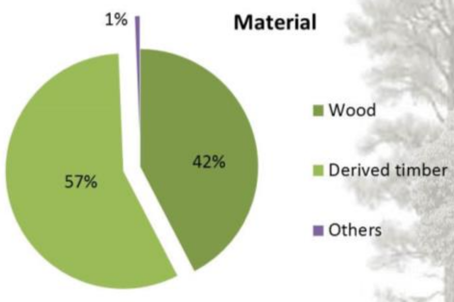


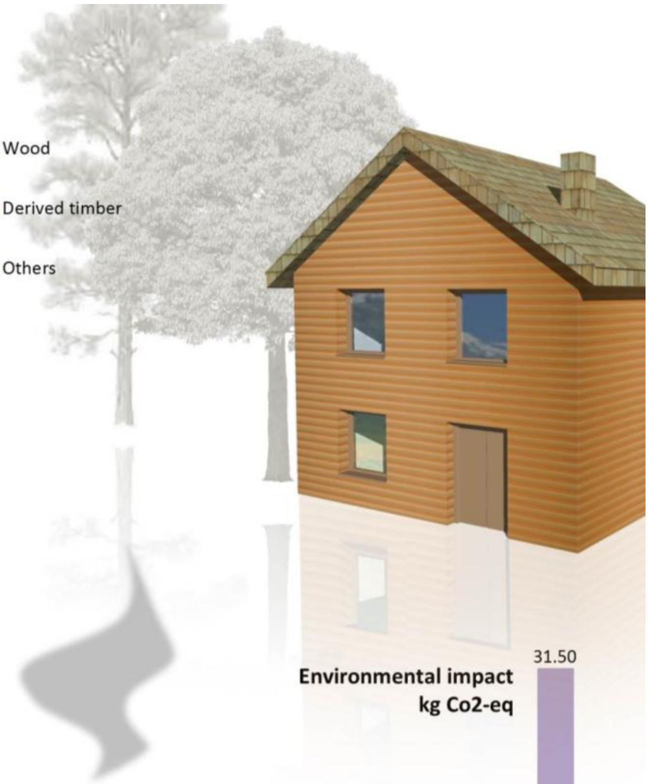
## A6. Timber frame with wood fiber insulation



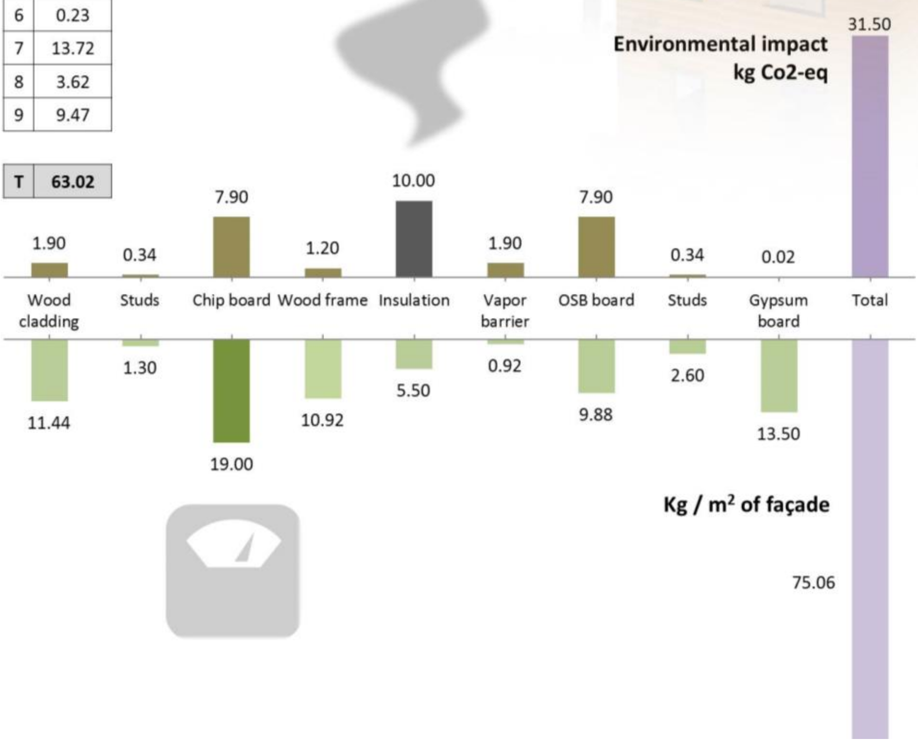

| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | m²°C/W |
| | | | Rse | 0.04 |
| 1 | 0.022 | 0.15 | R1 | 0.15 |
| 2 | 0.025 | ---- | R2 | 0.18 |
| 3 | 0.019 | 0.23 | R3 | 0.08 |
| 4 | 0.05 | ---- | R4 | 0.18 |
| 5 | 0.05 | 0.039 | R5 | 1.28 |
| 6 | 0.001 | ---- | R6 | ---- |
| 7 | 0.019 | 0.13 | R7 | 0.15 |
| 8 | 0.05 | ---- | R8 | 0.18 |
| 9 | 0.015 | 0.15 | R9 | 0.10 |
| | | | Rsi | 0.13 |
| T | 0.251 | | RT | 2.467 |
| | | | U= 1/Rt | 0.405 |

| A5. Definition of layers | N |
|---|---|
| WOOD/Conifer medium density (435 - 520 kg/m$^3$) | 1 |
| AIR CAVITY/ Studs | 2 |
| WOOD/Chip board(density < 1200 kg/m$^3$) | 3 |
| AIR CAVITY/ Timber frame | 4 |
| INSULATION/Wood fiber wool (density = 110 kg/m$^3$) | 5 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/m$^3$) | 6 |
| WOOD/Orientated strand board (OSB) (density < 650 kg/m$^3$) | 7 |
| AIR CAVITY/ Studs | 8 |
| GYPSUM BOARD (density: 750 - 900 kg/m$^3$) | 9 |

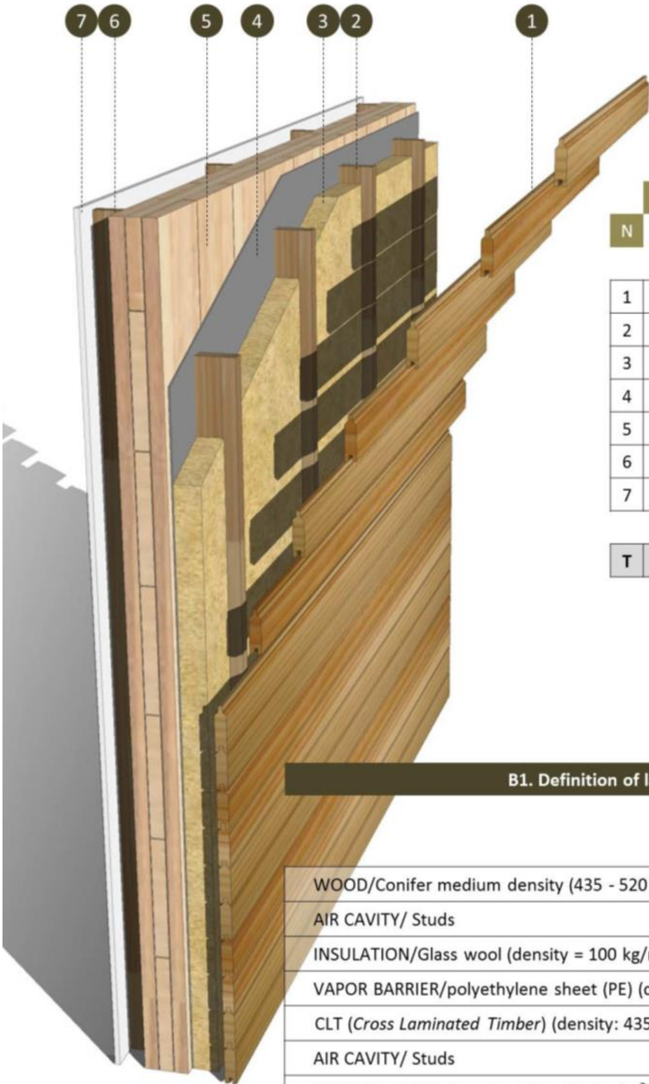


| N | Price (€/m²) |
|---|---|
| 1 | 12.62 |
| 2 | 1.44 |
| 3 | 4.63 |
| 4 | 5.19 |
| 5 | 12.10 |
| 6 | 0.23 |
| 7 | 13.72 |
| 8 | 3.62 |
| 9 | 9.47 |
| **T** | **63.02** |

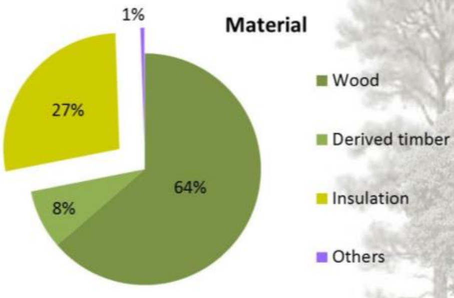


**B1. CLT façade with external wood layer**

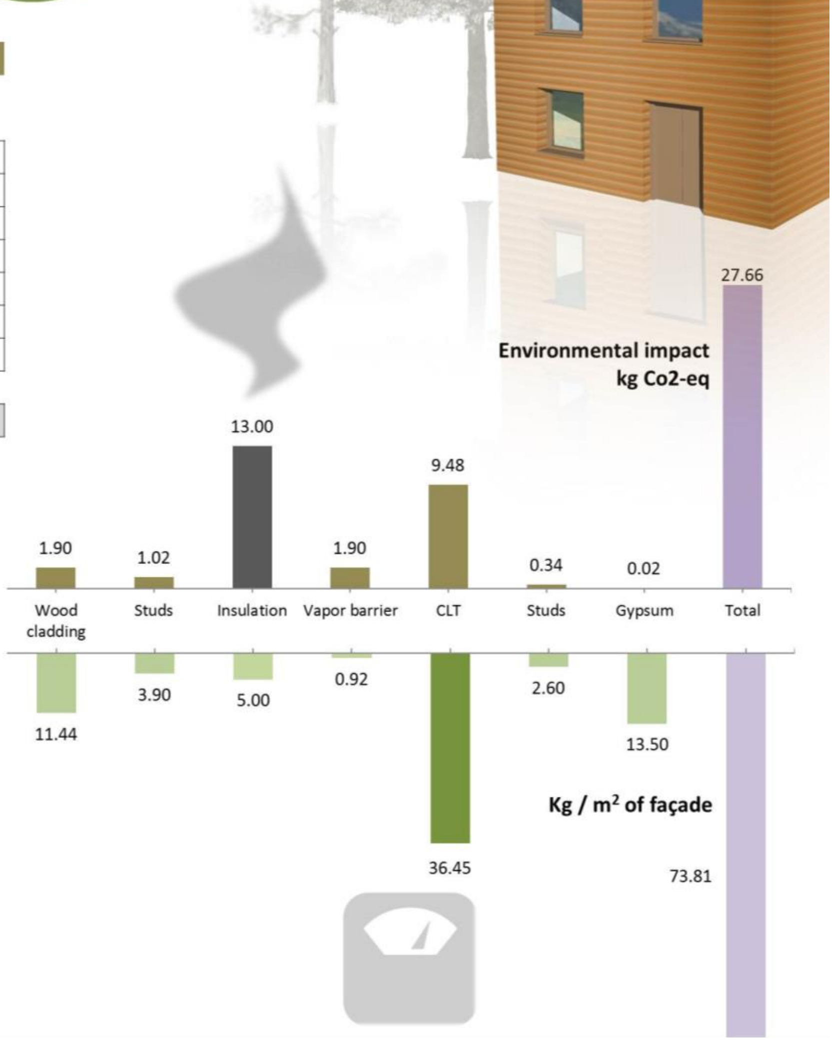



| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | m²°C/W |
| | | | Rse | 0.04 |
| 1 | 0.022 | 0.15 | R1 | 0.15 |
| 2 | 0.025 | ---- | R2 | 0.18 |
| 3 | 0.05 | 0.04 | R3 | 1.25 |
| 4 | 0.001 | ---- | R4 | ---- |
| 5 | 0.081 | 0.18 | R5 | 0.54 |
| 6 | 0.05 | ---- | R6 | 0.18 |
| 7 | 0.015 | 0.25 | R7 | 0.06 |
| | | | Rsi | 0.13 |
| **T** | **0.244** | | **RT** | **2.527** |
| | | | **U= 1/Rt** | **0.396** |

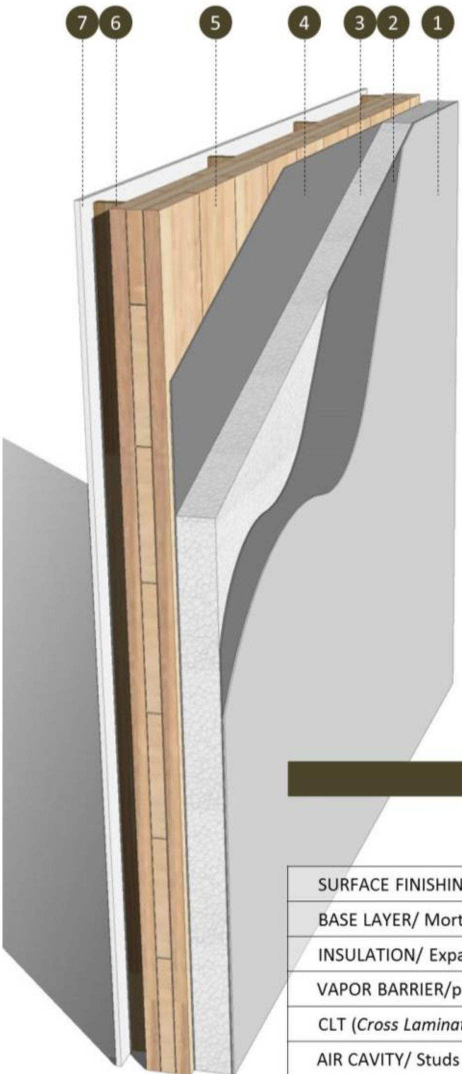
| B1. Definition of layers | N |
|---|---|
| WOOD/Conifer medium density (435 - 520 kg/m$^3$) | 1 |
| AIR CAVITY/ Studs | 2 |
| INSULATION/Glass wool (density = 100 kg/m$^3$) | 3 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/m$^3$) | 4 |
| CLT (*Cross Laminated Timber*) (density: 435 - 520 kg/m3) | 5 |
| AIR CAVITY/ Studs | 6 |
| GYPSUM BOARD (density: 750 - 900 kg/m$^3$) | 7 |




| N | Price (€/m²) |
|---|---|
| 1 | 12.62 |
| 2 | 5.44 |
| 3 | 6.34 |
| 4 | 0.23 |
| 5 | 58.49 |
| 6 | 3.62 |
| 7 | 5.47 |
| **T** | **92.21** |

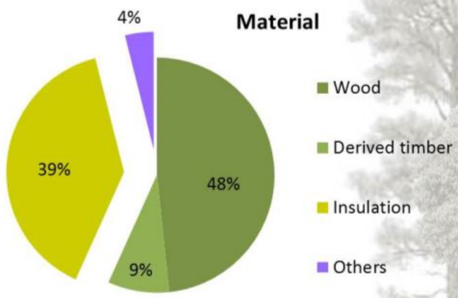


## B2. CLT façade with external thermal insulation composite systems

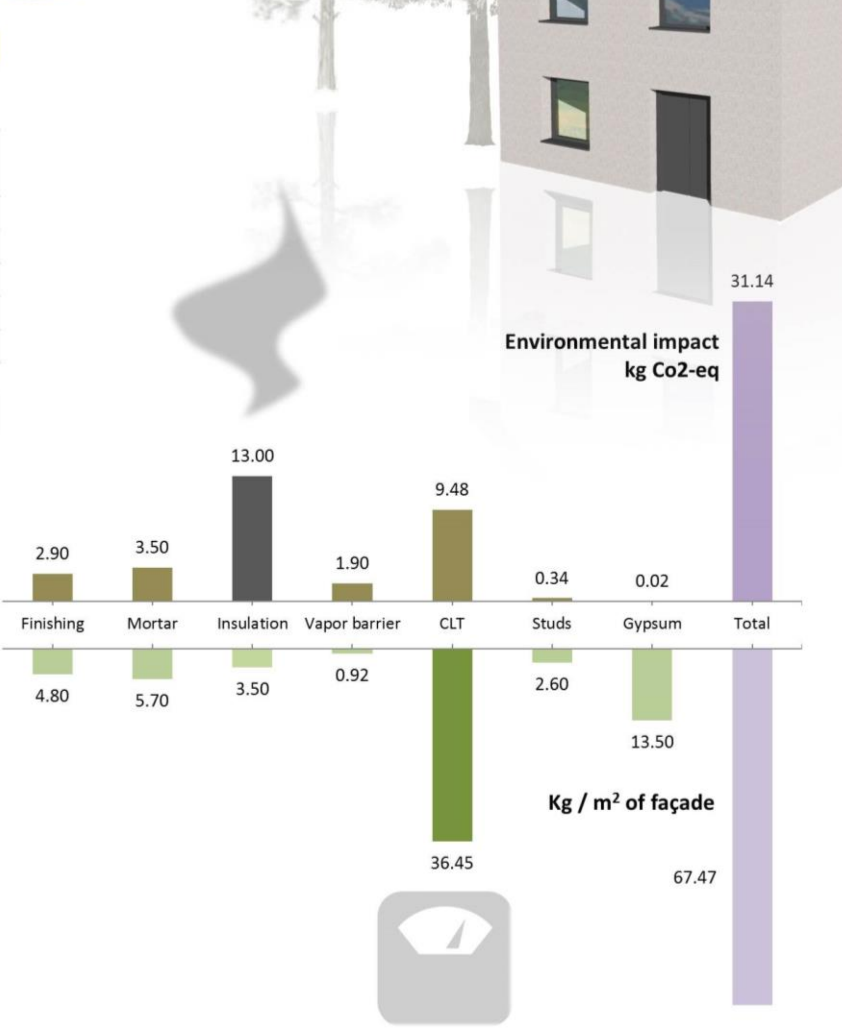



| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | m²°C/W |
| | | | Rse | 0.04 |
| 1 | 0.003 | 0.2 | R1 | 0.02 |
| 2 | 0.003 | 0.15 | R2 | 0.02 |
| 3 | 0.07 | 0.04 | R3 | 1.75 |
| 4 | 0.001 | ---- | R4 | ---- |
| 5 | 0.081 | 0.15 | R5 | 0.54 |
| 6 | 0.05 | ---- | R6 | 0.15 |
| 7 | 0.015 | 0.25 | R7 | 0.06 |
| | | | Rsi | 0.13 |
| **T** | **0.223** | | **RT** | **2.705** |
| | | | **U= 1/Rt** | **0.370** |

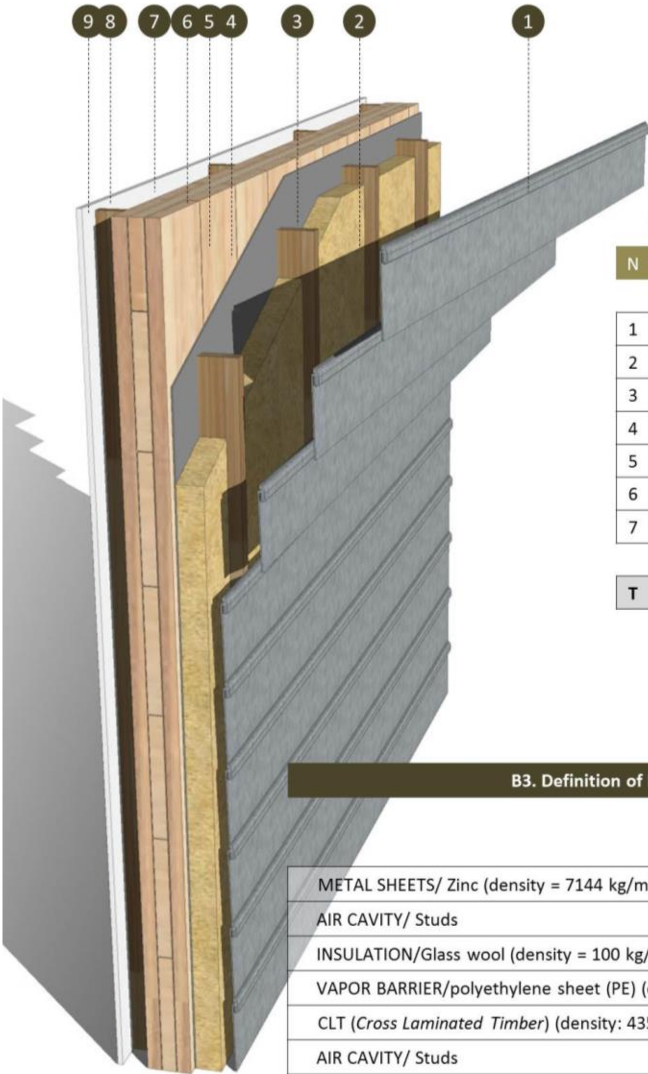
| B2. Definition of layers | N |
|---|---|
| SURFACE FINISHING/ SIKA thermocoat 5 (density: 1500 - 1600 kg/m³) | 1 |
| BASE LAYER/ Mortar with intermediate frame (density = 1900 kg/m³) | 2 |
| INSULATION/ Expanded polystyrene, EPS (density: 10 - 50 kg/m³) | 3 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/m³) | 4 |
| CLT (*Cross Laminated Timber*) (density: 435 - 520 kg/m3) | 5 |
| AIR CAVITY/ Studs | 6 |
| GYPSUM BOARD (density: 750 - 900 kg/m³) | 7 |




| N | Price (€/m²) |
|---|---|
| 1 | 44.00 |
| 2 | |
| 3 | 11.58 |
| 4 | 0.23 |
| 5 | 58.49 |
| 6 | 3.62 |
| 7 | 5.47 |
| **T** | **123.39** |

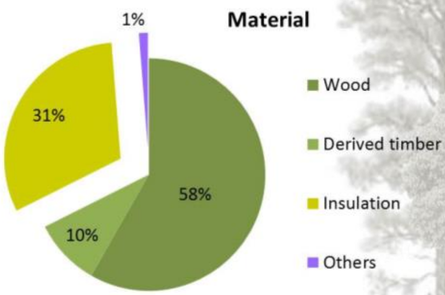


## B3. CLT façade with external metal cladding

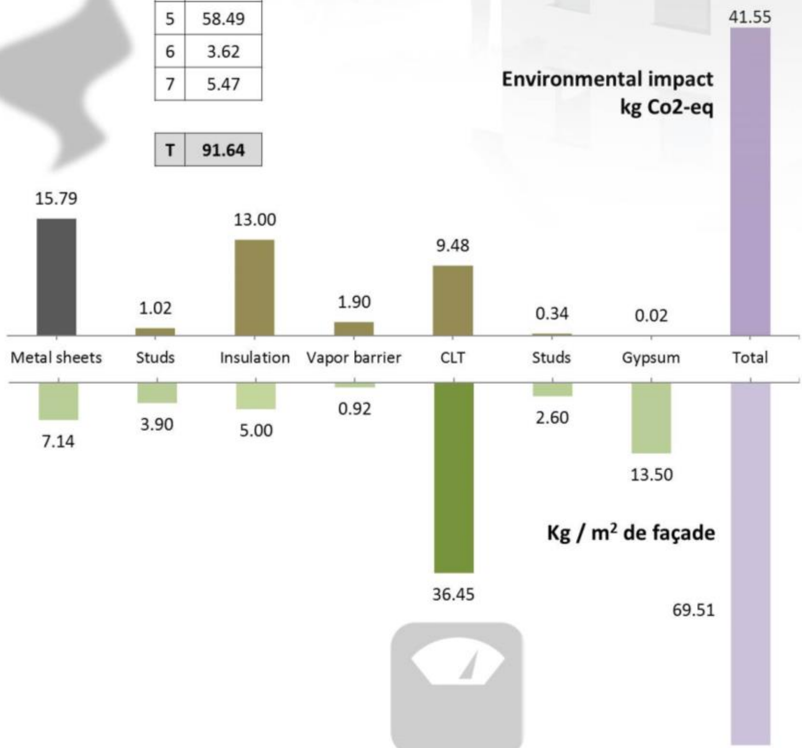



| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | $m^2$°C/W |
| | | | Rse | 0.04 |
| 1 | 0.001 | 112.2 | R1 | 0.00 |
| 2 | 0.025 | ---- | R2 | 0.18 |
| 3 | 0.05 | 0.04 | R3 | 1.25 |
| 4 | 0.001 | ---- | R4 | ---- |
| 5 | 0.081 | 0.18 | R5 | 0.45 |
| 6 | 0.05 | ---- | R6 | 0.18 |
| 7 | 0.015 | 0.25 | R7 | 0.06 |
| | | | Rsi | 0.13 |
| **T** | **0.223** | | **RT** | **2.290** |
| | | | **U= 1/Rt** | **0.437** |

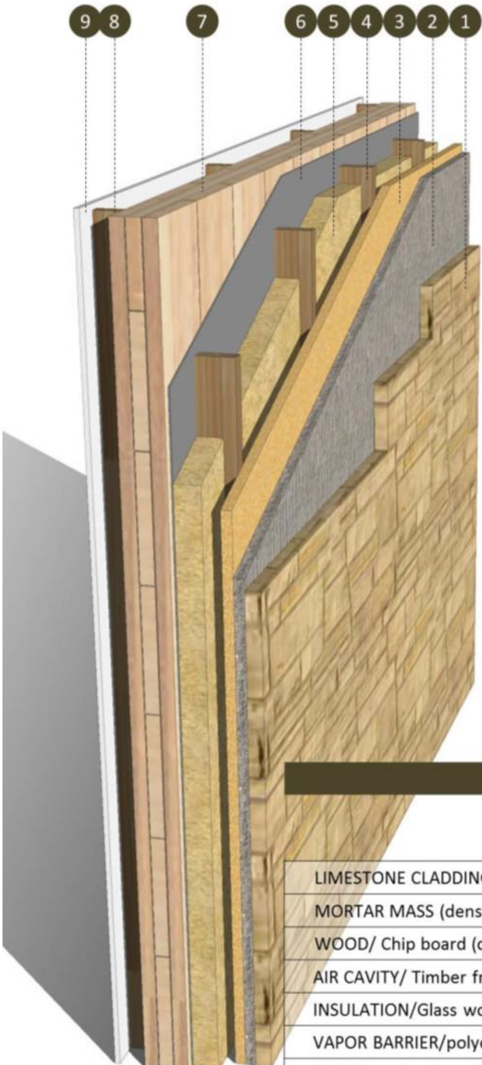
| B3. Definition of layers | N |
|---|---|
| METAL SHEETS/ Zinc (density = 7144 kg/$m^3$) | 1 |
| AIR CAVITY/ Studs | 2 |
| INSULATION/Glass wool (density = 100 kg/$m^3$) | 3 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/$m^3$) | 4 |
| CLT (*Cross Laminated Timber*) (density: 435 - 520 kg/m3) | 5 |
| AIR CAVITY/ Studs | 6 |
| GYPSUM BOARD (density: 750 - 900 kg/$m^3$) | 7 |




| N | Price (€/m²) |
|---|---|
| 1 | 12.05 |
| 2 | 5.44 |
| 3 | 6.34 |
| 4 | 0.23 |
| 5 | 58.49 |
| 6 | 3.62 |
| 7 | 5.47 |
| **T** | **91.64** |

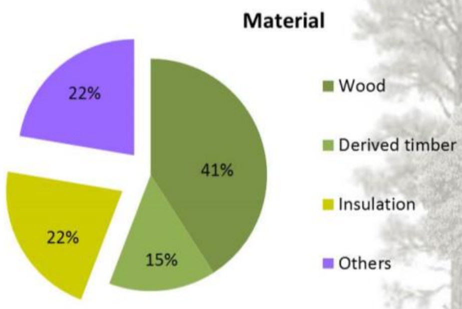


## B4. CLT façade with external stone cladding

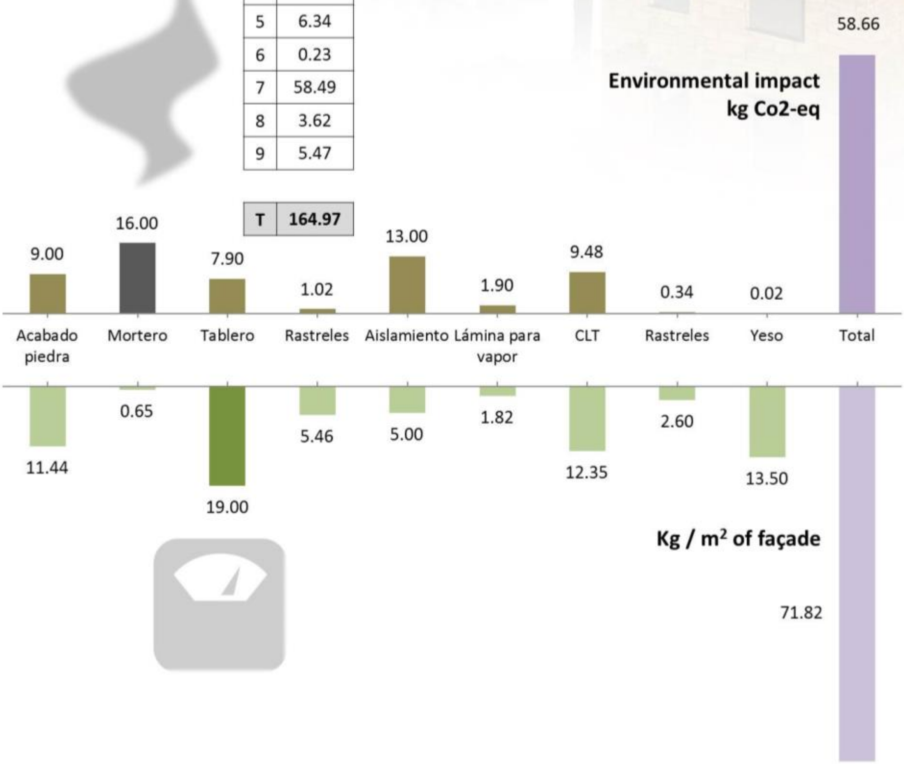



| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | m²°C/W |
| | | | Rse | 0.04 |
| 1 | 0.03 | 0.15 | R1 | 0.01 |
| 2 | 0.02 | 0.18 | R2 | 0.05 |
| 3 | 0.019 | 0.23 | R3 | 0.08 |
| 4 | 0.025 | 0.18 | R4 | 0.18 |
| 5 | 0.05 | 0.04 | R5 | 1.25 |
| 6 | 0.001 | 0.17 | R6 | ---- |
| 7 | 0.081 | 0.13 | R7 | 0.45 |
| 8 | 0.05 | 0.18 | R8 | 0.18 |
| 9 | 0.015 | 0.25 | R9 | 0.06 |
| | | | Rsi | 0.13 |
| **T** | **0.291** | | **RT** | **2.431** |
| | | | **U= 1/Rt** | **0.411** |

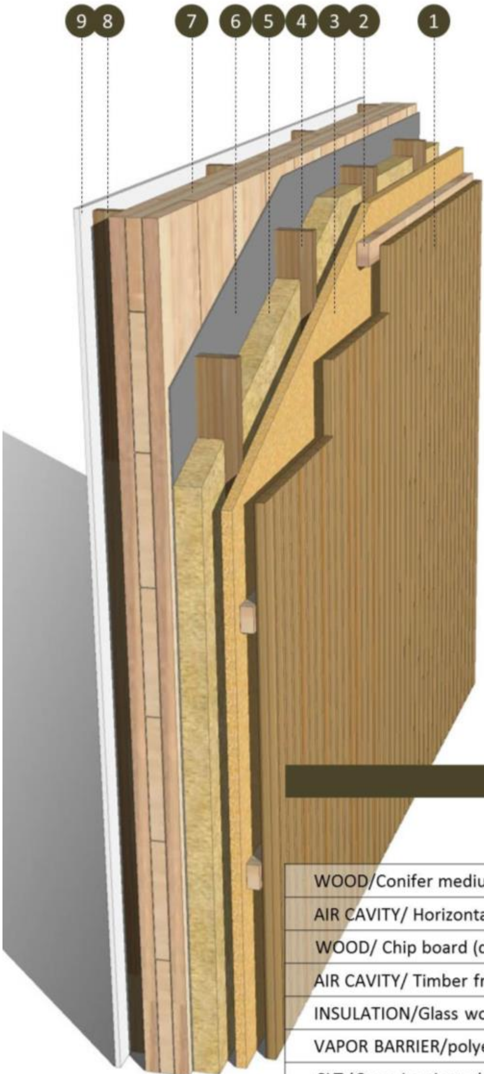
| B4. Definition of layers | N |
|---|---|
| LIMESTONE CLADDING (density = 2600 kg/m3) | 1 |
| MORTAR MASS (density: 250 - 2000 kg/m3) | 2 |
| WOOD/ Chip board (density < 1200 kg/m$^3$) | 3 |
| AIR CAVITY/ Timber frame | 4 |
| INSULATION/Glass wool (density = 100 kg/m$^3$) | 5 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/m$^3$) | 6 |
| CLT (*Cross Laminated Timber*) (density: 435 - 520 kg/m3) | 7 |
| AIR CAVITY/ Studs | 8 |
| GYPSUM BOARD (density: 750 - 900 kg/m$^3$) | 9 |




| N | Price (€/m²) |
|---|---|
| 1 | 49.21 |
| 2 | 33.36 |
| 3 | 4.63 |
| 4 | 3.62 |
| 5 | 6.34 |
| 6 | 0.23 |
| 7 | 58.49 |
| 8 | 3.62 |
| 9 | 5.47 |
| T | 164.97 |

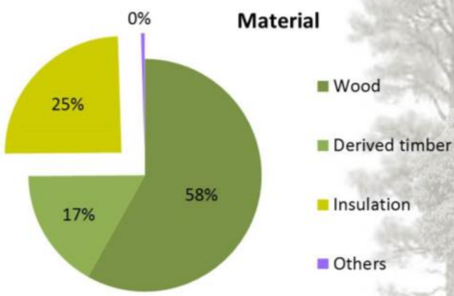


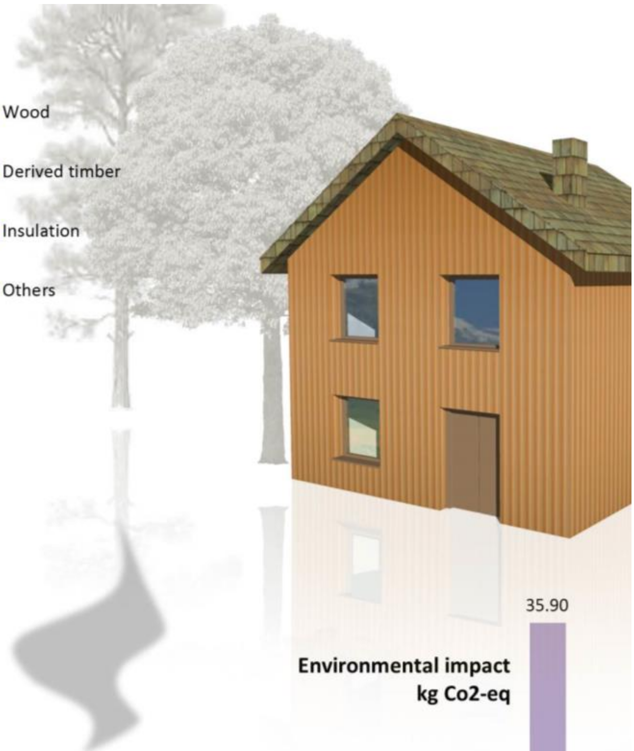
## B5. CLT façade with external wood slats



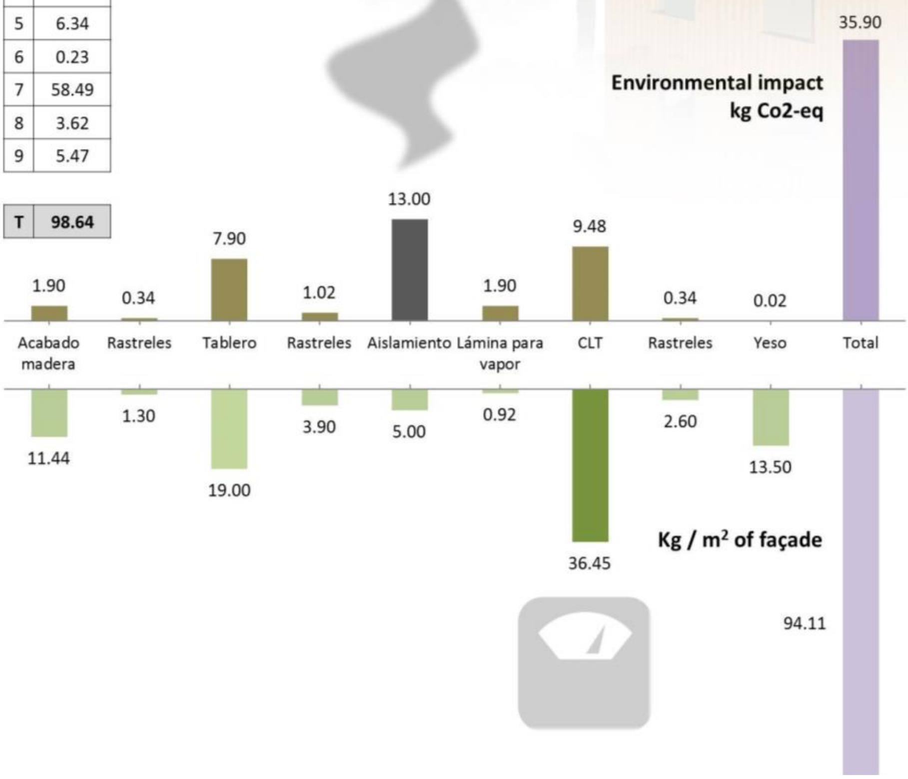

| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | m²°C/W |
| | | | Rse | 0.04 |
| 1 | 0.022 | ---- | R1 | ---- |
| 2 | 0.025 | ---- | R2 | ---- |
| 3 | 0.019 | 0.23 | R3 | 0.08 |
| 4 | 0.025 | ---- | R4 | 0.18 |
| 5 | 0.05 | 0.04 | R5 | 1.25 |
| 6 | 0.001 | ---- | R6 | ---- |
| 7 | 0.081 | 0.15 | R7 | 0.54 |
| 8 | 0.05 | ---- | R8 | 0.18 |
| 9 | 0.015 | 0.25 | R9 | 0.06 |
| | | | Rsi | 0.13 |
| **T** | **0.288** | | **RT** | **2.463** |
| | | | **U= 1/Rt** | **0.406** |

| B5. Definition of layers | N |
|---|---|
| WOOD/Conifer medium density (435 - 520 kg/m³) | 1 |
| AIR CAVITY/ Horizontal studs | 2 |
| WOOD/ Chip board (density < 1200 kg/m³) | 3 |
| AIR CAVITY/ Timber frame | 4 |
| INSULATION/Glass wool (density = 100 kg/m³) | 5 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/m³) | 6 |
| CLT (*Cross Laminated Timber*) (density: 435 - 520 kg/m3) | 7 |
| AIR CAVITY/ Studs | 8 |
| GYPSUM BOARD (density: 750 - 900 kg/m³) | 9 |

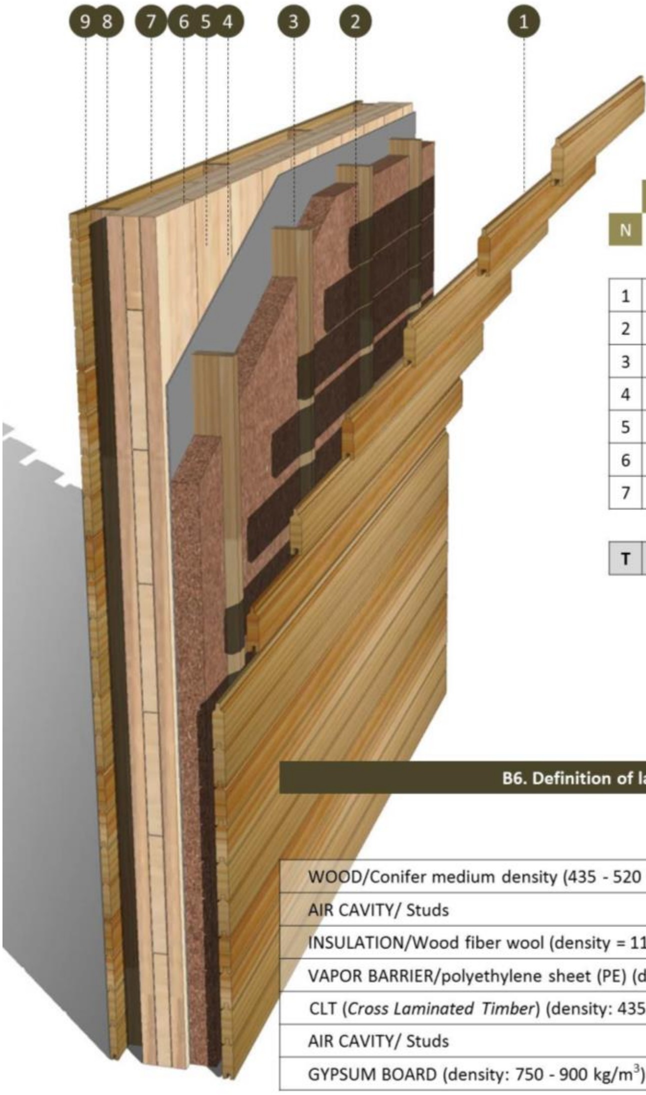


| N | Price (€/m²) |
|---|---|
| 1 | 12.62 |
| 2 | 3.62 |
| 3 | 4.63 |
| 4 | 3.62 |
| 5 | 6.34 |
| 6 | 0.23 |
| 7 | 58.49 |
| 8 | 3.62 |
| 9 | 5.47 |
| **T** | **98.64** |



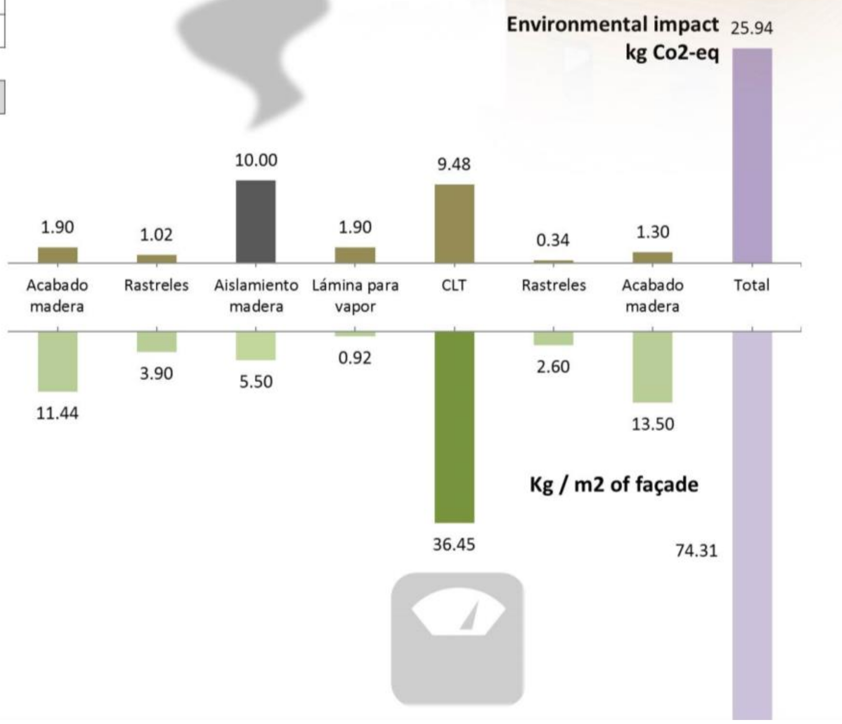
## B6. CLT façade with wood fiber insulation




| N | e | λ | | R |
|---|---|---|---|---|
| | m | W/m°C | | m²°C/W |
| | | | Rse | 0.04 |
| 1 | 0.022 | 0.15 | R1 | 0.15 |
| 2 | 0.025 | ---- | R2 | 0.02 |
| 3 | 0.05 | 0.04 | R3 | 1.28 |
| 4 | 0.001 | ---- | R4 | ---- |
| 5 | 0.081 | 0.18 | R5 | 0.45 |
| 6 | 0.05 | ---- | R6 | 0.18 |
| 7 | 0.015 | 0.25 | R7 | 0.10 |
| | | | Rsi | 0.13 |
| **T** | **0.244** | | **RT** | **2.347** |
| | | | **U= 1/Rt** | **0.426** |

| B6. Definition of layers | N |
|---|---|
| WOOD/Conifer medium density (435 - 520 kg/m$^3$) | 1 |
| AIR CAVITY/ Studs | 2 |
| INSULATION/Wood fiber wool (density = 110 kg/m$^3$) | 3 |
| VAPOR BARRIER/polyethylene sheet (PE) (density = 910 kg/m$^3$) | 4 |
| CLT (*Cross Laminated Timber*) (density: 435 - 520 kg/m3) | 5 |
| AIR CAVITY/ Studs | 6 |
| GYPSUM BOARD (density: 750 - 900 kg/m$^3$) | 7 |


| N | Price (€/m²) |
|---|---|
| 1 | 12.62 |
| 2 | 5.44 |
| 3 | 12.10 |
| 4 | 0.23 |
| 5 | 58.49 |
| 6 | 3.62 |
| 7 | 9.47 |
| **T** | **101.97** |



### 7.1.1 Comparison of façades

A comparison of façades is realized in order to analyse the sustainability of them, related to both economic and environmental issues. In this case, their transmittance is similar in order to consider the same energy efficiency.

In general, the CLT (Cross Laminated Timber) solutions are more expensive than timber frame structures. If the catalogue solutions are compared, the CLT enclosures are between 1.33 and 1.62 times more expensive than the timber frame enclosures. Apart from that, the transportation of this material also supposes more energy consumption such as space transportation requirements because of their volume. However, its execution is very fast and allows saving time, which supposes the investment of less economical resources for this project phase. Besides, new alternative of module buildings made of CLT are being studied in order to construct multi-story buildings in less time, combining with steel structures [163].

On the other hand, timber frame is a lighter structure, easier to transport due to its volume and weight. However, in general, timber frame solutions imply more execution time and joints. Nowadays, timber frame modules are designed in order to shorten this inconvenience and make easier and faster its construction. Some of them even include integrated installations such as mechanical ventilation with heat recovery (MVHR), in order to optimise as much as possible the execution time in-situ and promote the use of more energy efficient solutions [164].

In terms of environmental impact, although both of them are quite similar, the timber frame solutions have slightly more impact than CLT façades. The difference is principally due to wood boards, such as chipboards and OSB (Orientated Strand Board). While CLT is a structure element that acts as a plane support for other elements, insulation and vapour barriers among others, timber frame needs, in general, two extra wood boards to close the system and support the other enclosure layers. Because of that, timer frame façades in case 1, 2, 3 and 6 has between 16.33 and 17.65% more impact than those made of CLT. However, the configuration 4 and 5 has slightly less impact in the timer frame solution. That occurs because in the CLT solution an extra wood board is required increasing the amount of layers in those two cases. As a result, the difference between them is 4.84 and 7.91 for each configuration.

If the amount of wood is analysed, the less use of wood the higher is the environmental impact. Wood material without cement, glues or other adhesives are more environmental friendly than derived wood products made with those substances. At the same time, derived wood products are less harmful than other natural products such as stone or metal sheets. In this case, although they are durable and recyclable, their extraction and fabrication requires a lot of energy. Apart from that, these materials are not renewable. The most harmful products are the most industrialized products such as glass wool or vapour barriers made of polyethylene.

It is important to realize a previous study of the materials and systems in order to select the most accurate solutions, considering all the factors that influence the building materials sustainability [165].

## 7.2 Conclusions

In conclusion, the CLT solutions are in general more expensive than timber frame structures. As it is known, CLT is an innovative material in expansion mainly due to its ecological, mechanical strength and easy to assembly in-situ properties. Its use has to be more spread in order to cut down its price and get it more competitive, overall for residence buildings. It is also made of high volume of wood which increment its value

On the other hand, timber façades are cheaper but they are no conventional constructions in our territory due to the lack of culture around this type of solutions. This implies an extra social effort in terms of giving information and promoting their environmental benefits.

*“Only after Winter comes do we know that the pine and the cypress are the last to fade”*

Confucio

551 BC-478 BC

# CHAPTER 8
# Conclusions

# 8 Conclusions

In order to study the thermal behaviour of external claddings made of wood, material characterization was realized. In this case, the thermal conductivity of natural, chemical treated and heat-treated Radiata-pine were obtained through two different methods. Apart from conductivity, other thermal properties such as specific heat and resistance to water vapour diffusion are also obtained through different tests. By them, it is demonstrated that the application of protection treatments do influence in material thermal properties, which in this case is related to Radiata-pine. The detailed conclusions are presented next:

**Thermal characterization of Radiata-pine**

In general terms, it is appreciated less thermal conductivity fluctuation when Radiata-pine is protected with chemical substances or heat-treatment. However, the lowest conductivity value obtained by test box is registered for the natural wood sample, when gradient between surfaces and material average temperature are the lowest. After conditioning the samples to 23°C temperature and 50% relative humidity, the density of chemical and heat-treated wood is slightly lower than natural wood density, which may imply that they have less cellulose or lignin.

The fluctuation along the tests of the natural wood thermal conductivity is twice higher than the fluctuation of the chemical treated sample and four times the heat-treated one. The heat-treated wood is the most stable, as its conductivity difference is only 0.0034 W/(m·°C), while treated wood with chemical substances has a difference of 0.0065

W/(m·°C) between the highest and the lowest conductivity value, and natural wood has a difference of 0.0143 W/(m·°C).

Test box method based on the thermocouples and UNE-EN 12664 [44] procedure was assessed. In both cases, the conductivity of natural wood (1) increases more drastically than the other samples. In case of chemical treated wood (2), it has less conductivity variation than the previous one. The heat-treated wood (3) represents the sample with the least variation of its thermal properties.

However, the resulted thermal conductivity was different as both method represent different thermal situation. The method stablished by test box represents the material exposed to air and the thermal behaviour of both elements is linked. In case of UNE-EN 12664 procedure, it does not contemplate nor convection coefficient nor its behaviour depending on material surface.

In case of using transmittance detector equipment, this is closer to test box method, as it also uses the test box to produce the necessary temperature gradient between surfaces. However, it considers that the convection coefficients are constant, which it is not as it was demonstrated by thermocouples. Both exterior and interior convection coefficients vary, although the exterior one varies less as the temperature in this side is more constant.

Heat-treated wood represents the least variation in terms of convection, which indicates that it is more insulated. In case of natural wood (1), its superficial resistance is the highest which in principle would indicate that it is the least insulated. However, the temperature cycles inside the test box are as long as the cycles of the heat-treated wood (3), while chemical treated wood (2) has shorter cycles. That means that the temperature inside the box reaches the operational temperature at the same time. That is, both samples (1, 3) requiring the same time duration to heat the inner box until reach the operational temperature, as it was mentioned in section 3.2.2.2.

In order to guarantee the correct use of test box, the risk of Radiata-pine condensation was also estimated for each test (a, b, c, d). By these estimations, it is demonstrated that the lower is the gradient of temperature, the lower is this risk. However, at the same time, the higher is the error in the conductivity values as the flux is minor and other effects can become more impact.

Due to that, it is validated that these tests are not recommendable for less than 3 °C gradient of temperature between material surfaces. That is, for this material, Radiata-pine, both tests “a” and “d”, which corresponds to 40 and 28 °C inside the test box, are more susceptible to have an error, the first one due to the higher influence of transient convection inside the test box, and the second one due to the estimated condensation risk.

On the other side, there is a relation between transmittance and permeability, as the sample with most resistance to water diffusion (3) has similar results by test box and UNE-EN 12664 procedures, while the other samples (1, 2) have higher error. This implies that the hygrothermal behaviour in natural and chemical treated wood is more evident, because their conductivity highly varies depending on temperature and humidity. However, heat-treated wood is more stable which means that the difference of temperature and humidity do not influence in the same way.

The thermal mass and inertia of natural and chemical treated Radiata-pine are quite similar. Natural wood has more density and less specific heat than chemical treated wood. These values got compensate and the resulted thermal mass and inertia become similar. On the other hand, heat-treated wood represents the lowest volume, density, specific heat and thermal conductivity. As a result, this implies that it has the lowest thermal mass and inertia.

Apart of the material characterization, getting to know the influence of the boundary conditions in wood properties makes easier to understand its possibilities as sustainable construction product, overall when the product is highly exposed to climate. Due to that, a bench of simulations was realized. Those are the conclusions related to Energy Simulation:

### Energy simulation

From the modelling of five solutions made of tongue-and-groove boards (D1, D2, D3, D4, D5), shown in section 4.1., it is concluded that the higher is the perimeter exposed to exterior; the lower is its thermal resistance, when the total thickness is the same in two cases.

According to their simulation through THERM sv.73 software, the third solution (D3) is the least efficient in comparison with the rest of solutions, taking into account the same total thickness. In contrast, the most efficient is the first one (D1), which has more material and less discontinuousness.

On the other hand, the fourth solution (D4) has less material than the third one but it is more efficient, because its thermal resistance is slightly higher. That proves that the design influences directly in energy efficiency during its use phase, even considering the same total thickness. In this study, moisture flux was not considered, as this software does not allow this kind of assessment.

In terms of global sustainability, the mechanized processes also represent energy consumption, which derives in less sustainable solutions if the whole life cycle of the product is considered. Due to that, although being the least energy efficient solution during the use phase, in case of production phase, solutions such as D5 represent the least environmental impact as it is less mechanized. Besides, this solution has less costs and raw material consumption, which also interferes in sustainable development.

In order to analyse the hygrothermal behaviour of construction materials WUFI Pro software is commonly used. It also allows simulate heat transfer along time, which is not possible with THERM tool. In contrast, it does not allow study complex geometries as those simulated by THERM.

In order to simulate the heat transfer of the Radiata-pine samples by test box, WUFI Pro is used. In this case, the transient transmittance is obtained and compared. For that, generic properties and tested ones are introduced in the model. The boundary conditions are based on test “b”, which corresponds to 22 °C and 36 °C for exterior and interior temperatures respectively.

As a result, although heat-treated wood has lower thermal conductivity than natural and chemical treated one, depending on the boundary condition it does not have to be the solution with the lowest transmittance. That is, the lowest is the thermal conductivity of material, the lower is the superficial thermal resistance. In case of low thickness solutions, that implies more relevance, as both material resistance (Rm) and superficial thermal resistance (Rs) are closer. The material resistance is obtained by the development of expression (4-1), which directly depends on material thickness and thermal conductivity.

For the hygrothermal study a basic wooden façade solution is simulated. In this case, a comparison between claddings made of natural (1), chemical treated (2) and heat-treated (3) Radiata-pine is assessed in case 1, 2 and 3 respectively. UNE-EN 12664 conductivity values obtained for each sample in Chapter 3 were considered, as well as, resistance to water vapour diffusion, specific heat and emissivity properties obtained through tests.

It is demonstrated that the transient transmittance analysis for hygrothermal materials is complex, as in different months the lowest transmittance belong to a different solution. The hygrothermal behaviour plays an important role when its response to weather data is assessed, because the temperature and humidity are changing constantly along time.

However, analysing the months with the most energy consumption, an optimization of the most suitable hygrothermal materials for specific façade systems could be possible.

Finally, in order to understand both convection coefficients and test box behaviour, its Computational Fluid Dynamics simulation is performed by Design Builder software. In this case, the attention is paid to the inside behaviour of the air, as it influences the global transmittance. It is demonstrated that the test works correctly as the main amount of heat passes across the sample. It also shows that there is an important air movement inside. Because of that, the convective laminar flux is only produced in the outside face of the sample, as it was contemplate in the principles described in section 3.2.2, Chapter 3.

Apart of material characterization and energy simulations, the influence material ageing was also studied, as interferes in the development of the physical and thermal properties of the material. In relation with this, material durability tests were carried out for each sample (1, 2 and 3). Those are the conclusions reached:

**Durability**

The samples; natural, chemical treated and heat-treated Radiata-pine were exposed to climate during two years to test their deterioration, from January 2015 to December 2016. During the first period of tests, related to the first three months, there were sunny cloudless days, rain and even snow during some days. Due to the sharp and fast variation of those elements makes the samples deterioration growing up faster.

The most remarkable appearance changes take place from March to April, when the material is not adaptable to environment yet. In fact, there is a huge difference in colour between these months. While during March the colour is similar to original one, in April both natural (1) and heat-treated (3) sample become grey. However, chemical-treated one (2) changes from green to pale brown colour, turning its appearance to more natural colour.

After April, both sample 1 and 3 appear to be the same, which makes difficult to distinguish them. In terms of cracks they are also similar, which are wider than the fissures of sample 2. If rugosity is analysed, natural and heat-treated Radiata-pine also presents the most variation, while chemical treated Radiata-pine keeps less deteriorated.

However, in terms of thermal behaviour, the least variation of thermal conductivity after weathering is presented by the heat-treated wood (3), while the natural wood (1) presents a variation more than two times higher. In case of chemical treated wood (2), its difference respect to sample 3 is lower than sample 1.

Although the third sample is the most stable material in terms of thermal conductivity, the conductivity variation of the first sample is the most beneficial in terms of energy efficiency.

If durability is important to the sustainable development, other factors also play an important role. In order to analyse and compare the sustainability of different façades made of wood, a method based on MIVES methodology is developed. After that, this method was applied to a detached house in different cases. The conclusions are presented next:

**Sustainability**

As the range of stakeholders (developers, designers, contractors, end-users, etc.) involved in the construction industry often generates conflicting interests, it is developed a decision-making methodology that unifies the criteria in relation to the environmental sustainability of timber façades.

This methodology is based on the MIVES concept and, like the Spanish Structural Concrete Code (EHE-08) [126] and the Spanish Structural Steel Code (EAE-11) [127], aims to establish a quick indicator for quantifying the degree of "environmental sustainability" that may be assigned on the basis of information from the agents that intervene in the design of a timber façade. It implies uniformity of the different measurement units, it supplies global (aggregated) results and partial indexes, and it quantifies each indicator, criteria and result; it can be used to enhance the environmental sustainability of timber façades and to reduce the impacts that are generated, in those areas where it has been awarded a lower score.

In addition, it is easy and quick to apply both for technicians who are developing the project and for those who assess such information in a tendering (bidding) process. In fact, the simplicity of the example given in this study has made it easy to see that changes in the material, such as its background and environmental certification, generate significant changes in the overall result.

The proposed methodology includes lines of action that improve the sustainability of wooden façades, considering the economic situation and the particular characteristics of each country, thereby enhancing such initiatives. It is flexible enough for use in other parts of the world, although it would have to be adapted to the reality of each country.

After defining this methodology, a case study of a building was assessed. Then, changes such as the origin of the wood products, the environmental accreditation of manufacturer, and the increment of wood in the project were also evaluated. By means of this methodology, it was demonstrated that, in this case study, the material origin and the environmental accreditations of manufacturers can be more relevant than the increment of 18 % wood in the project. This methodology brings us closer to sustainable development.

Apart from the sustainability evaluation of a whole house, a catalogue of wooden façades was also made. Through this catalogue, thermal transmittance, costs and carbon print of different solutions are exposed. The conclusions obtained by the comparison of systems are presented next:

**Wooden façade catalogue**

By means of the compilation of wooden façades in a catalogue, it is concluded that the CLT solutions are in general more expensive than timber frame structures. As it is known, CLT is an innovative material in expansion mainly due to its ecological, mechanical strength and easy to assembly in-situ properties. Its use has to be more spread in order to cut down its price and get it more competitive, overall for residence buildings. It is also made of high volume of wood which increment its value

On the other hand, timber façades are cheaper but they are no conventional constructions in our territory due to the lack of culture around this type of solutions. This implies an extra social effort in terms of giving information and promoting their environmental benefits.

Once all conclusion are exposed and analyse, some suggestion of future research are presented:

## 8.1 Suggestions of future research

Test box was created to test wood samples in order to obtain their thermal conductivity by means of heat transfer by convection. It is an interesting tool to study both material thermal conductivity and convection behavior of air. In fact, in this case it is demonstrated that the higher is the material conductivity, the higher is the superficial thermal resistance.

This effect gains relevance in the transmittance of the solution when material thickness is only 2 cm, and it represents different convection coefficients depending on natural, chemical treated and heat-treated Radiata pine sample.

This method focuses on heat transfer. However, measuring humidity inside and outside the chamber and also material water content, other properties such as permeability would be study in order to foreseen its hygrothermal behavior. Not only thermal conductivity is influenced by the variation of temperature, but also the water content, because of that a further research is necessary.

On the other hand, material deterioration also takes importance as it also influences in material properties. However, depending on protection products this ageing varies. In this case, both visual analysis during a year and posterior thermal tests were also realized, in order to measure it. It was demonstrated that not only appearance changes but also properties such as thermal conductivity, resistance to water vapour diffusion and emissivity. The development of material along time and its variability in thermal response is also a subject of interest.

Apart from that, it is necessary to gain knowledge about the iteration of the material with its surroundings. That is, getting to know the influence of the boundary conditions in wood properties makes easier to understand its possibilities as sustainable construction product. In this research, a hard emphasis in the importance of convection coefficients definition was realized. However, more knowledge about it is necessary to define more accurate analysis models for energy simulation, in order to foreseen energy losses.

In this research, it is also learnt how to analyze different solutions of external wooden cladding taking into account their design and geometry. If material properties are important, its disposition and design also influences its thermal behavior. Wood is light and easy-to-work material which allows different forms. Due to that, a further research implementing tests to evaluate the conclusions obtained through this kind of simulations, related to joined wood boards design, would also be a new research line.

In order to evaluate the sustainability of the timber façade, it was developed a decision-making methodology that unifies the criteria in relation to the environmental sustainability of timber façades. The application of this methodology brings us closer to sustainable development. For future needs, this methodology can assume new sustainable criteria to develop, such as costs, carbon emissions and energy efficiency of wooden façades.

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