FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

ENERGY AUTONOMOUS BUILDINGS

Housing Project

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To my dad and brother,

"To the engineer falls the job of clothing the bare bones of science with life, comfort and hope."

Herbert Hoover

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To my father, for his unconditional love and support. Because more than my achievement, this is yours. To my brother, for the patience and affection he always gave me.

ABSTRACT

The buildings are responsible for 40% of global energy consumption and allied to that, the growth of the global population and the increase of energy costs became the main reasons for the self-supply of heat and electricity being an imperative objective for new and existent buildings.

Thus, in this work are identify a set of active and passive solutions, which, in a combined way, develop the thermal performance of a residential building – "Sky House", located in Esposende, allowing it to become energetically autonomous, not needing to recourse to external energy sources. The identified and suggested solutions for the building have their performance numerically evaluated and study.

The program EnergyPlus is the tool used to execute the thermo-energetic simulations for the diverse scenarios considered, until the reach of the final proposal of solutions to be implemented in the study case. All the commands of the program used are identified and described.

This work turns evident that the study and implementation of passive solutions improve the energy performance of the buildings, and the use simultaneously of an active solution – a renewable energy source, allows the reach of the energy autonomous of the buildings.

KEYWORDS: Active Solutions, Passive Solutions, Energy Autonomous Buildings, Energy Efficiency, EnergyPlus

RESUMO

Os edifícios são responsáveis por 40% do consumo global de energia, e aliado a isso, o crescimento global da população, e o aumento dos custos da energia, tornam-se os principais motivos para que a auto-produção de calor e energia seja um objetivo imperativo para os edifícios novos e os já existentes.

Assim, neste trabalho são identificados um conjunto de soluções ativas e passivas, que de forma integrada, promovam um bom desempenho térmico do edifício "Sky House", localizado em Esposende, permitindo que este se torne energeticamente autónomo, não necessitando de recorrer a fontes externas de energia para o seu funcionamento em serviço. As soluções identificadas e propostas para o edifício serão estudadas, sendo numericamente avaliado o seu desempenho.

O programa EnergyPlus é a ferramenta utilizada para executar as simulações termo energéticas para os diversos cenários considerados, até à elaboração da proposta final de soluções a serem implementadas no caso de estudo. Todos os comandos do programa utilizados são identificados e descritos.

O trabalho desenvolvido torna evidente que o estudo e a implementação de soluções passivas melhoram o desempenho energético dos edifícios, e que a utilização simultânea de uma solução ativa – fonte de energia renovável, permite alcançar a autonomia energética dos edifícios.

PALAVRAS-CHAVE: Soluções Ativas, Soluções Passivas, Edifício Energeticamente Autónomo, Eficiência Energética, EnergyPlus

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LIST OF SYMBOLS, ABBREVIATIONS, AND NOMENCLATURES

C_p – Specific Heat [J/kg.K]

e – thickness [m]

Rse - outside surface thermal resistances [m^2.ºC/W]

Rsi – inside surface thermal resistances [m^2.ºC/W]

U – heat transfer coefficient [W/m^2.ºC]

λ – thermal conductivity [W/m.ºC]

ρ – density [kg/m^3]

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

CO_2 – Carbon Dioxide

OSB – Oriented Strand Board

SHGC - Solar Heat Gain Coefficient

°C – Degrees Celsius

1
INTRODUCTION

1.1. Framing and Presentation of the Work

Nowadays, the concerns about climate change and the dwindling natural resources, plus population growth, require an enormous effort from the construction sector to build green and reduce the environmental impact. In reality, the construction sector is responsible for 40% of CO_2 emissions and 36% of world energy use, according to the World Green Building Council.

For that, the European Union is committed to developing a decarbonised energy system, setting a goal to reduce greenhouse emissions by at least 40% by 2030 as compared with 1990, and increase the renewable energy consumed. This figured an opportunity that cannot be missed to ramp up the decarbonisation of the buildings and the construction sector, contributing to achieving the Paris Agreement commitment and the United Nation Sustainable Developments Goals. Following that, the EU Green Tagging strategy includes recommendations for nearly zero energy buildings (nZebs), a building with very high energy performance. The nearly zero-energy required should be covered from renewable sources, including sources produced on-site or nearby.

Portugal is in the top 10 European Countries with the best climate, with an average of 300 days of sunshine per year, being an excellent place to exploit bioclimatic concepts. It also has many natural and renewable resources, such as cork, whose insulating characteristics can be exploited. Therefore, Portugal is an ideal country to improve the energy performance in new construction and rehabilitation using adequate construction techniques and technologies. Despite that, between 2014 and 2019, the majority of certified residential have a D energy class, and only 25.7% obtained a classification between A+ and B-.

Due to these facts, this dissertation proposes to develop a numeric study of the active and passive solutions that can be implemented to achieve energy autonomous houses, buildings that function without support and services from public facilities, operating without fossil fuels, and purchase of electricity from the grid.

1.2. Objectives of the Work

This work intends to identify a set of active and passive solutions, which, in a combined way, develop the thermal performance of a residential building – "Sky House", allowing it to become energetically autonomous. The identified and suggested solutions for the building have their performance numerically evaluated by the program EnergyPlus.

Thus, the established partial objectives are:

- Identify active and passive solutions to improve the thermal performance of the buildings;
- Optimise the study case with active and passive solutions;
- The numerical study of the active and passive solutions for the study case;
- Develop a final proposal of solutions to be implemented in the study case.

1.3. Outline

Chapter 1 presents a brief introduction of the work, the purpose of the dissertation, and its objectives.

Chapter 2 regards to state of the art, where are identify and described passive and active solutions that promote the energy efficiency and autonomy of the buildings.

Chapter 3 presents the program used in the thermo-energetic simulations - EnergyPlus, describing all the commands utilized and their function.

Chapter 4 describes the study case – Sky House, and the numeric simulations performed by implementing active and passive solutions in the base project.

Chapter 5 presents the results obtained from the thermo-energetic simulations executed and a critical analysis of them.

To terminate, in Chapter 6 are presented the principal conclusion and achievements of the work developed and some recommendations for future works in this specific research area.

2

BUILDING ENERGY EFFICIENCY: PASSIVE AND ACTIVE SOLUTIONS

2.1. INTRODUCTION

The growth of the population, the increase of CO2 emissions, and the boost in the energy costs result in the need to create sustainable and energy-efficient buildings. In this way, the concept of autonomous energy house represents a new paradigm of intelligent energy use and a further development to achieve the true decarbonisation of the construction sector.

Since the beginning of the 20th century, the efforts to promote clean solutions and improve buildings design have resulted in the invention of many types of energy-production equipment and efficient heating, cooling, and ventilation. In this perspective, passive and active solutions that improve buildings energy-efficient must be present and reflect upon the project's early stages of development.

2.2. PASSIVE SOLUTIONS

2.2.1. INTRODUCTION

Building energy efficiency requires the use of passive sustainable solutions that improve the energy performance of the building. In this way, passive solutions provide maximum comfort for the occupants, and at the same time, reduce the energy needs for heating and cooling. So, these passive solutions control energy flows with, for example, the increase of solar gains or the decrease of thermal losses.

2.2.2. BUILDING ORIENTATION

The orientation of the buildings is one of the passive solar strategies. Good orientation provides passive solar heating and cooling, allowing the sun to be a free source. The best balance between capturing a cooling breeze and sunlight is defined by heating and cooling demands.

Based on the sun's movements, the windows must be on the southern side of the building to absorb the sun's heat energy to warm the building during the winter. The building's orientation must be completed in the summer with a shading system to keep the building cold. Inadequate orientation and lack of appropriate shading can exclude winter sun and cause overheating in the summer, letting the sun strike glass surface, increasing solar gains (Figure 2.1) [1].

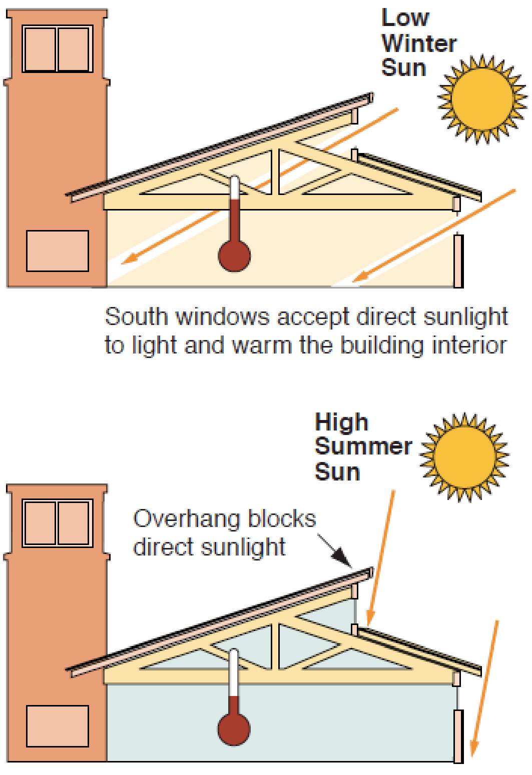


Figure 2.1 - Building Orientation and the Shading System [1]

Placing the building must consider factors like the topography, climate, landform, or proximity to neighbouring buildings and trees.

Proper orientation of the building, plus the thermal mass and the appropriate insulation and glazing, can lower the heating demands.

2.2.3. Building Envelope

The building envelope is the physical boundary between the conditioned environment (heated or cooled) and the unconditioned environment and includes the opaque components – such as walls and roofs and the transparent components – like the windows. These elements should keep the interior space comfortable for the occupants and minimise the heat transfer between the interior and exterior [2].

The building envelope is a crucial aspect of the building´s energy efficiency, and it is affected by numerous parameters, such as the heat transfer coefficient, thermal inertia, or thermal bridges. In the envelope design, special attention is needed to each of the elements that compose it, since each of these layers has specific qualities that will be crucial in the building's thermal behaviour. Also, the geometric configurations (for example, the building volume or ratio of windows) can affect the building´s performance. The typical heat loss in a house is represented in Figure 2.2.

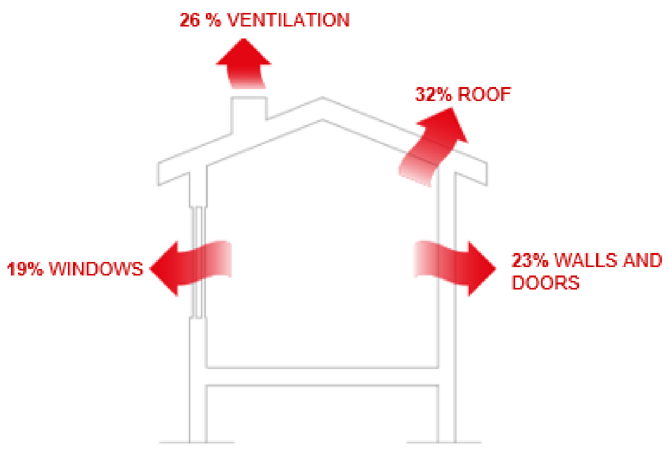


Figure 2.2 - Typical heat loss in a house [3]

2.2.3.1. Influencing factors of Thermal Performance of Building Envelope

- Heat Transfer Coefficient

The heat transfer coefficient takes into account the various heat transfer phenomena through the elements. This coefficient is defined by the heat flux that crosses, per unit of time, a unit area, per unit of temperature, in continuous operation. So, the heat transfer coefficient – U [W/m2.°C] comprehends the heat phenomena that occur on the surface of the elements, between the interior and external environment that is separated by the component. The coefficient depends on the thermal conductivity of each of the elements that compose the surface and the thickness, if the element is homogeneous (like concrete or the insulation materials), and the thermal resistance if it is a heterogeneous material (such as the brick). The convention´s and radiation's consideration is taken by the inside and outside surface thermal resistances – Rsi and Rse. If the value of the heat transfer coefficient is low, the surface is well isolated. On the other hand, a high value alerts to a thermally inefficient surface (Figure 2. 3) [4].

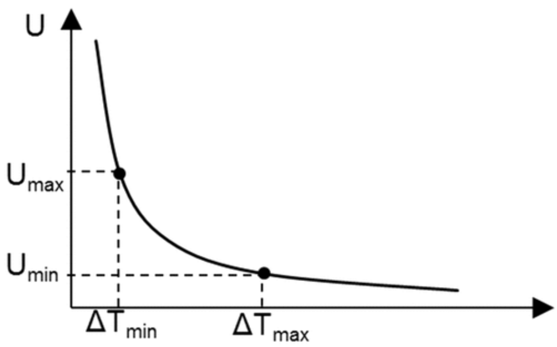


Figure 2. 3 - Relationship between heat transfer coefficient and the indoor and outdoor temperature [5]

The value of U, heat transfer coefficient, can be determined by Equation 2.1:

$$u = \frac{1}{(Rse + \sum \frac{e}{\lambda} + Rsi)} \left[W/m^2 . ^\circ C\right] \quad (2.1)$$

, e [m] represents the thickness, λ [W/m.ºC] the thermal conductivity, and Rsi and Rse [m^2.ºC/W] the inside and outside surface thermal resistances.

- Thermal Inertia

According to Yannas and Maldonado Ed. [6], the term thermal inertia describes the capacity of a building to store and release heat. It is a property related to thermal conductivity and the capacity of volumetric heat. It is responsible for flattens out heat flow fluctuations, reducing indoor air temperature peaks and the delay between accumulation and energy release [7].

In summer, thermal inertia can be applied to reduce heat flow to the building's interior if used with natural ventilation. The materials that compose the walls absorb the heat during the day, and at night, the thermal mass will slowly release stored heat, and with natural ventilation - through open windows, the leet cool air goes in, and the heat goes out (Figure 2.4). The more significant the difference between day and night temperature, the more beneficial the thermal inertia [7].

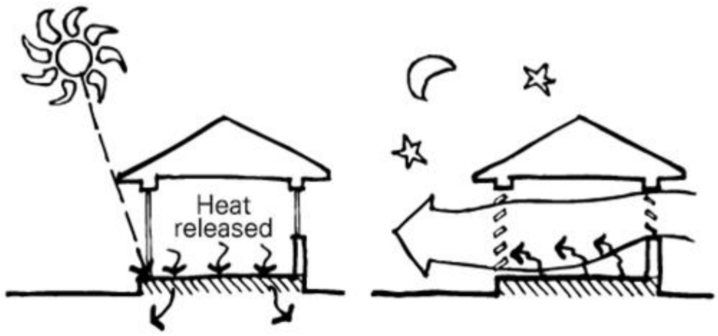


Figure 2.4 - Thermal Inertia and Natural Ventilation on summer periods [8]

Thermal inertia can positively impact indoor conditions during the winter periods: the solar and internal gains during the day are collected and then gradually released, providing part of the heating load (Figure 2.5). Using a higher heat capacity structure improves the reduction of cooling load peak, reducing the energy consumption in air-conditioned buildings [7].

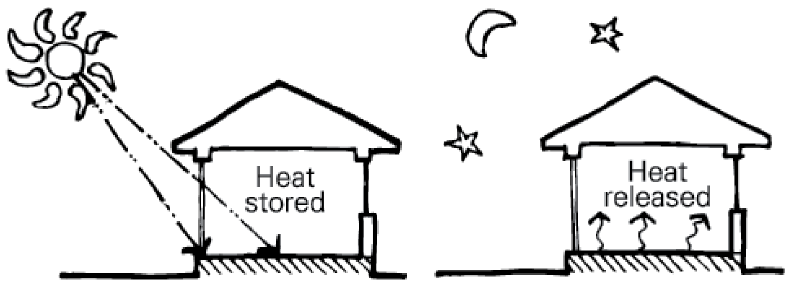


Figure 2.5 - Thermal Inertia on winter periods [8]

However, the benefits of thermal inertia depend on diverse parameters, such as the climate conditions, the thermal-physical properties of the building (the building materials must have a high thermal conductivity value and high thermal capacity to store heat efficiently, and also the location and distribution of thermal mass are important), insulation, ventilation, occupancy, and internal heat gains. To obtain the most remarkable result is fundamental to improve the relation between these parameters [7].

- Thermal Bridges

A thermal bridge is a section of the building envelope where the thermal transmittance is significantly higher than the surrounding area due to thermal insulation discontinuation, occurring when a material with high thermal conductivity penetrates or discontinues a layer of low thermal conductivity material (usual insulation) - see Figure 2.6. It can also happen where building elements are joined, like exposed concrete floor slabs and beams that penetrate the exterior walls. Therefore, the insulation materials should be placed without gaps and installed in ways that remain in the appropriate position over time [9].

The thermal bridges origin a considerable heat loss, occupant discomfort and can cause damage and hygiene problems, like mould growth and surface condensation. The extent of these effects determines the severity of the thermal bridge. In very well insulated buildings, the thermal bridges' effect can be significant and responsible for a substantial heat loss through the building envelope [9].

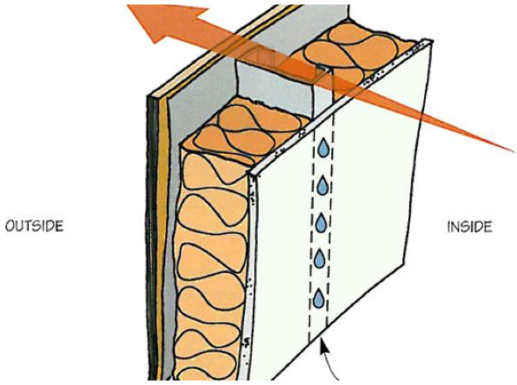


Figure 2.6 - Thermal Bridge [10]

There are two types of thermal bridges: linear and point. The linear thermal bridges (ψ) disrupt the thermal envelope's continuity and happen along a certain envelope length. Common examples of linear thermal bridges include concrete balcony connections with the floor slab going through the wall, floor supports, and window to wall junctions. The point thermal bridges (χ) only occur in one spot, like steel balconies, canopies, roof extensions, etc. [11].

Thermal bridges can be avoided during the design stage, when modifications can be simply incorporated. After the construction, repairing thermal bridges is costly and can be difficult.

- Insulation Materials

Insulation materials have characteristics of high thermal resistance and the ability to decrease the heat flow rate. So, the building insulation can keep the heat or cool inside the house and limit the surrounding heat flux. There is a considerable variety of insulation materials, such as fibreglass, mineral woof, foam, etc.

In addition to contributing to achieving the buildings' energy efficiency, these materials also bring other benefits, including fire protection, avoiding condensation, and sound control.

In the building envelope, the use of thermal insulation will directly influence the building heat gain or loss. Beyond the use of insulation, the location of that material will also affect the wall's thermal performance: the insulating material should be installed close to the heat inflow or outflow location.

The following table (Table 2.1) presents some of the materials used for insulation, with the respectively thermal conductivity.

Table 2.1 - Thermal conductivity - Insulation Materials

	Material	Thermal conductivity – **λ**(W/(m·°C)
Building Envelope	Fibreglass	0.04 – 0.033
	Rockwool	0.037
	Polythene	0.041
	Expanded Polystyrene	0.038 – 0.037
	Extruded Polystyrene	0.032 – 0.030
	Cellulose	0.54 – 0.046

2.3.2.2. Exterior Walls

The primary function of the exterior walls is to protect the interior spaces from the surrounding environment. The external walls need to be strong, stable, and durable, resisting the weather, ground moisture, and the passage of airborne and impact sound. It is also important the contribute of these elements to the buildings' energy efficiency due to the thermal mass properties.

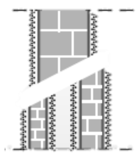
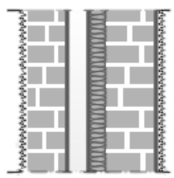
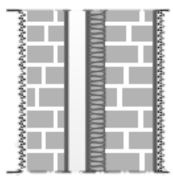
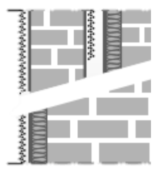
External walls' structure and thermal properties influence the building's thermal conditions and energy demand for heating and cooling. The relation between thermal insulation and heating is evident, but it also needs to consider overheating. It is essential that the efficient thermal insulation does not conflict with comfort conditions [12].

2.3.2.2.1. The evolution and change of buildings façades in Portugal

The majority of the buildings in Portugal do not have thermal insulation. If the building is previous to 1990 and has never been rehabilitated, it is almost sure that it does not have isolation.

The next table (Table 2.2) will be presented the most common type of façades in Portugal, during the years.

Table 2.2 - Type of façades in Portugal during the years [13]

Period of time	Before 1960	1960 - 1990	1990 - 2006	2006 - 2013	After 2013
Type of façade	 Loose or rigged stone wall	 Single or double brick wall	 Double brick wall	 Double brick wall	 Double or simple brick wall, isolated outside
Insulation	-	-	0 – 20 mm	40 – 50 mm	50 – 60 mm
% of buildings by type of façade	25%	44%	22%	8%	1%

2.3.2.2.2. Possible Solutions

As seen previously, insulating the exterior walls is beneficial for two main purposes, when it comes to conserving energy: it helps with air sealing and with the heat loss/gain cycle that occurs year round, improving the thermal performance of the building. It is noted that the temperature difference on the outside surface between insulated and uninsulated walls is around 3ºC. Simultaneously, it is observed that the freezing point is positioned inside the wall, when it does not have insulation, and the freezing point moves within the insulation, which will decrease the thermal stress when the wall has insulation. Insulating the exterior walls can be done by internal or external wall insulation [14].

From the perspective of energy efficiency, external wall insulation is the most proper way to ensure a uniform application, correcting any existing thermal bridge. It also improves the wall´s thermal inertia and limits heat loss, which results in a building cooler in the summer, and warmer in the winter.

The external wall insulation can be done with ETICS – External thermal insulation composite system or with a ventilated façade (Figure 2.7).

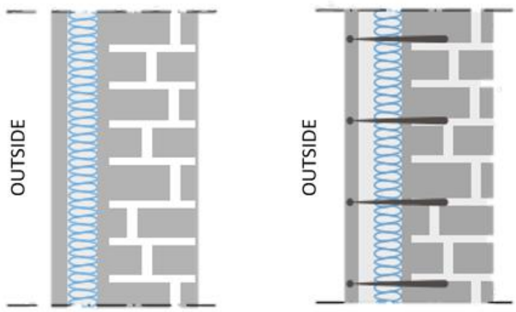


Figure 2.7 - ETICS and Ventilated façade

- ETICS – External Thermal Insulation Composite System

ETICS is the abbreviation for External Thermal Insulation Composite System and can be applied to increase the energy efficiency of new and existing buildings. This system is developed with prefabricated insulation panels, bonded or mechanically fixed into the wall, and reinforced rendering, with one or more layers applied directly to the insulation. In the Portuguese market, the insulation panels are usually expanded polystyrene (EPS), adhesively attached to the substrate, covered with a coat reinforced with fibreglass mesh and a finish coat acrylic-based (Figure 2.8) [15].

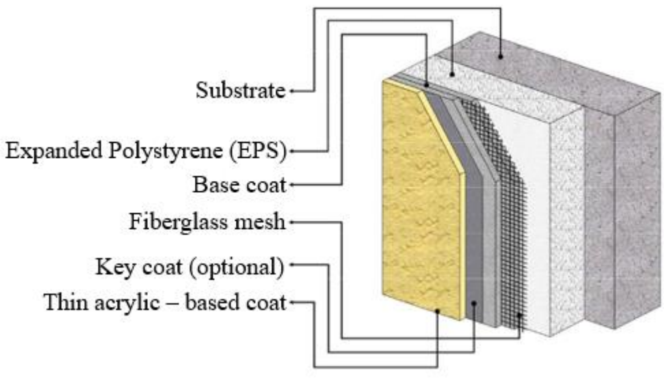


Figure 2.8 - Schematic Illustration of ETICS available in Portuguese market [15]

This system allows the reduction of the thermal bridges due to the continued thermal insulation of the building envelop (Figure 2.9) and result in a higher thermal mass on the inside. Due to that, the thermal comfort during the winter increases, and in the summer periods, the heat flow fluctuations slow down. Besides that, the façades durability increase because they are protected from the climate loads.

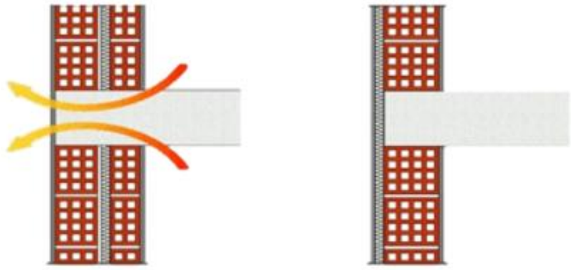


Figure 2.9 - Reduction of the thermal bridges [15]

- Ventilated Facade

A ventilated façade is built with an air gap between the cladding and the insulation. This air passage must be opened in some parts, creating a way for continuous natural ventilation. The air gap allows a constant release of water vapour from the building, keeping the insulation dry. The system consists of thermal insulation, an aluminium frame and ventilated façade panels in a variety of materials (Figure 2.10). It can be applied to new or restored buildings [16].

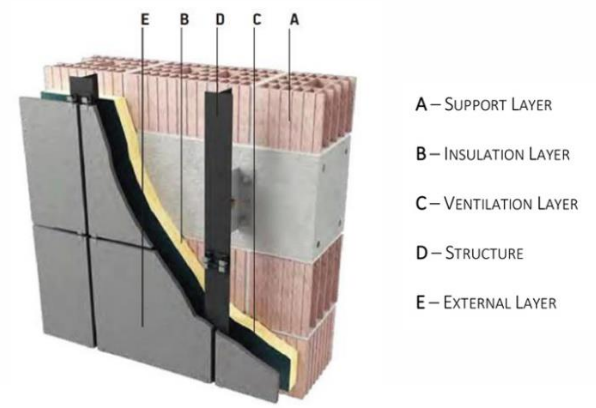


Figure 2.10 - Schematic Example of Ventilated Façade [17]

The ventilated facade system optimises the bearing wall thermal inertia and reduces the thermal bridges due to the continuous insulation. This system protects the enclosure wall from climatic agents, decreases thermal expansion, avoids moisture and condensations, and improves acoustic insulation. As a result, it is considered an effective system in terms of solving the building´s insulation.

One of the major conditioning factors for the choice of the ventilated façades is the high initial investment due to the cost of the external cladding materials (like natural stones or ceramic tiles). In addition, the installation of this system also requires specialised labour. Thus, the ETICS is a more common solution compared to ventilated façade, possibly due to the initial investment, which is lower [18]. However, the maintenance costs should also be taken into account. For the ventilated façade, these costs are low-priced, compared to the ETICS, due to completely independent cladding elements that allow isolated replacements. ETICS adds a disadvantage in terms of maeintance, requiring that the initial characteristics of the system remain guaranteed [19].

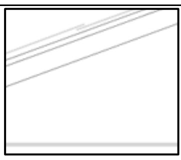
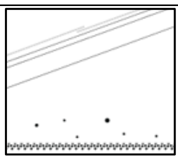
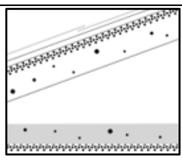
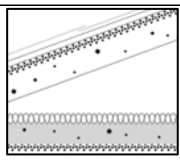
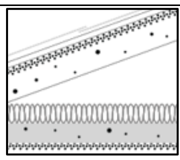
2.3.2.2. Roof

Although the roof's principal objective is to keep the water out of the buildings with correct drainage, they also have to ensure that in the summer periods there are not heat gains, and in the winter periods do not have heat losses. So the roofs are fundamental for the comfort of a building. On average, the roofs are the cause of 30% of the heat losses in a home. For this reason, the thermal insulation of the roofs must be a priority.

2.3.2.2.1. The evolution and change of roofs in Portugal

The first regulation of buildings' thermal behaviour was published in 1990, so buildings previous to that year are unlikely to have thermal insulation on the roof. Table 2.3 shows the evolution of roofs in Portugal.

Table 2.3 - Type of roofs in Portugal during the years [20]

Period of time	*Before 1960	*1960 - 1990	*1990 - 2005	*2006 - 2013	*After 2013
					
Type of roof	Pitched roof with wood structure	Pitched roof with a concrete structure	Pitched roof with a concrete structure	Pitched roof with a concrete structure and isolation on the bottom chord	Pitched roof with a concrete structure and isolation on the bottom chord
Insulation	-	-	-	60 – 70 mm	70 – 80 mm

*year of construction

Currently, the roof type most used in Portugal continues to be the pitched roof coated with ceramic or concrete tiles (Figure 2.11).

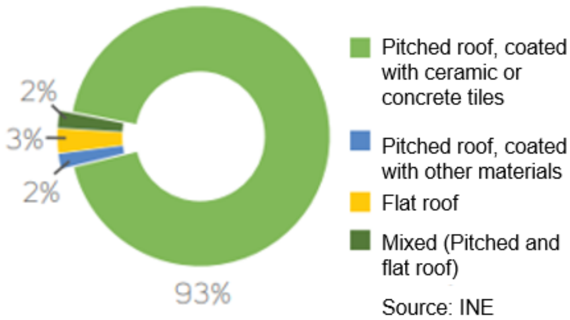


Figure 2.11 - Type of roofs in Portugal [20]

2.3.2.2.2. Possible solutions

The roof's thermal insulation is considered a priority energy efficiency component, reducing the energy needs and minimising the need for equipment to heat and cool the interior spaces. It is also useful to avoid overheating in the summer due to solar gains. Beyond the insulation, it is also necessary on roofs to proper the right amount of ventilation. Roof ventilation works by letting cool and dry air intake at the roof's edge and releasing the humid and warm air through exhaust vents. So, proper roof ventilation is a balancing act. Additionally, the roof materials' correct specification can improve energy efficiency and mitigate the urban heat island effect.

In flat roofs, the insulation material is applied in the exterior, and the preferred solution should be an inverted roof. In this system, the thermal insulation is put over the waterproofing and superiorly guarder by heavy protection. This system should be used on detriment of the solution where the thermal insulator is the waterproofing support because it allows the increase of the useful life of the waterproofing, protecting it from significant thermal amplitudes.

For pitched roofs with habitable space (an attic, for example), the exterior insulation should, whenever possible, be placed under the roof and up the waterproofing of the slab. If the space in the pitched roof's interior is not liveable, the insulator material can be applied to the pavement.

The pitched roofs can also be classified as warm or cold roof. The insulation is attached to the floor decking and rafters in a warm roof, giving the most thermal protection. In the cold roof, the insulation is placed between the floor joists and needs ventilation (Figure 2.12) [21].

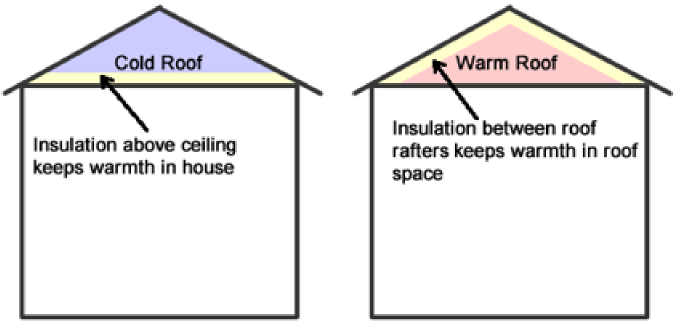


Figure 2.12 - Cold Roof and Warm Roof Difference [22]

A solution that presents a good energy performance is the cool roofs. On the external surface are applied cold materials, characterised by high solar reflectivity and thermal emissivity values. These materials reduce the solar radiation absorption and release the heat absorbed by the roof [23].

Further to these traditional solutions, green roofs are also a possibility, working as a protective barrier against solar radiation.

- Cool Roof

A Cool Roof is a system that reflects the solar heat due to the reflective and emissive materials' properties. These roofs are made of highly reflective and emissive materials that maintains cooler than traditional materials during peak temperatures (Figure 2.13). The high solar reflectance – ability to reflect sunlight and the high thermal emittance – ability to radiate heat, of cool materials help roofs to absorb less heat and stay up to 23 – 33 ºC cooler than conventional materials during the summer period. These cool roofs are considered a passive radiative cooling technique [24] [25].

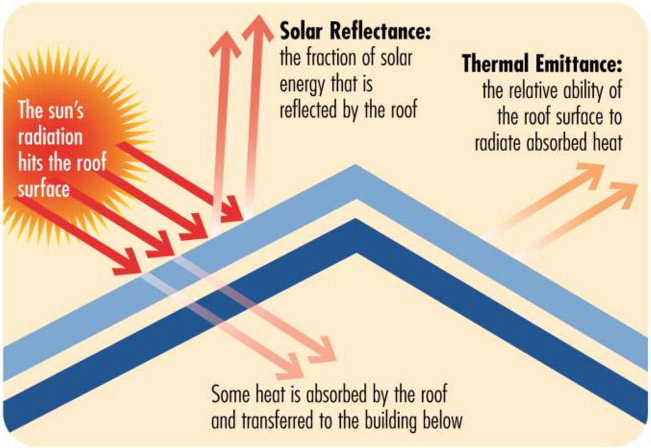


Figure 2.13 - Cool Roof Advantages [24]

The cool materials are a specific category of paints distinguished by the high solar reflectance, which reduces solar radiation absorption compared to the traditional materials. These materials also have a high infrared emittance dissipating the heat without transferring it to the buildings inside spaces.

- Green Roof

A green roof, or a living roof, is a roof covered with vegetation. This roof is a passive technique that works as a protective barrier against solar radiation, stopping it from reaching the building structure.

Below the vegetation and above the structural support, the system is composed of a waterproofing membrane, drainage, and isolation (Figure 2.14). There are four varieties of green roofs: extensive, intensive, semi-intensive, and brown roofs.

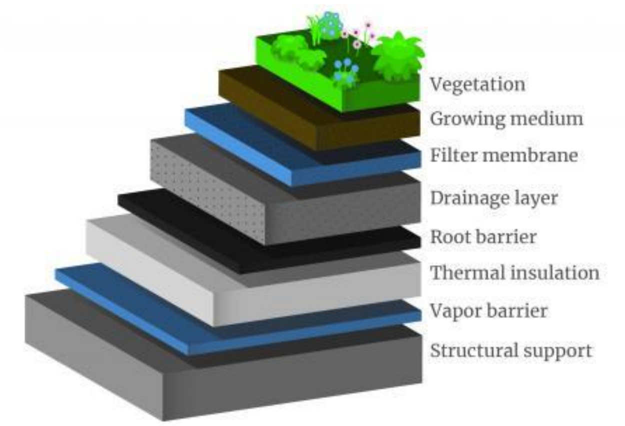


Figure 2.14 - Common Green Roof Layers [26]

The main disadvantages of these roofs are the initial cost and the additional mass of the soil substrate and retained water that has to be taken into account on the structural project.

The advantages are numerous, such as the increase of sound isolation, the reduction of air pollution, and greenhouse gas emissions, but the principal is reducing the energy use because the green roof absorbs the heat, acting as a thermal insulator. This roof reduces the total direct and diffuse radiation that focuses on the roofs, providing insulation. The green roofs also reduce the roof membrane's temperature fluctuations, decreasing the thermal stress and heat gain. Further, in locals where the solar irradiance values and the temperature during the day are high, the occupants' thermal comfort is improved [27].

In various parts of the world, especially in Europe, the application of green roofs is well established.

2.3.2.3. Windows

As a building envelope component, the windows provide architectural expression to the façades and allow lightning and ventilation and let in the solar radiation, which heats the indoor spaces. They also create visual contact with the outside environment. In opposite to these benefits, the windows usually are week elements on the building energy system, with thermal losses and high solar heat gain, because their thermal transmittance is lower than the walls.

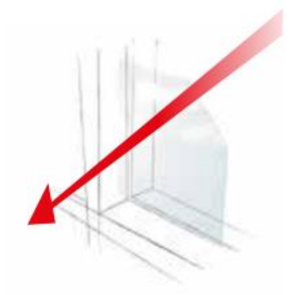
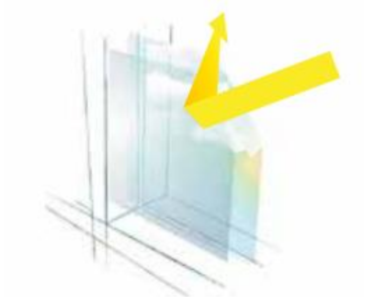
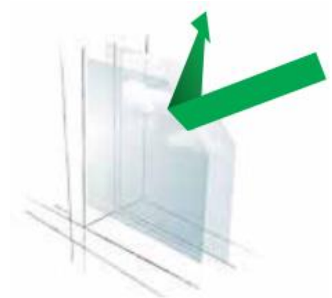
There are some easy ways to check the thermal characteristics: visible condensation on windows when the temperature difference between interior and exterior space is significant, or an uncontrolled airflow can indicate that the windows are inefficient and have a poor performance [28].

2.3.2.3.1. Window solutions installed in Portugal

The most window solution installed on the Portuguese buildings is low quality, the major single-paned windows, with weak thermal performance.

The following table (Table 2.4) indicates the distribution of the window solutions installed in Portugal [28].

Table 2.4 - Window Solutions installed in Portugal

		
72,3% to 75,4%	18,9% to 22,8%	6,0% to 7,0%
Single Paned Windows	Double Paned Windows	Double Paned Windows with Thermal Break

2.3.2.3.2. Possible solutions

An adequate frame can help in the prevention of heat and cold transfer. This element can be made of various materials, such as aluminium, vinyl, or wood. The glass is also a critical element of the windows. The choice of proper glass prevents the heat from escaping and protects against heat from UV rays. The use of a double-paned instead of a single-paned window provides better insulation and less energy waste. The space between the panes could contain gas or air, and the thickness may variate. The use of gas allows solutions with better energy performance. For the type of window opening, as a general rule, the sliding windows present the worst performance in terms of energy efficiency [29].

For windows facing north, with lower solar radiation, it is necessary to pay attention to the thermal transmission coefficient (Uw), to minimise heat losses to outside; for facing soul windows, with high exposure and no sun protection, it is necessary caution on the solar factor of the glass (in these circumstances, the best solutions are glasses with solar factor under 0.56).

Further the traditional windows, also exist the smart windows distinguished in passive or active control. These windows allow varying the amount of heat and light that penetrate through the glass surface [30].

The passive dynamic systems do not need an electrical stimulus for their action. The system reacts to natural incentives, like heat (thermochromic and thermotropic glazing) or light (photochromic glass) [30].

- Triple Glazing Window

Usually, single glazing achieves a U-value of around 4.5 W/m²K, and the most efficient double glazing can reach a U-value of 1.2 W/m²K. Recently, super-efficient triple glazing has been produced. The triple glazing contains three panels of glass, divided by two cavities, filled with argon (Figure 2.15). This window can reach a U-value between 0.8 and 0.5 W/m²K. Beyond energy efficiency, this system also reduces cold spots and cold downdrafts, and in the summer, the solar gain decrease [31].

Figure 2.15 - Triple Glazing Window [32]

- Thermochromic glazing

The thermochromic windows **(**Figure 2.16**)** are the most progressive dynamic window technology available. This glass uses the heat from direct sunlight to colorate the window when needed. The more intense and straight the sunlight is, more darker the glass will convert. This way, the glass remains transparent when the temperature is lower and becomes opaque for higher temperatures. This change in the colour of the glass reduces the heat load coming into the building. The glass transmission accustoms continuously over a spectrum of temperatures, creating a natural balance and the greatest use of daylighting [30].

This glass can be used on windows, doors, and skylights and does not need control equipment, being installed as a traditional window.

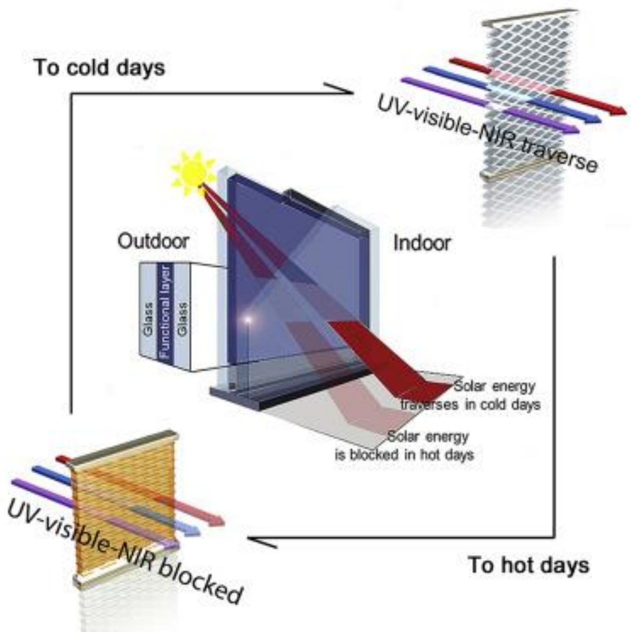


Figure 2.16 - Diagram of a Thermochromic Window [33]

2.3.4. Sun Control and Shading Devices

Sun protection is an essential aspect of energy-efficient building design strategies. This element has the main objective of controlling the entry of the sun´s heat into the building. It is essential that in the winter, these protections can be opened to maximise the solar gains, and in the summer, the protection should allow the control of the excess solar energy, preventing the overheating of the spaces. According to LNEC, sun protection can reduce the indoor temperature between 1 to 10 ºC [34].

The design of adequate shading devices depends on the solar orientation. For example, the fixed overhangs are very efficient at shading south-facing windows in the summer because the sun angles are high. Nevertheless, this same design is incapable of blocking low afternoon sun from west-facing windows [35].

The sun protection can be exterior (fixed or movable) or interior (movable or between glass or window). The most effective sun protection is the exterior, preventing heat until 96%, while indoor sun protection only prevents 62% heat gain. This type of device can have a significant impact on the building aspect. The sooner these devices are considered on most of the buildings, the more probable they can be well integrated into the overall projects [34].

2.3.4.1. Possible solutions

External shading devices are better and more efficient than internal ones, so in the possible solutions will only be analyse the external ones. The external shading devices are fixed to the outside of the window or attached to the building envelope.

- Vertical Shading Device

The vertical shading devices (Figure 2.17) consist of pilasters, louvre blades, or projecting fins in a vertical position. Their performance is measure by the horizontal shadow angle. These devices are more efficient for the northern, easter, and west orientation than the southern one [36].

Figure 2.17 - Vertical Shading Device [37]

- Horizontal Shading Device

Horizontal shading devices (Figure 2.18) are usually in the form of canopies, long verandas, movable horizontal louvre blades, or roof overhangs. The vertical shadow angle measures their performance. These devices are more efficient for the southern orientation [36].

Figure 2.18 - Horizontal Shading Device [37]

- Egg-Crate Devices

The egg-crate devices (Figure 2.19) are a combination of vertical and horizontal devices. They are generally in the form of grill blocks or decorative screens. Both horizontal and vertical shadow angles determine their performance. These devices are more efficient for easter and west orientation [36].

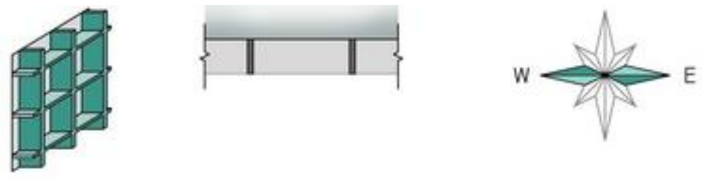


Figure 2.19 - Egg-Crate Devices [37]

2.3.5. Natural Ventilation

The natural ventilation of the buildings is the process through which indoor air is replaced by fresh outdoor air and has the potential to save cooling energy. Natural ventilation can improve thermal comfort in the summer by increasing daytime airspeed and high night natural rates by a simple act like opening the windows. This can be beneficial in buildings with excessive internal or solar heat gains.

Natural ventilation needs wind or the chimney effect. In the chimney effect, the cool air enters on the first floor, absorbs heat, rises, and exits through upstairs windows [38].

Factors like the location, the position, design, and environmental conditions must be analysed to reach energy saving through natural ventilation.

Natural ventilation must be an imperative factor to be taken into account for the building designers, included in the passive control strategies, to reduce the demand for mechanical ventilation and air conditioning [39].

2.3.5.1 Possible solutions

The specific strategy and design of natural ventilation systems will differ based on the building type and local climate. Nonetheless, the amount of ventilation will depend on the design of internal spaces and the area and opening position in the building [38].

- Solar chimney

The solar chimney is designed to maximise the ventilation effect, generating enough temperature difference between the inside and outside of the building to induce and satisfactory air flow rate. In summer, the temperature difference between the inside and the outside of the buildings is small. So, the ventilation which works on the principle of stack ventilation is deficient.

A solar chimney is an air channel in which air flow's primary driving mechanism is thermal buoyancy. The essential elements are a transparent cover and openings -inlet and outlet (see Figure 2.20). The solar radiation passes through glazing and is absorbed in the wall surface, heating the chimney's air by convection and radiation. The reduction in the air density makes it rise, which is replaced by air from below [40] [41].

Solar chimneys are commonly used to afford ventilation for cooling but can also be used for heating [41].

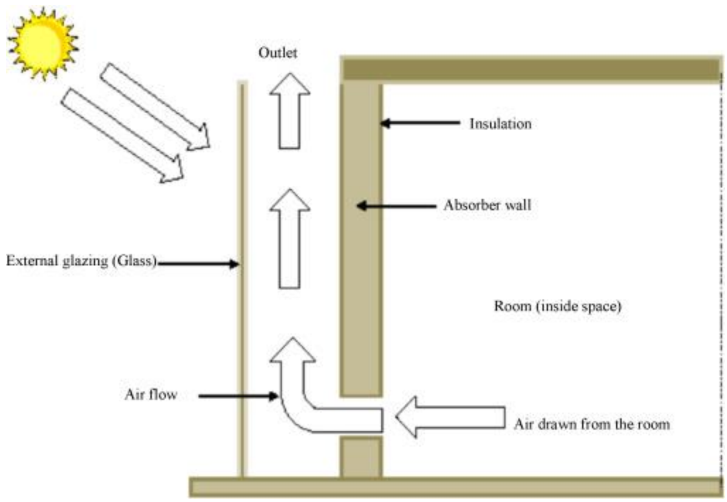


Figure 2.20 - Schematic of Solar Chimney [40]

- Operable Windows / Skylights on the top floor

Another way to benefit from the convection to disperse heat is the natural ventilation by installing operable windows or skylights on the top floor. These devices can be fully opened, allowing the rising air to exit and be replaced by cooler outdoor air, entering through an open window at a lower level.

However, it is essential to coordinate natural ventilation and mechanical space conditioning to avoid that ventilation does not conflict with mechanical heating and cooling. To restrict possible conflicts are available automatic controls that shut off HVAC operation – heating, ventilation, and air condition when windows are left open [43].

The scheduled natural ventilation, with window operation in fixed schedules, can provide nighttime cooling and improve indoor comfort and air quality [43].

2.3.5.2 Airtightness

A perfectly airtight envelope is one of the essential principles to achieve energy-efficient buildings. Airtightness is the capacity of the buildings to not let in or out the air. If the building envelope is not airtight enough, the uncontrolled air leakage reduces the thermal insulation's energy efficiency, reducing heat resistance of the structure and increasing losses by ventilation [44].

To achieve this, the buildings must be designed with an uninterrupted and continuous airtight layer, the junctions and connection details need particular attention, and the thermal bridges must be eliminated.

2.4. Technologies Active Solutions

2.4.1. Introduction

Society is heavily dependent on fossil fuels: roughly 80 per cent of global energy consumption still comes from this type of energy, a major contributor to global carbon emissions and greenhouse gas production. Because of that is urgent the use of renewable energy solutions.

In this way, the necessary action is to incorporate this clean energy into the buildings planning and design. The integration of renewable energy technologies is successful in offsetting building electrical and thermal energy loads [45].

The resources generally used for building applications include solar, geothermal, and biomass. The appropriate renewable energy technology selection must consider some factors, like the available energy resource at or near the building location, the available area for installing renewable energy technology, cost, local regulations, the architectural features, etc. [45].

2.4.2. Photovoltaic Panels

Photovoltaic (PV) devices produce electricity directly from sunlight via an electronic process that occurs naturally in particular types of materials, called semiconductors [46]. A single PV device is known as a cell, producing about 1 or 2 watts of power [47]. These cells are made of different semiconductor materials. To increase PV cells' power output, they are connected together in chains to form larger units, known as modules or panels [47]. These modules can be used individually, or can be combined to create arrays. Due to this modular structure, PV systems can be assembled to satisfy any electric power need [48].

These PV modules and arrays are just one part of a PV system, which also includes mounting structures to point panels toward the sun, components that take the direct-current (DC) electricity produced by modules and transform into alternating-current (AC), called an inverter (Figure 2.21). The alternating-current (AC) is the electricity that is used to power all the needs in buildings. The generated energy is stored in solar batteries, allowing be used at convenient times, or streamed directly in the grid [47].

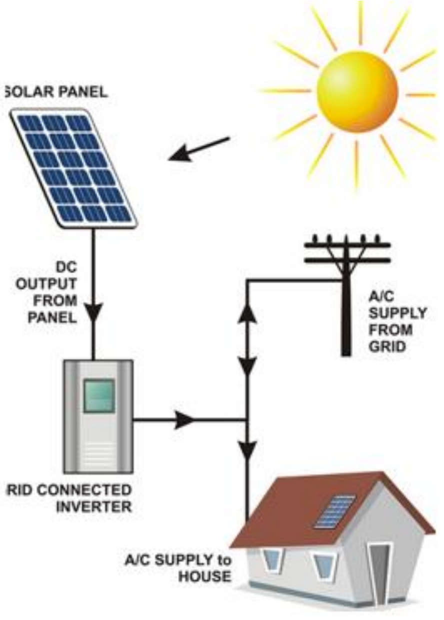


Figure 2.21 - PV system [49]

Solar photovoltaic panels can be integrated or attached to the building's roof or facade in two configurations based on installation and construction methods: building applied photovoltaics (BAPV) and building integrated photovoltaics (BIPV).

2.4.2.1. Building Attached Photovoltaic (BAPV)

In BAPV, the PV modules are directly attached to the buildings, with mounting structures and moving rails (Figure 2.22). Because of that, the PV modules do not apply any direct effect on the building structure and function. These PV modules are installed at certain titl angles on the roof or façades (BAPV-wall, BAPV sloped roof) or on horizontal roof and vertical walls [50].

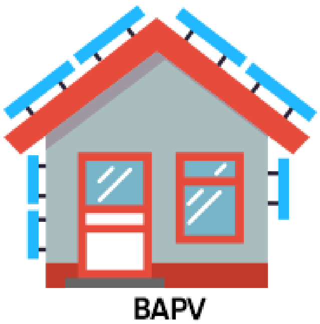


Figure 2.22 - BAPV Configuration [51]

2.4.2.2. Building Integrated Photovoltaic (BIPV)

In BIPV, the PV modules are integrated into the building envelope, usually into roofs or façade (BIPV-roof, BIPV façades) – see Figure 2.23. In this case, the PV modules replace the traditional building envelope materials, in the form of transparent or semi-transparent glass. Consequently, the BIPV system has an impact on the envelope of the building and its functionality. A complete BIPV system includes: the PV modules, a charger controller, power storage, power conversion equipment (to convert the DC output to AC), and backup power supplies [50].

Nonetheless, the electrical configuration is similar for both formats.

Figure 2.23 - BIPV Configuration [51]

2.4.2.3. Technological Solutions

The photovoltaic panels are divided into two main categories: monocrystalline or polycrystalline. The distinction between these two technologies is in the purity of the silicon used: monocrystalline panels have solar cells made from a single crystal of silicon, while polycrystalline solar panels have solar cells obtained from many silicon fragments (see Figure 2.24) [52].

Figure 2.24 - Polycrystalline and Monocrystalline Solar Cell [53]

Monocrystalline solar panels have a higher efficiency than polycrystalline due to being formed by only a single crystal, which results in more room for the electrons to move. Polycrystalline solar panels usually have a lower price [52].

2.4.2.4. Battery Energy Storage

For the Solar PV systems, it is essential to consider a battery to store the excess of energy generated during the day, so it can be consumed later, when necessary, without resorting to the electrical grid. The battery selection depends on the energy storage demand, which will influence the choice of the storage capacity.

Exists a vast market of batteries, however the more common are the lead-acid and the lithium-ion batteries. The lead-acid batteries present a lower price, but the lithium-ion batteries require less maintenance and have a longer lifespan [54].

For the selection of the battery is necessary a careful analysis, since it is the element that requires a higher investment, and it is also subject to one or more replacements during the life span of the Solar PV System.

2.4.3. Biomass System

The term biomass comprehends various materials, including wood from various sources, agricultural residues, and animal and human waste that can be burned to produce energy. It can be used for heating (see Figure 2.25), electric power generation, and combined heat and power [55].

The difference between biomass and fossil fuels is the timescale required for replacement: fossil fuels deplete faster than they are replaced, and the biomass can be replaced relatively quickly, being recognised as carbon neutral.

The available equipment for small-scale heating with wood includes firewood stoves, firewood boilers, wood chip-fuelled boilers, wood pellet stoves, and wood pellet boilers.

The firewood stoves can be utilised to heat small houses, and the thermal efficiency of modern firewood stoves may be high as 80%. The firewood boilers are designed to burn bigger pieces of wood than wood stoves and reach more than 90% efficiency. Wood chip-fuelled boilers can provide heat in larger houses, and the automatic operation and lower emissions are the benefits compared to firewood boilers [56].

The pellet stoves are more sophisticated than firewood stoves. Usually, these stoves have a small fuel pellet storage, from which the pellets fall into the combustion chamber. Compared to the firewood stoves, the advantages are entirely automatic operation, greater efficiency, and easier use. The wood pellet boilers usually are placed in a basement or in a separate container outside the house. They are also automatic [56].

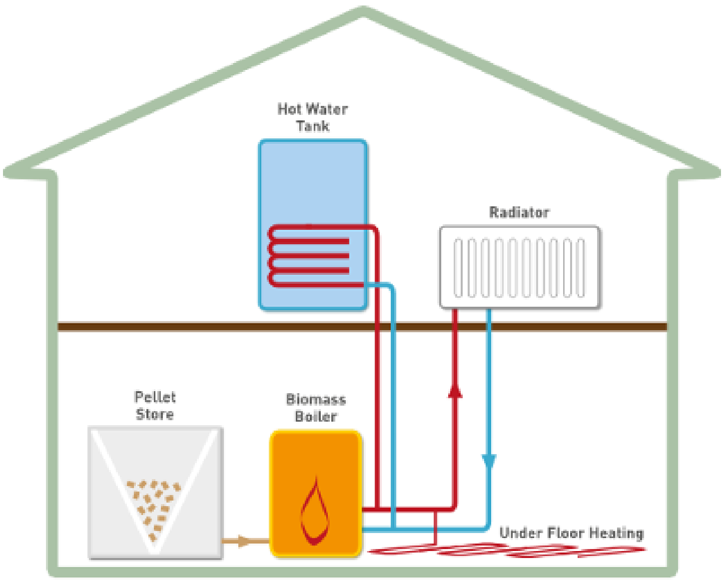


Figure 2.25 - Biomass Boilers [57]

2.4.4. HEAT PUMP

A heat pump can be defined as a device that extracts heat from the air, ground, or water, concentrates it to a higher temperature and delivers it elsewhere, such as a central heating system. This way can replace a traditional fossil fuel heating, such as a gas or oil boiler.

The heat pump system is conceived to extract more significant heat energy from the surrounding environment than the energy they consume and can be used domestically to provide hot water and space heating. In space heating, it is providing hot water to under-floor heating, radiators or supplying hot air.

2.4.4.1. Air Source Heat Pump

An air source heat pump absorbs heat from the outside air to space and water heating (Figure 2.26), and it can be an air-to-water system or air-to-air system.

Air-to-water systems absorb the heat from the outside air and transfer that heat to water, providing hot water for direct use or to supplying radiators or underfloor heating systems. The air-to-air system furnishes hot air that circulates on a warm air circulation system, moving around the house [58].

Both systems need electricity to run, but the heat output is more significant than the electricity input, making it an energy-efficient method.

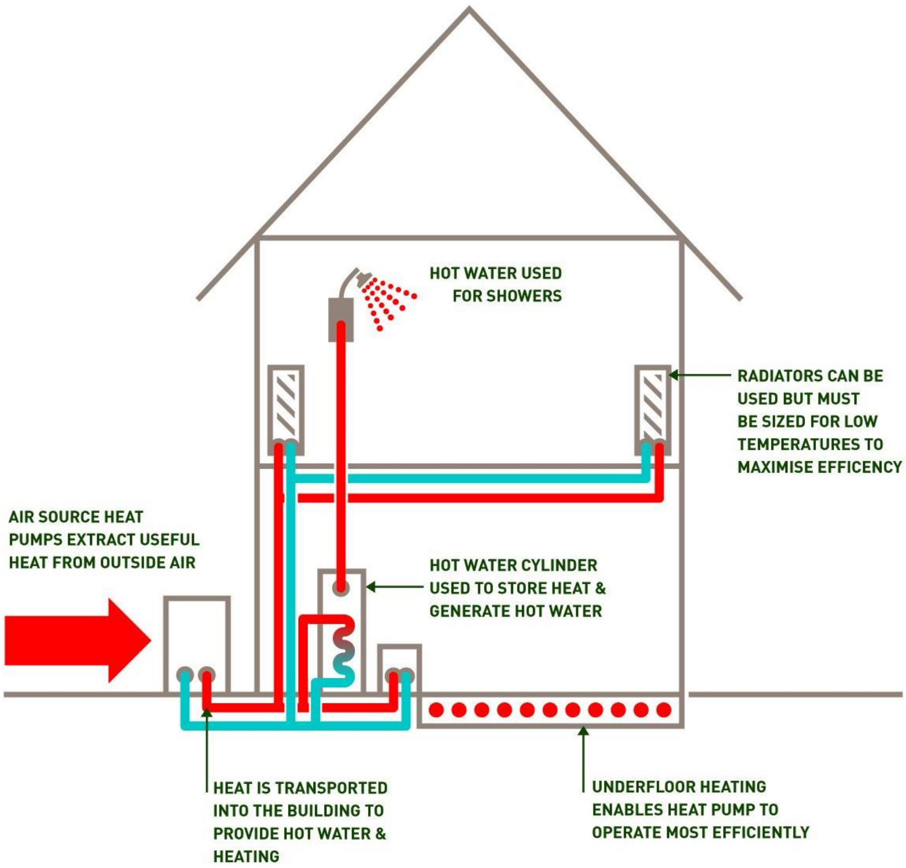


Figure 2.26 - Air Source Heat Pump [59]

2.4.4.2. Water Source Heat Pump

Water source heat pumps absorb heat from a local water source, such as a lake, river, borehole, etc., and convert it into useful energy to heat. Depending on the type, the water is pumped through the heat pump, or a special refrigerant fluid is pumped through pipes located in the water [60].

A water-to-water heat pump can extract heat from a flowing source of low temperature water (like groundwater) and deliver that heat to another higher temperature water stream. It is only compatible with hydronic radiant HVAC systems, such as radiators or radiant floor heating [61].

A water-to-air heat pump transfers the underground heat energy from water to indoor air and is only compatible with forced-air HVAC systems (heating, ventilation, and air conditioning systems). This system pumps supply forced air heating in the winter and in the summer supply central AC [62].

The water-to-water heat pumps only can supply heat or hot water. However, the water-to-air heat pump can provide both heat and air conditioning (AC) [62].

2.4.4.3. Ground Source Heat Pump

A ground source heat pump extracts heat from the ground (Figure 2.27) and can be used for space and water heating. A mixture of water and antifreeze absorb the ground heat and passes through a compressor that raises it to a higher temperature [63]. This is a continuous process, as long as heating is required.

This source is the most stable because the ground stays at a relatively constant temperature so that the heat pump can be used throughout the year.

Even though the heat pump needs electricity to run, it uses less electrical energy than the heat produce.

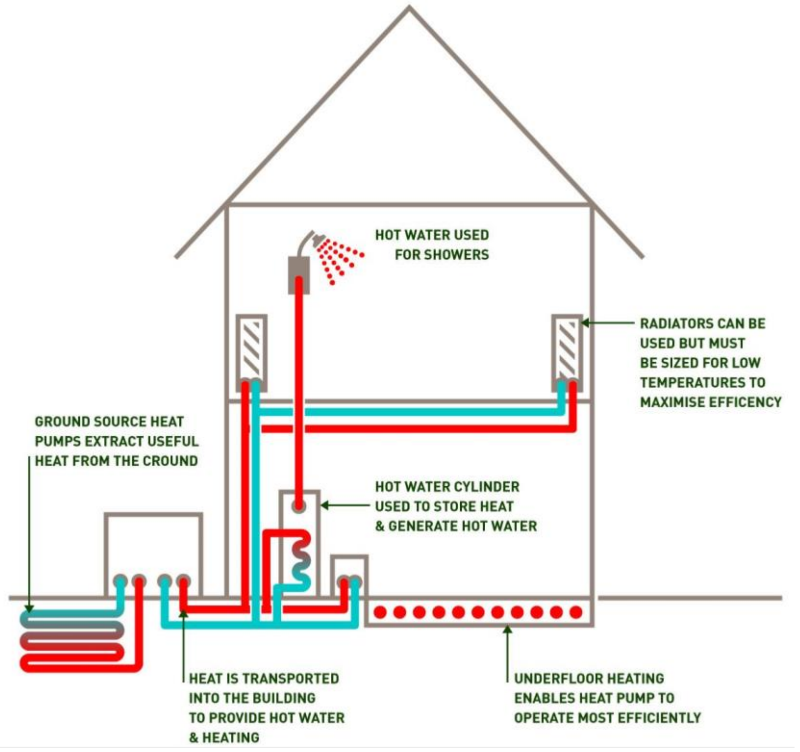


Figure 2.27 - Ground Source Heat Pump [64]

2.3. Chapter Synthesis

The viable measures to improve buildings' energy efficiency can be grouped into passive and active solutions. The passive solutions include the building's components that influence thermal capacitance, transmittance, inertia, solar gains, and ventilation. The active solutions incorporate solutions for space heating/cooling and domestic hot water production.

- Passive solutions considered are the orientation, the building envelope, shading and sun control devices, and the natural ventilation.

  1. For the building's orientation, the objective is to identify the optimal orientation angle for getting the minimum solar radiation in summer and the maximum in winter.
  2. The building envelope constitutes the limit between the interior and exterior conditions: the right selection for the exterior walls and roof of the constructive system and materials and the choice of windows with a higher performance that restricts the heat and loss gain contributes to improving indoor comfort conditions and reducing energy consumption.
  3. Of equal value is implementing shading devices to protect the building's transparent parts against unwanted solar radiation.
  4. Natural ventilation is one of the most efficient approaches to achieve indoor comfort.

- Active solutions are energy sources and were only considered renewable energy technologies: photovoltaic panels, biomass system, and heat pump.

  1. Solar PV system, allied with storing the energy produced in batteries for later use, is the most viable alternative for all power needs, providing a reliable green energy solution.
  2. Biomass system use plant or animal material as fuel to produce electricity or heat, being a good and reliable technology that offers net-zero CO2 emissions.
  3. There are three types of sources for heat pumps: air, water source and ground. The heat pumps are used to warm and less frequent to cool by transferring thermal energy from a cooler to a warmer space. The most current type is the air source heat pump.

Table 2.5 and Table 2.6 lists the solutions considered:

Table 2.5 - Passive Solutions

Passive Solutions
Building Orientation
Building Envelope (Exterior Walls, Roof, Windows)
Sun Control and Shading Devices
Natural Ventilation

Table 2.6 - Active Solutions

Active Solutions
Photovoltaic Panels
Biomass System
Heat Pump

3

THERMO-ENERGETIC SIMULATION

3.1. INTRODUCTION

The use of computer simulations is a very interesting way to obtain the thermal and energetic behaviour of buildings. Thus, in this work here developed a computer simulation software – EnergyPlus, is used to obtain energy simulations of the building under study in terms of thermal energetic behaviour.

EnergyPlus simulates buildings' thermal and energy behaviour (for heating, cooling, ventilation, and lighting), allowing an analysis of the different characteristics. It is free, open-source, and cross-platform - operates on Windows, Mac, and Linux. It is also considered one of the most robust energy simulation tools. The development of EnergyPlus is financed by the U.S Department of Energy´s (DOE) Building Technologies Office (BTO) [65]. The choice of using this program has been made considering all the advantages mentioned, and also because the university has experience using this tool.

The program reads the inputs and writes output to text files. First, it is necessary to design the building model in the program, entering the multiple data that describes the building, as de geometry, dimensions, and constitution. From that, the program runs the simulation, calculating what is asked by the user. For the simulation, the program takes into account the climate data file proposed by the user. Then, the program produces the results, which need to be interpreted to the conclusions be formed (see Figure 3.1).

The information and procedures described below take as a case the thermal and energetic simulations for the specific single-family residential building "Sky House. For this building, will be incorporated a set of active and passive solutions that promote a good energy performance, allowing to reach energy autonomy in order to be not necessary to make use of external sources of energy. Thus, the implemented solutions will be subject to a numerical study to evaluate their performance.

For simulations of buildings with different characteristics or for a distinctive analysis, the program and its configurations must be adjusted.

As a personal observation, the program does not have an easy-to-access user interface. It requires an exhaustive series of data inputs, being frequently necessary to make use of other dissertations, papers, tutorials, and documentation provided by the program.

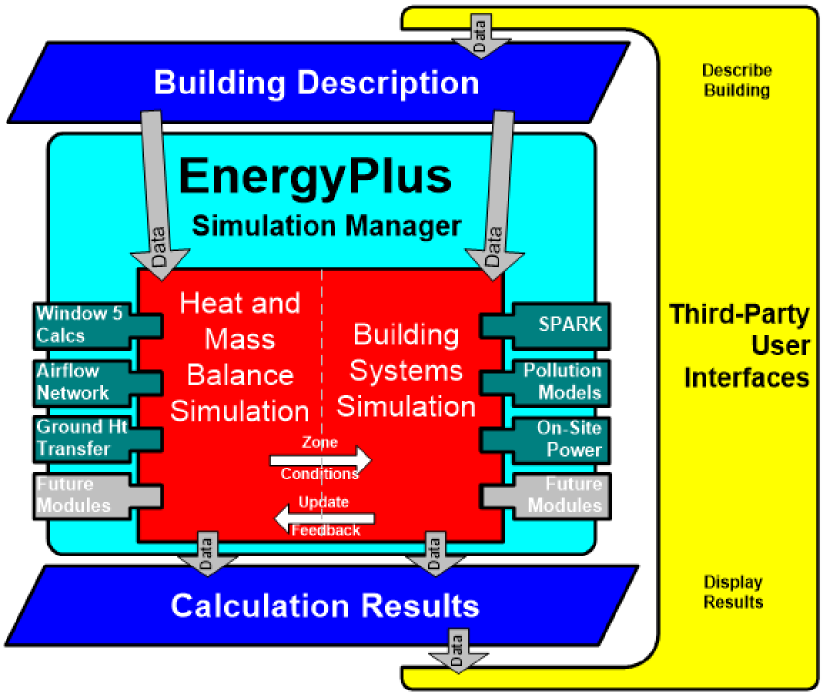


Figure 3.1 - Scheme of operation of EnergyPlus [66]

3.2. Balance Equation

For the calculation of the energy needs of the building, the balance calculation calorific value in the interior of the thermal zones is based on the following equation (Equation 3.1):

$$C_z \frac{d\theta}{dt} = \sum_{i=1}^{Nsi} \dot{Q}_g + \sum_{i=1}^{Nsup} h_{si} A_i (\theta_{si} - \theta_i) + \sum_{i=1}^{Nzonas} m_{\dot{i}nf} C_p (\theta_e - \theta_i) + m_{\dot{c}oup} C_p (\theta_{zones} - \theta_i) + Q_{sis} \ (J) \quad (3.1)$$

where:

$c_Z \frac{d\theta_i}{dt}$ – Energy stored in the zone (J);

$\sum_{i=1}^{Nsi} \dot{Q}_{\dot{g}}$ – sum of internal charges by convection (J);

$\sum_{i=1}^{N\,sup} h_{si} Ai(\theta_{si}\text{-}\theta_i)$ – convection heat transfer from the interior surfaces (J);

$\sum_{i=1}^{Nzonas} m_{\dot{i}nf} C_p (\theta_e\text{-}\theta_i)$ - heat transfer due to infiltration of outside air (J);

$m_{\dot{c}oup} C_p (\theta_{zones} - \theta_i)$ – heat transfer due to air exchanges between zones (J);

Q_{sis}- heat flow associated with installed systems (J).

The algorithm of the EnergyPlus allows the processing of the variables existing in the equation in permanent switch due to the change of the building's interior and exterior parameters that condition the thermal behaviour [67].

3.3. Energy Simulation

In the program, the user needs to indicate a climate data file – Weather File, with the definitions of the different components of the building in study - Input file, allows to achieve the building's energetic and thermal behaviour. In Figure 3.2 is presented the program launch interface. Then, in “Simulate”, the simulation starts to run, and in the “View Results”, the results are presented.

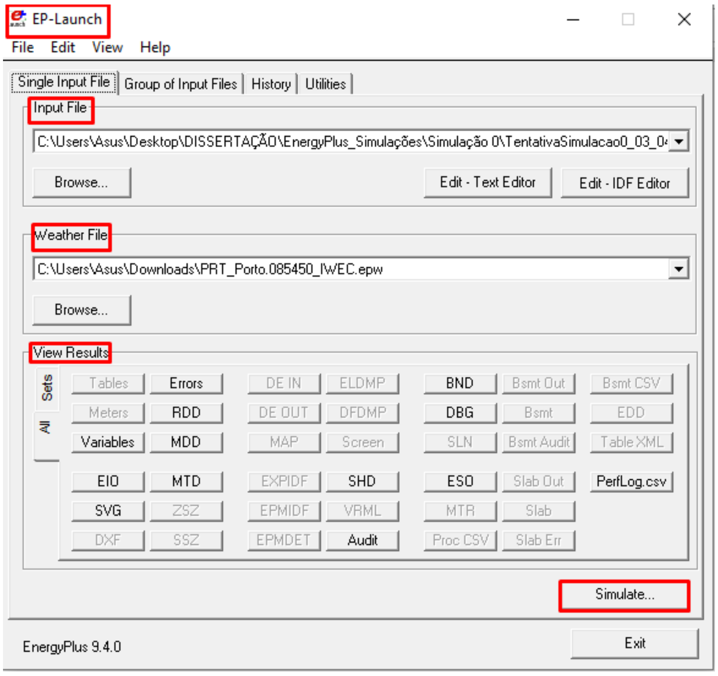


Figure 3.2 - EnergyPlus Launch Screen

The building will be modelled using EnergyPlus with a coordinated system, which is relatively time-consuming. There is also the option of using drawing tools such as Sketchup with an extension like OpenStudio to develop the building's geometric modelling.

3.4. Weather File

The weather file contains hourly information about the weather at the location under study. The EnergyPlus website gives two types of files: one with climatic values recorded in real-time by strategically placed meteorological stations, and the other based on the country's statistical data or area under consideration.

The building analysed is located in Esposende. Nonetheless, the weather file of this city is not available. In this way, the Oporto city's weather file is used, which has not the same clime, constituting an approximation. The weather file used is available on the program's website and is an IWEC (International Weather for Energy Calculations) data file – derived from up to 18 years hourly weather data, archived initially at the U.S. National Climatic Data Center. This weather file is completed with solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements [68].

3.5. IDF EDITOR

The command “IDF Editor” – Input data file (Figure 3. 3) describes the building and the HVAC system. It is divided into numerous building variables, which are redividing in various fields. It is in this command that definitions of materials, components, occupation, and use are inserted. In this part of the program, it is necessary to know the specific technical terms, which required the manual's study and interpretation [69].

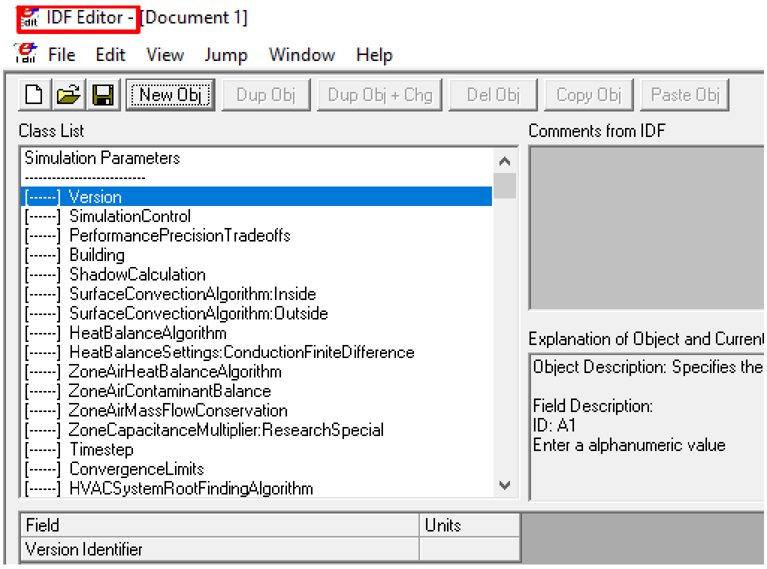


Figure 3. 3 - IDF Editor

3.5.1. GROUP – SIMULATION PARAMETERS

3.5.1.1. Building

The Building parameter establishes the building's information, such as the angle that the building makes with the North (15º), the type of surroundings (ocean), the convergence values, type of solar distribution (Full Exterior), and the maximum (25) and minimum (1) number of warmup days (Figure 3.4).

Regarding the solar distribution option, the choice of “Full Exterior” indicates that shadow patterns on exterior surfaces caused by detached shading, wings, overhangs, and the exterior surface of all zones are computed. The value of the maximum number of warmup days is relative to the building´s complexity, being the value 25 indicated for a current building. More than 25 would define a very complex building, which is not the case. These reference values can be found in the Input Output Reference document [70].

The converge values for loads and temperature are related to the imprecisions that can occur because the simulation do not reach the convergence in the analyses that precede the program's effective calculations.

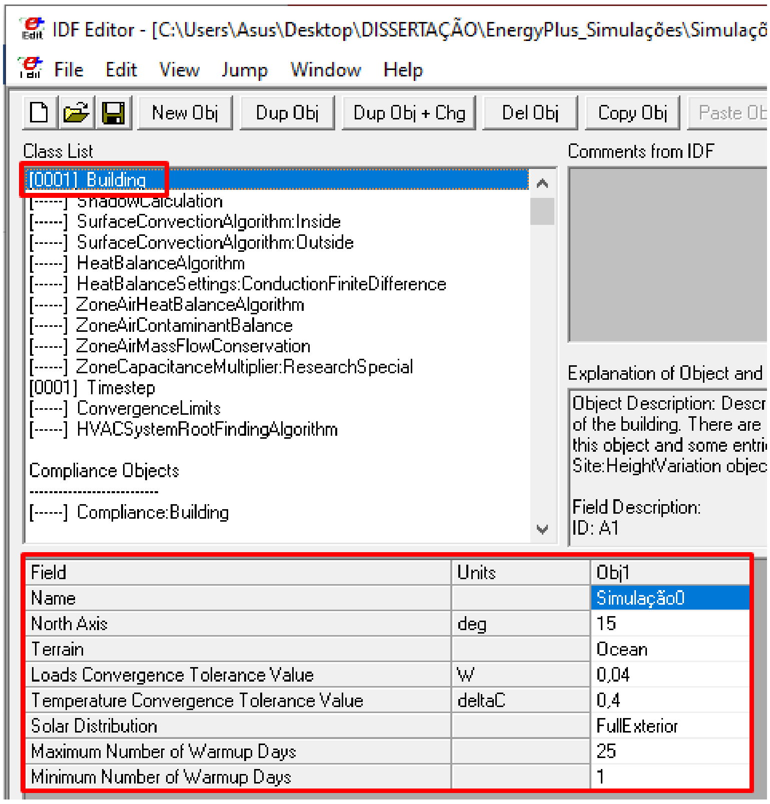


Figure 3.4 - Simulation Parameter: Building

3.5.1.2. Timestep

This parameter defines the number of time steps per hour (4) of the simulation – the subdivisions of time (hour) in the period for which the simulations are managed (Figure 3.5).

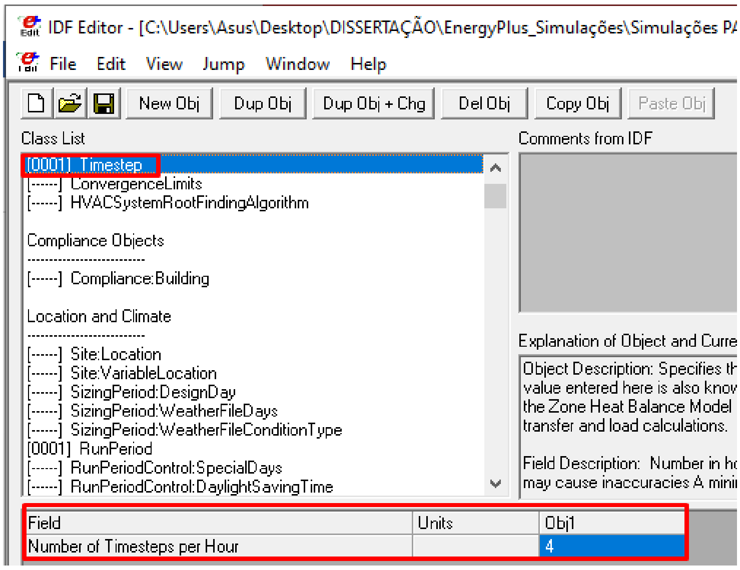


Figure 3.5 - Simulation Parameter: Timestep

3.5.2. Group – Location and Climate

This group of objects describes the ambient conditions for the simulation.

3.5.2.1. Run Period

The Run Period object (Figure 3.6) defines the simulation processing period: day, month, and year for the simulation's start and end. Furthermore, it also specifies if it is given special attention to extraordinary days, like weekends or holidays, and if the weather file considers snow and wind indicative values.

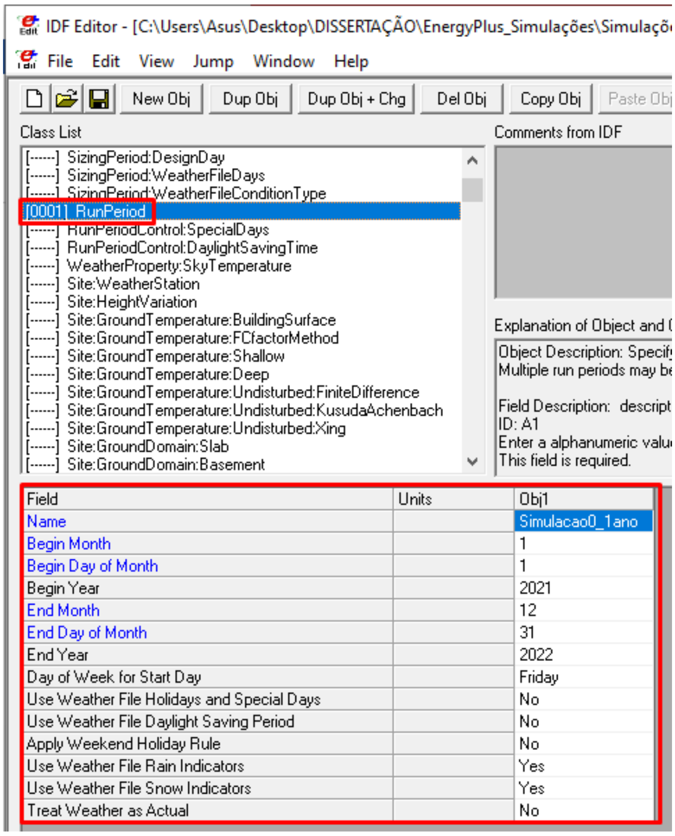


Figure 3.6 - Location and Climate: Run Period

3.5.3. GROUP – SCHEDULES

This group of schedules provides the user to determine the scheduling of many items, like occupancy density, thermostatic controls, or occupancy activity. So, it can be defined, for example, people's occupation, if the lighting or equipment will be on, etc. The programming of the operating schedules follows some standards, as shown in Figure 3.7.

3.5.3.1. Schedule Type List

The schedule types are used to validate a portion of the other schedules: seeing the example for the residential building occupation varies from 0 to 4 (admitting that the number of residents of the house will be four), and only takes integer values – Discrete (Figure 3.7).

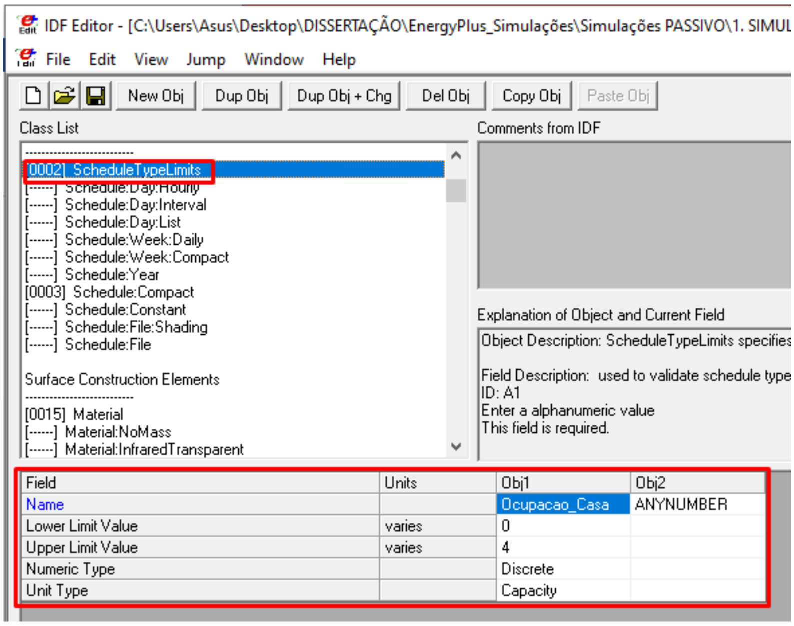


Figure 3.7 - Schedule Type List

3.5.3.2. Schedule: Compact

Here are defined the operating hours of each item. For example, the house occupation is defined for all the days of the week, from 7 PM until 8 AM the occupation is 100%, and from 8 AM until 7 PM the occupation is 0%. The schedule named "Constant" does not have a maximum or a minimum - Any number (Figure 3.8) to support the internal gains and natural ventilation.

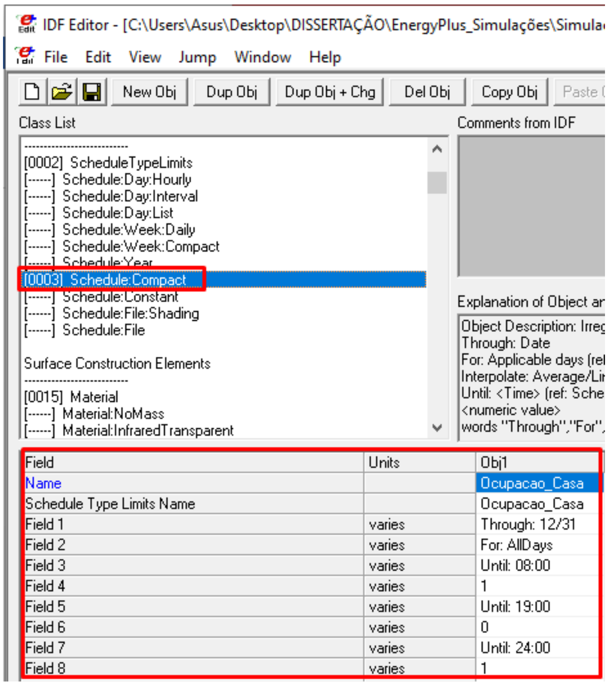


Figure 3.8 - Schedule Compact

3.5.4. Group – Surface Constructive Elements

The properties of the materials and the composition of the elements are inserted in this parameter. The elements are divided into “Material” for inserting the materials, “Material: Air Gap” for insert non ventilated air chambers, “Window Material: Glazing” for glass insertion, and “Construction” for the conception of the construction elements. The procedures and methods will be described below.

3.5.4.1. Material

First of all, it is necessary to know that the calculation algorithms used by the program EnergyPlus consider composed construction elements, such as walls and roofs, in materials organised in layers in series. Therefore, the heterogeneous compositions must be converted into homogeneous compositions with the equivalent thickness (Figure 3.9) [71].

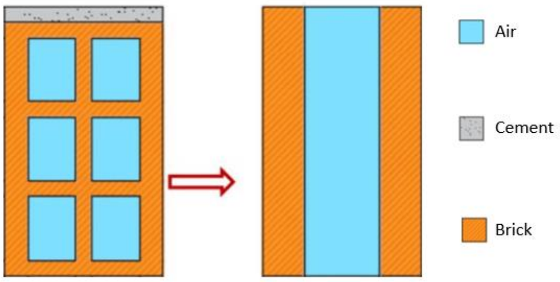


Figure 3.9 - Transformation of a heterogeneous wall into a homogeneous wall [72]

Thus, in this group, are introduced the materials that contribute significantly to the thermal inertia, their thickness, conductivity, density, and specific heat. It is also necessary to define each material's roughness, depending on the contact surface's texture (Figure 3.10).

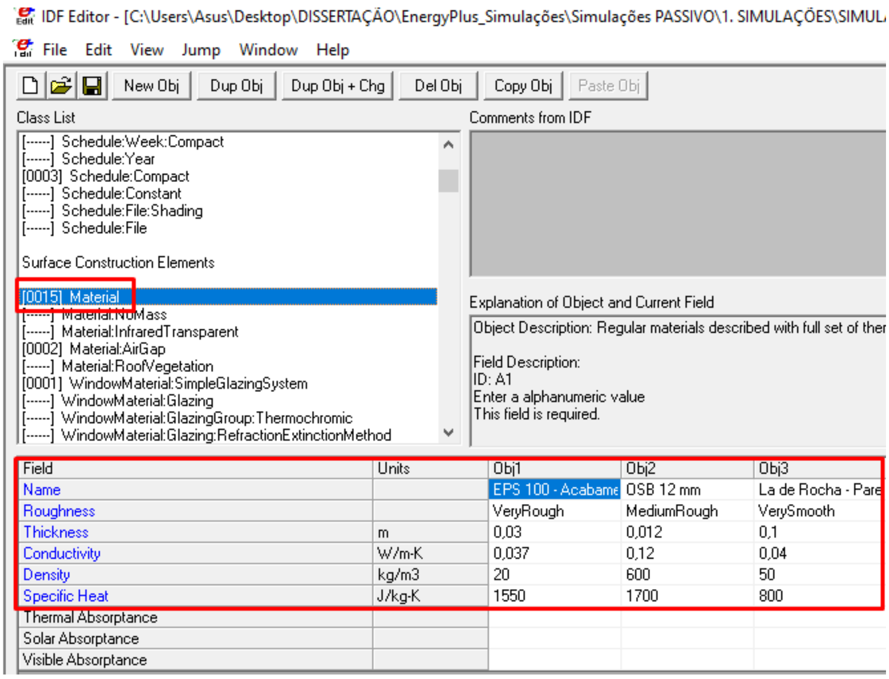


Figure 3.10 - Surface Construction Elements: Material

Extremely thin material layers should be dismissed because they will not contribute to the overall thermal resistance or heat capacity.

3.5.4.2. Material: Air Gap

This field defines the air spaces present in walls, floors, and roofs (Figure 3.11). The thermal resistance values depend on the thickness, nature of the air chamber, and the heat flow direction.

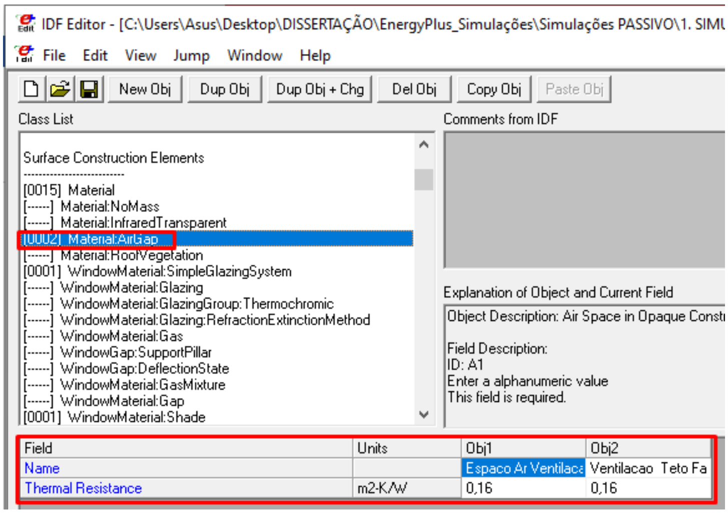


Figure 3.11 - Surface Construction Elements: Material Air Gap

3.5.4.3. Window Material: Simple Glazing System

The easiest way to introduce glass is through this parameter, where it is possible to define the windows as a whole. The characteristics necessary are the U-factor of windows (coefficient of thermal transmission) and the respective solar factor (Figure 3.12). The values of this coefficient are obtained in ITE 50, Annex III.

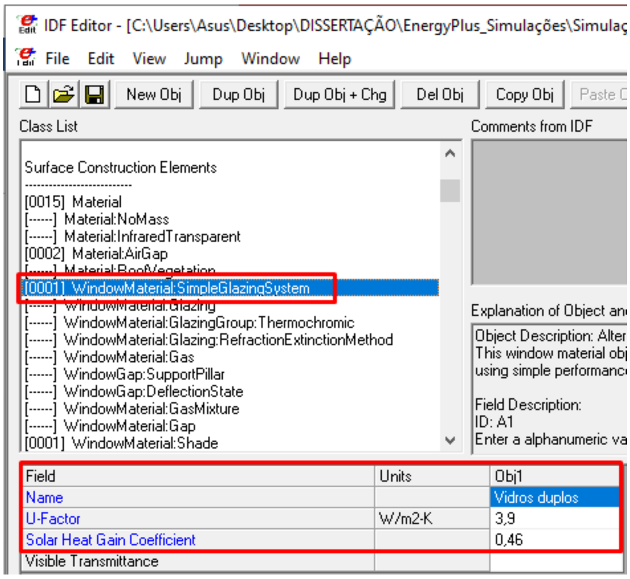


Figure 3.12 - Surface Construction Elements: Window Material

3.5.4.4. Window Material: Shade

Window shade elements such as curtains are defined in this field and designated by “shade” (Figure 3.13). It is required the value of the solar transmittance and reflectance, visible transmittance and reflectance, infrared hemispherical emissivity, infrared transmittance, thickness and conductivity. The values for these characteristics are available from ASRHAE (2001).

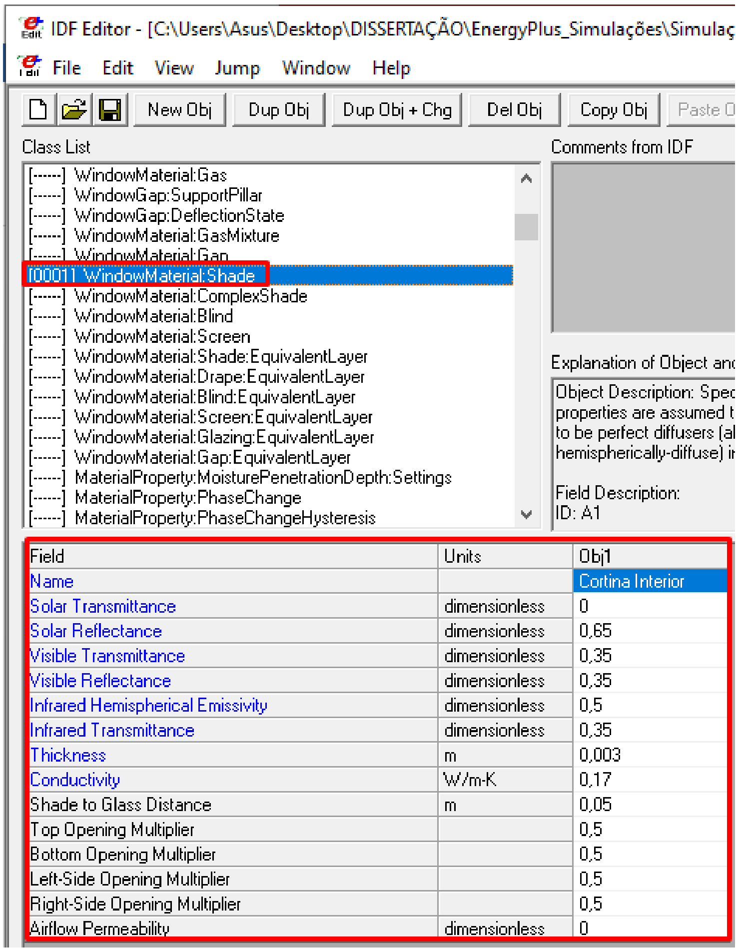


Figure 3.13 - Window Material: Shade

3.5.4.4. Window Material: Blind

In this field are defined the exterior shading elements, designated “Blind” (Figure 3.13). It is necessary to insert the slat width, the distance between them, thickness, and the material's conductivity.

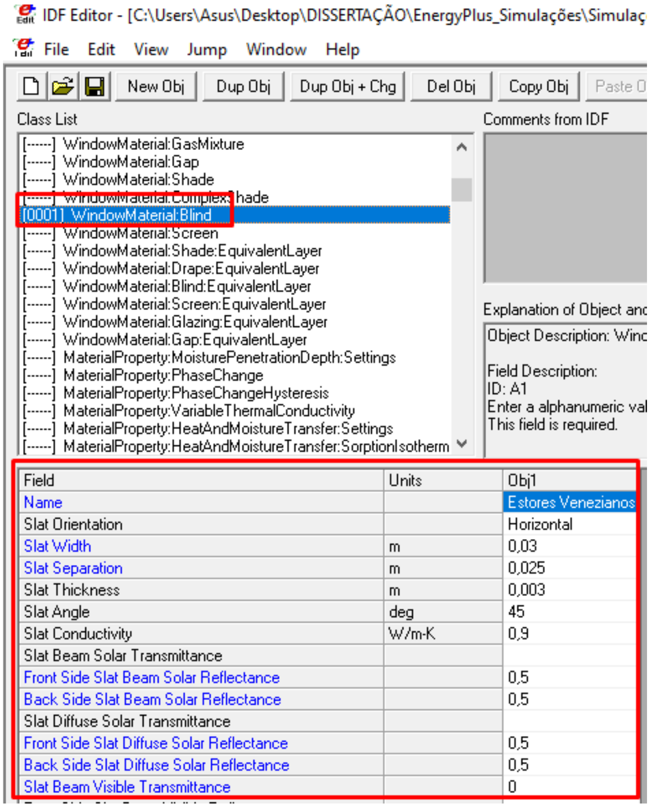


Figure 3.14 - Window Material: Blind

3.5.4.5. Construction

Once the building materials, air gaps, and glass are introduced and configures, the elements like walls, floors, and roofs can be "built" using the parameter "Construction". Each element must be constituted in sequence by the materials, from the outside to the inside (Figure 3.15).

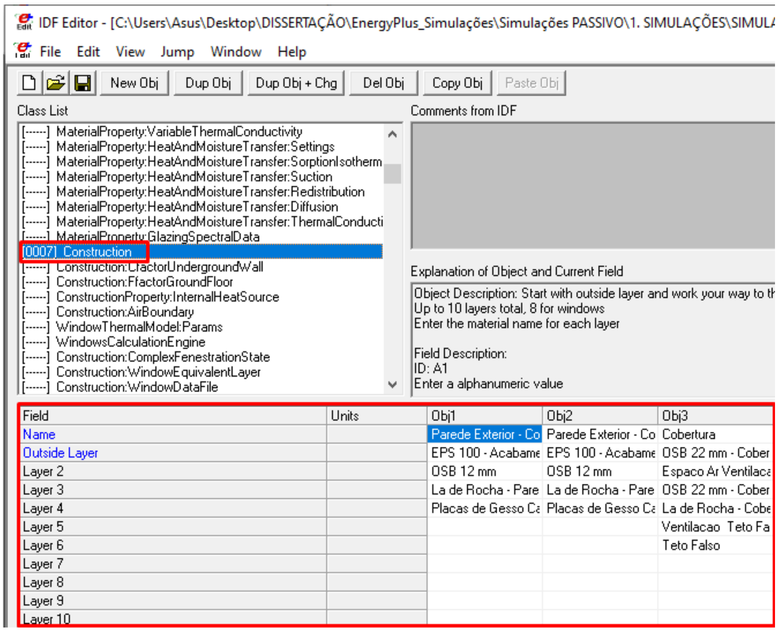


Figure 3.15 - Surface Construction Elements: Construction

3.5.5. Group – Thermal Zones and Surfaces

This group defines the thermal zone characteristics and the specifications of each surface model.

3.5.5.1. Global Geometry Rules

Previously of the definition of the building´s coordinates, it is required the stipulation of the parameters related to geometry. The introduction of the building´s geometry is done element by element, defining each vertex that constitutes them. The first vertex of each element is the upper left, observing from outside to the inside and following the clock's opposite count direction. The surfaces are measured from the outside, including the thickness of the elements. As the coordinates (x,y,z) (Figure 3.16) are inserted by the user, defining the option "Relative" is necessary.

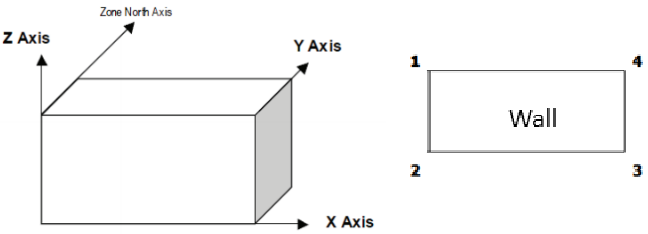


Figure 3.16 - Coordinate System of EnergyPlus [73]

3.5.5.2. Zone

A zone is a space with individual and specific thermal characteristics. In this way, the building was only divided into one zone – "Piso 0" (see Figure 3.17).

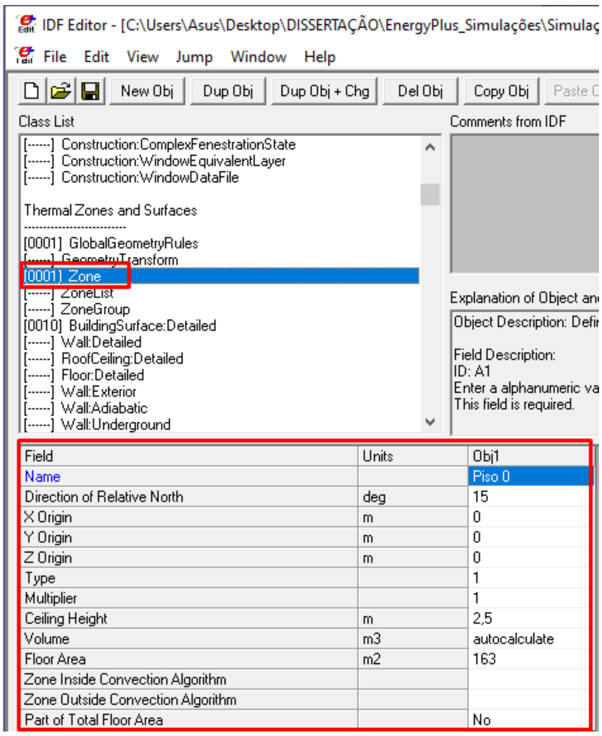


Figure 3.17 - Thermal Zone and Surface: Zone

3.5.5.3. Building Surface: Detailed

In this parameter is where the edifice is "built": each element is associated with a name (wall 1, for example), type of surface (wall, floor, roof), name of the construction of object to which it is associated in the "Construction" parameter, name of the zone to which it is related and the boundary conditions of the external surface (see Figure 3.18 and Figure 3.19). It is also necessary to define all the coordinates.

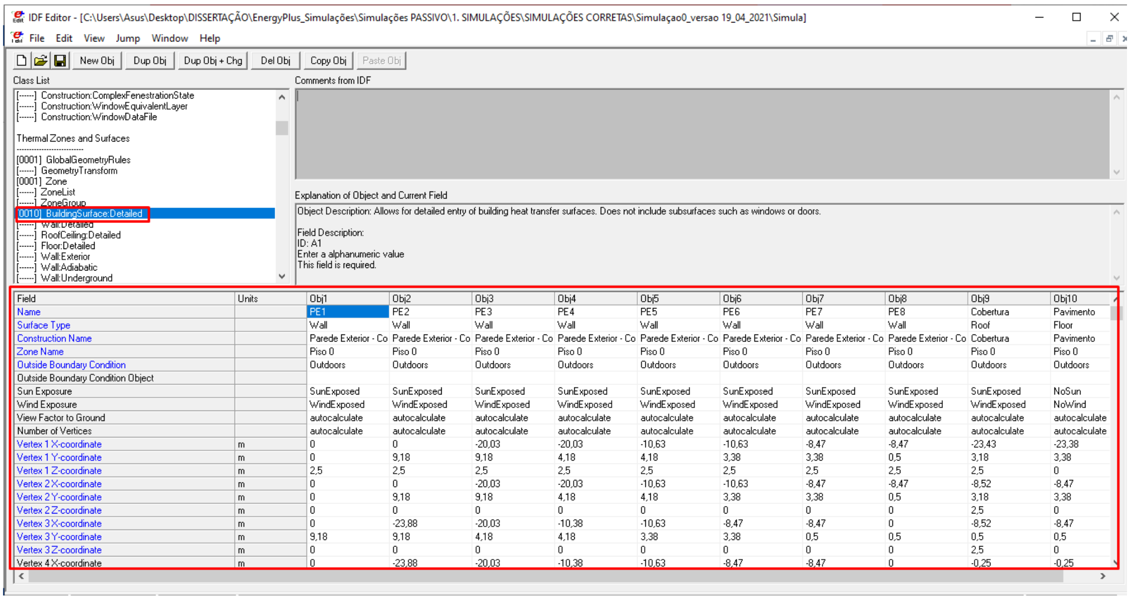


Figure 3.18 - Building Surface: Detailed

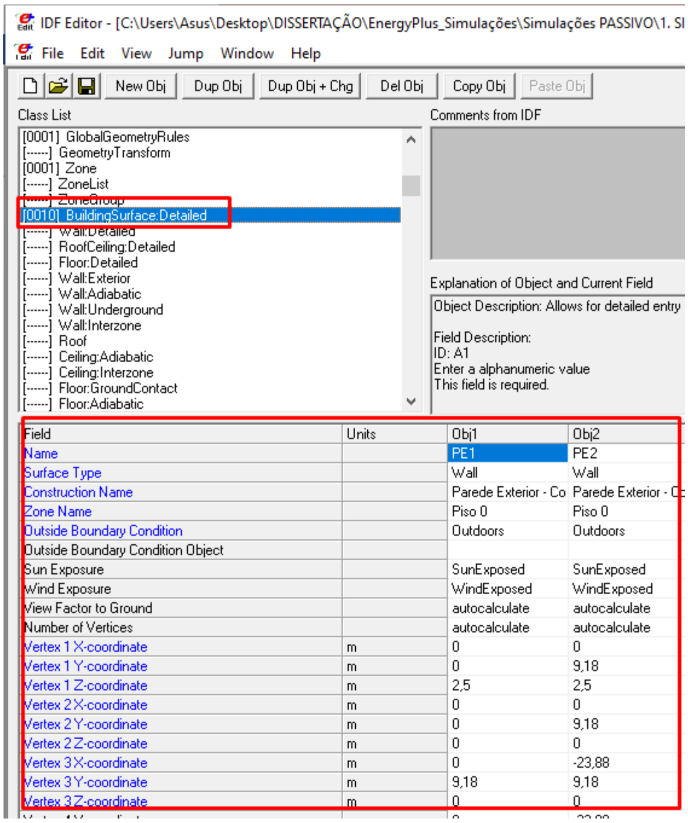


Figure 3.19 - Building Surface: Detailed (zoom of Figure 3.18)

3.5.5.4. Fenestration Surface: Detailed

In “Fenestration Surface: Detailed”, a parameter of “Thermal Zones and Surfaces” is defined information relative to opening surfaces – windows and doors. The methodology is similar to the previous parameter: is defined the name of the object (window 1, for example), surface type, name of the construction object to which it is related in the “Construction” parameter, name of the construction surface object, boundary conditions of the external face, and finally the coordinates (see Figure 3.20 and Figure 3.21).

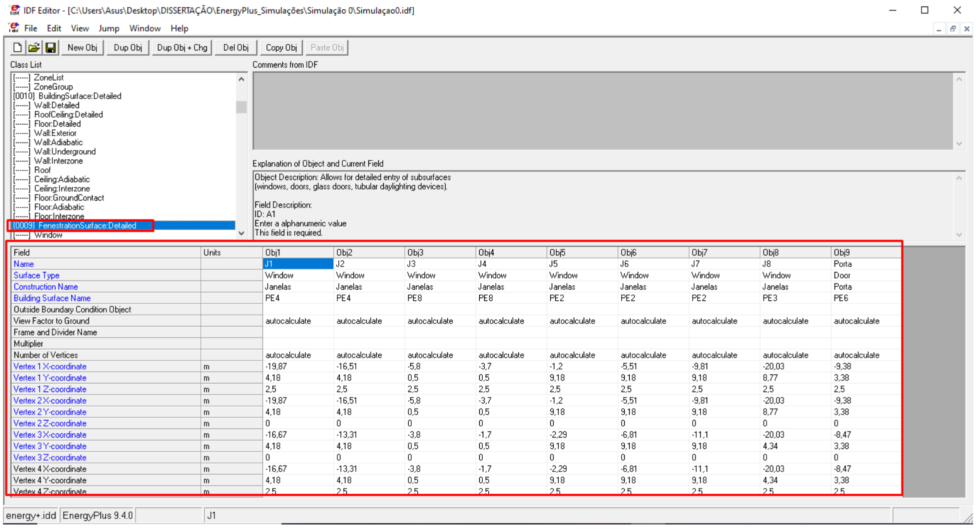


Figure 3.20 - Fenestration Surface: Detailed

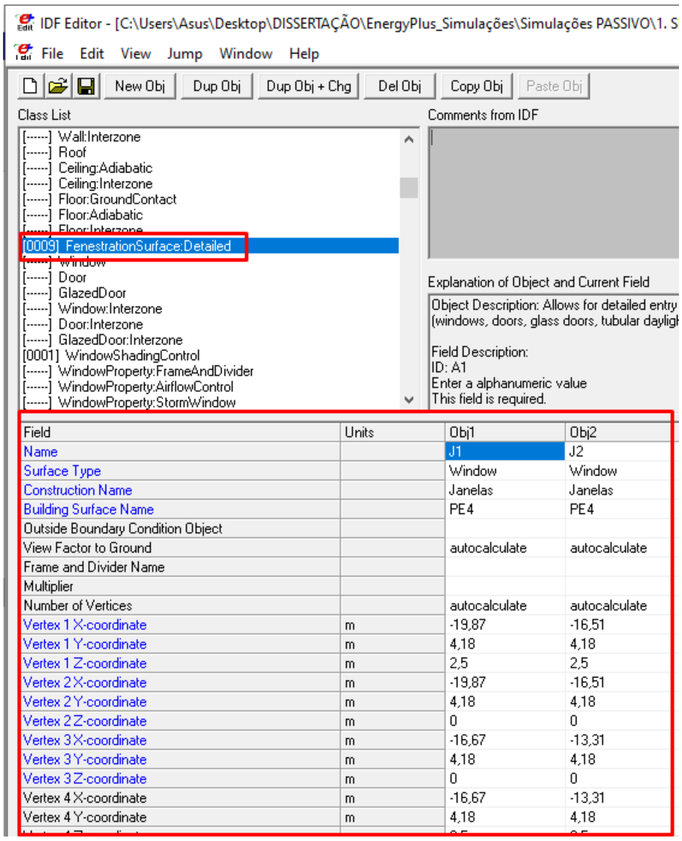


Figure 3.21 - Fenestration Surface: Detailed (zoom of Figure 3.20)

3.5.5.5. Window Shading Control

This field allows the definition of the shading device schedule and which windows have it. In the case of being fixed devices, is defined the schedule “Always on”.

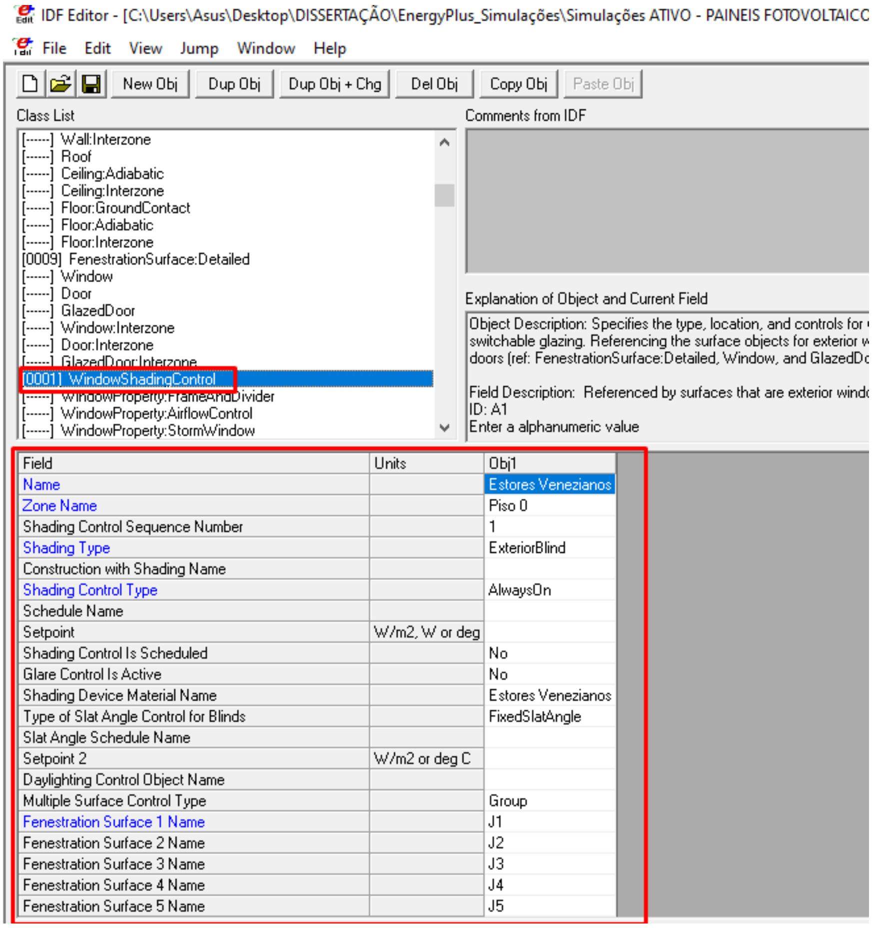


Figure 3. 22 - Window Shading Control

3.5.6. Group – Internal Gains

Not all the influence for energy consumption in the building is due to envelop and ambient conditions – this group defines additional internal gains that may come into action (people, light, and multiple types of equipment) [74]. It is here presented the example for “People”, but for “Light” and “Equipment” is followed the same logic.

3.5.6.1. People

This object is used to model the occupant´s effect on the space conditions. It is also required the input of carbon dioxide generation rate based [74]. In the example presented in Figure 3.23, it is considered that the building has a maximum of 4 occupants. The option for the schedule is defined previously in Schedule: Compact.

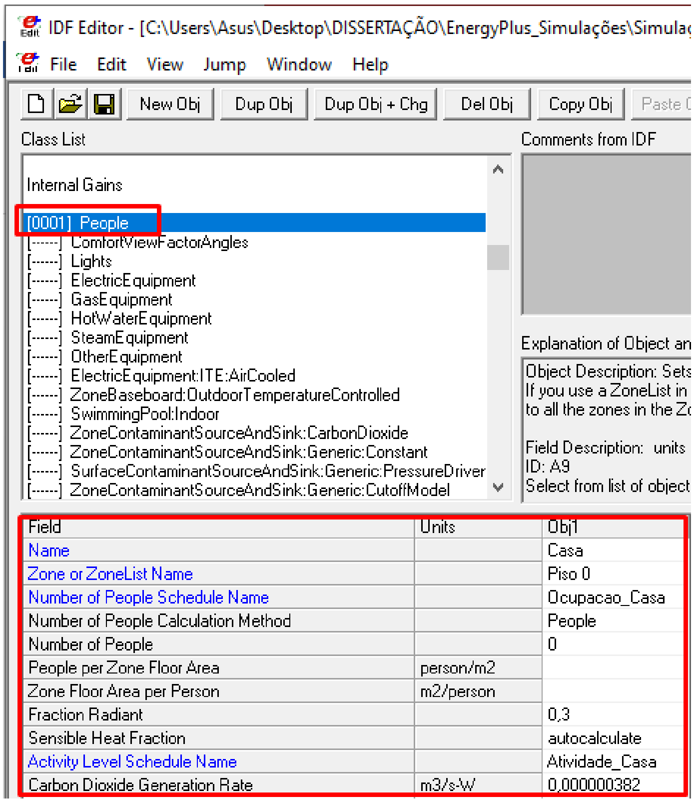


Figure 3.23 - Internal Gains: People

3.5.7. Group – Zone Airflow

The airflow between zones due to natural ventilation or mechanically induced ventilation is described in this group. Beyond that, it can also be used to model infiltration and mixing (zone to zone airflow) without operating the HVAC air distribution system [75].

3.5.7.1. Zone Infiltration: Design Flow Rate

EnergyPlus refers to ventilation as an "hourly renewal rate" – Rphn. It was set constant ventilation throughout all days for all the building zones with the previously defined ventilation schedule (Schedule: Compact). The minimum value for the hourly renewal rate for the heating season is 0,4 h^{-1} and for the cooling season is 0,6 h^{-1}. So, was set the ventilation with a renewal rate of 0,6 h^{-1} (see Figure 3.24) for the minimum required value to be always satisfied.

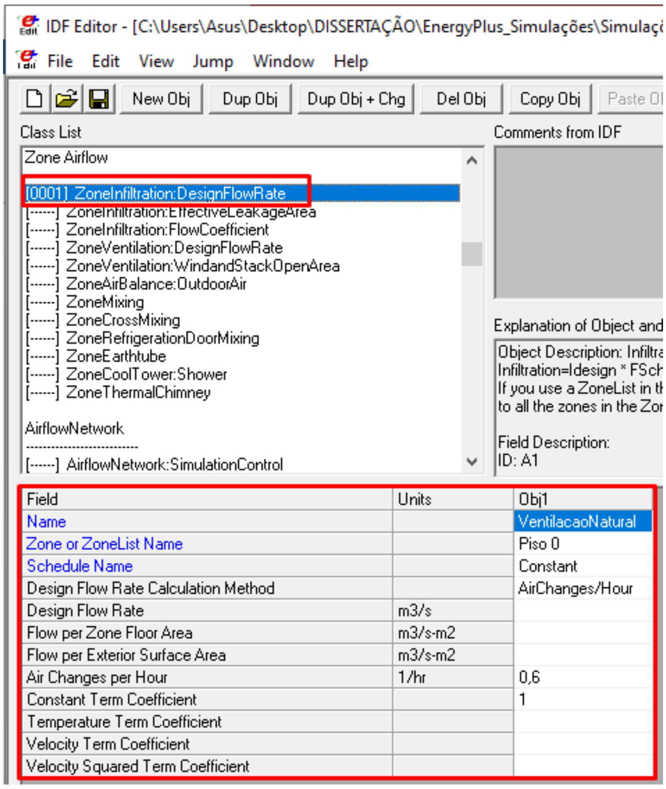


Figure 3.24 - Zone Infiltration: Design Flow Rate

3.5.8. HVAC TEMPLATE

In this group of objects are set the thermostats and HVAC systems.

3.5.8.1. HVAC Template: Thermostat

An HVAC system is characterized as a method of controlling heating, cooling, ventilation or air conditioning. Thus, in this object are defined the control condition, though the thermostat, by the definition of set points. These set points can be constant for the whole simulation or with schedules (determined in Schedule: Compact). The thermostat is a target, and the HVAC system will try to meet it with a deadband.

3.5.8.2. HVAC Template: Zone: Ideal Load Air System

The model Ideal Load Air System allows the simulation of thermal loads (amount of energy required to be added or extracted from a space by the HVAC system to maintains occupants comfortable) without the need to model the HVAC system in detail.

3.5.9. ELECTRIC LOAD CENTER – GENERATOR SPECIFICATION

This group of inputs is linked to electric power that serves the building. The EnergyPlus has multiple types of electric generators that could serve the building model (such as combustion turbine, micro turbine, photovoltaic panels, etc.). If these extra inputs are not defined is assumed that the building has a connection to utility grid service.

3.5.9.1. Generator: Photovoltaic

This object is used to define an array of PV modules and how they will be modelled (Figure 3.25).

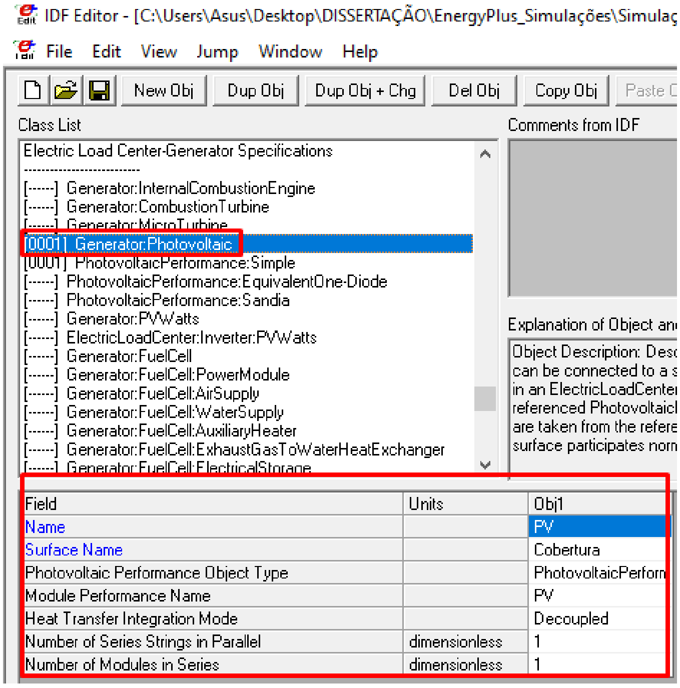


Figure 3.25 - Generator: Photovoltaic

3.5.9.2. Photovoltaic Performance: Simple

This object defines a simple model of photovoltaic. It is necessary to introduce the efficiency of the cells (see Figure 3.26). The model is useful to obtain the values for annual production and peak power.

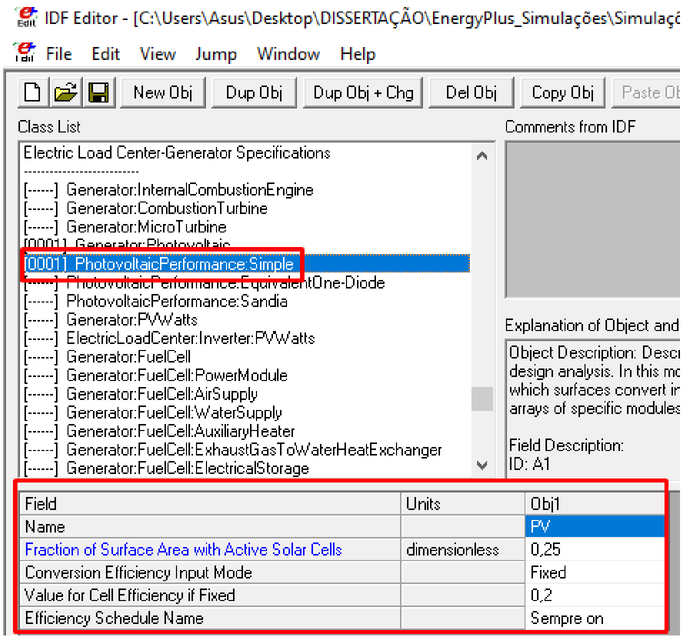


Figure 3.26 - Photovoltaic Performance: Simple

3.5.9.3. Electric Load Center: Generators

The Electric Load Center: Generators object is utilised to provide a list of the generators to incorporate in the simulation and theirs rate power output. An electric generator is a device that converts mechanical energy obtained from an external source (solar incident energy) into electrical energy as an output.

3.5.9.4. Electric Load Center: Inverter: Simple

This object is used to model the conversion from the Direct Current (DC) output of a photovoltaic solar panel into Alternating Current (AC). It uses a fixed efficiency, that usually ranges from 95% to 98% (see Figure 3.27).

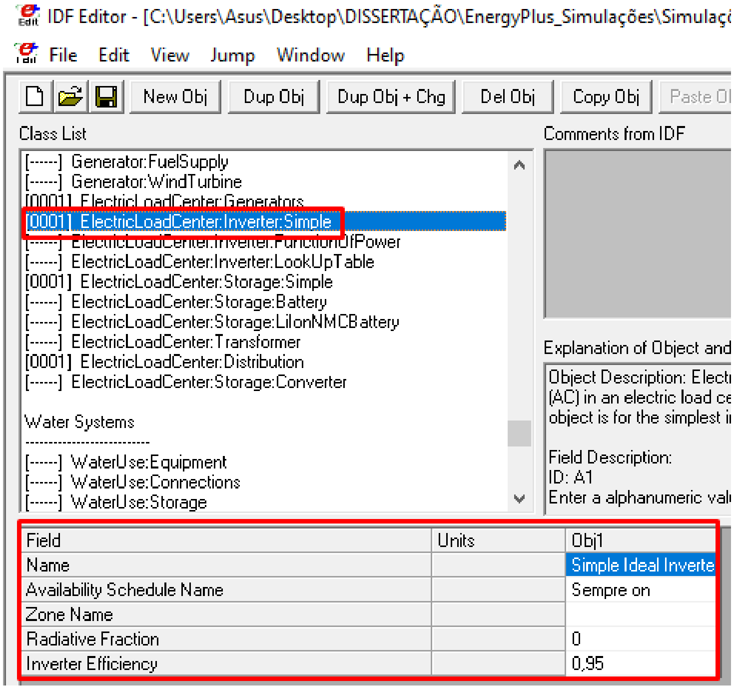


Figure 3.27 - Electric Load Center: Inverter: Simple

3.5.9.5. Electric Load Center: Storage: Simple

This object is used to model a battery for electrical storage in a simple way.

3.5.9.6. Electric Load Center: Storage: Distribution

Electric Load Center: Distribution object (Figure 3.28) introduces on-site electricity generators and/or storage in the simulation. By using this input, the program presents numerous reports for the electricity used, generated on-site, stored, exported etc.

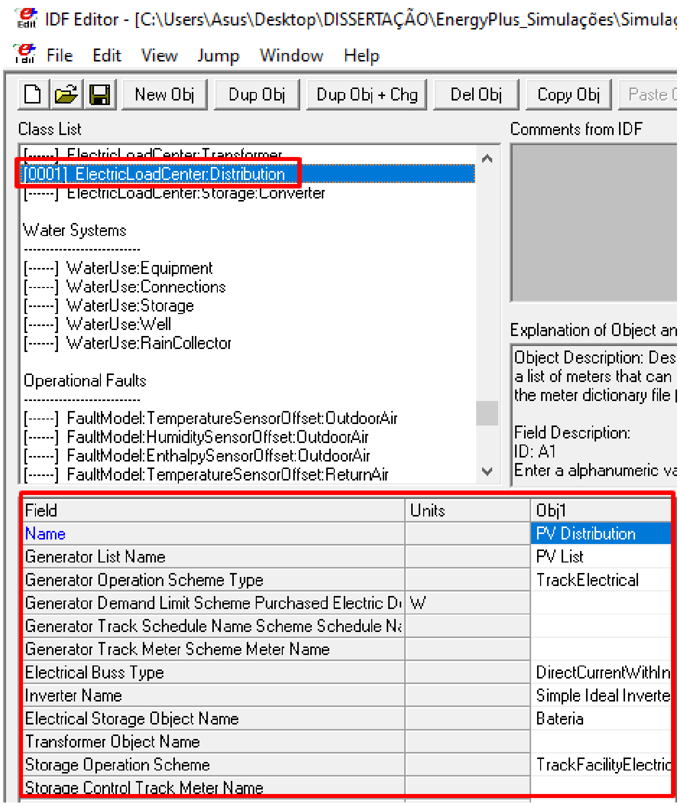


Figure 3.28 - Electrical Load Center: Distribution

3.5.10 Group – Output Reporting

The program EnergyPlus allows an extensive variety of outputs, and numerous items can be used to stipulate that, having the user the liberty to define the outputs that provide the necessary data.

3.5.10.1 Output: Variable

The parameter used to stipulate the outputs is "Output: Variable". The Figures Figure 3.29 and Figure 3.30 illustrates the settings for the program provides the following outputs:

- Zone Operative Temperature;
- Zone Ideal Loads Zone Total Heating Rate;
- Zone Ideal Loads Zone Total Cooling Rate;
- Generator Produced DC Electricity Rate.

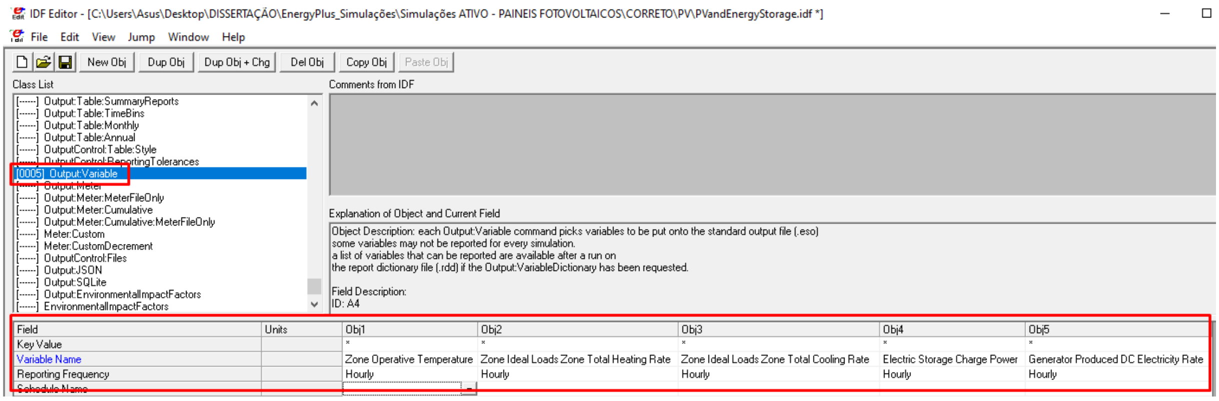


Figure 3.29 - Output: Variable

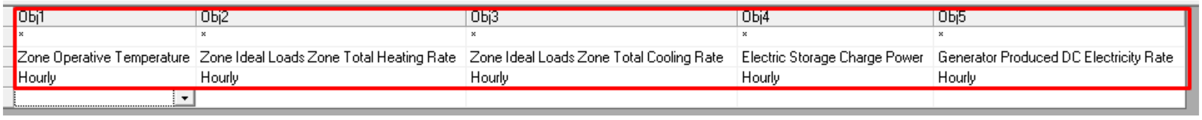


Figure 3.30 - Output: Variable (zoom from Figure 3.29)

3.6. Synthesis of Used Parameters

Table 3.1 summarises all the parameters used in the simulations executed with the program EnergyPlus (weather file, inputs and outputs).

Table 3.1 - Used Parameters Summary

<table>
<tr><td colspan="5">EP Launch</td></tr>
<tr><td colspan="5">Input File</td></tr>
<tr><td>Weather File</td><td colspan="4">IDF Editor</td></tr>
<tr><td rowspan="4">Oporto (IWEC file)</td><td rowspan="4">Simulation Parameters</td><td rowspan="3">Building</td><td rowspan="3">North Axis: 15
Terrain: Ocean
Loads Converge Tolerance Value: 0,04
Temperature Converge Tolerance Value: 0,4
Solar Distribution: Full Exterior
Maximum Number of Warmup Days: 25
Minimum Number of Warmup Days:1</td><td>Output</td></tr>
<tr><td>Variables</td></tr>
<tr><td rowspan="2">Zone Operative Temperature
Zone Ideal Loads Zone Total Heating Rate
Zone Ideal Loads Zone Total Cooling Rate</td></tr>
<tr><td>Timestep</td><td>Number of Timestep per Hour: 4</td></tr>
</table>

	Location and Climate	Run Period	1 year - 2021	Generator Produced DC Electricity Rate
	Schedule	Compact	Standard: 7 PM until 8 AM 100%, 8 AM until 7 PM 0% Non-Standard: 7 PM until 8 AM 100%, 8 AM until 7 PM 50%	
	Surface Construction Elements	Material	Roughness, thickness, conductivity, density and specific heat of each material that compose the building	
		Material: Air Gap	Thermal resistance of air spaces;	
		Window Material: Simple Glazing System	U factor and Solar Heat Gain Coefficient of windows (double-pane and triple glazing window)	
		Window Material: Shade	Interior Curtains	
		Window Material: Blind	Exterior Blinds	
	Thermal Zones and Surfaces	Global Geometry Rules	Relative Coordinate System; Starting Vertex Position: Upper Left Direction: Counter clockwise	
		Zone	1 zone: Piso 0	
		Building Surface: Detailed	Coordinates of walls, floor and roof	
		Fenestration Surface: Detailed	Coordinates of windows and doors	
		Window Shading Control	Interior Curtains or Exterior Blinds, Always On	

	Internal Gains	People	Standard: 4 residents Non-Standard: 8 residents	
	Zone Airflow	Design Flow Rate	Hourly Renewal Rate: 0,6 h^{-1}	
	HVAC Template	Thermostat	Operative Temperature: 18 to 24 °C	
		Zone Ideal Load Air System	Allows the simulation of thermal loads without detailed the HVAC system	
	Electric Load Center	Generator Photovoltaic	Define an array of PV modules	
		Generator	List of generators incorporate in the simulations	
		Inverter: Simple	Model the conversion from DC to AC; Efficiency used: 95%	
		Storage: Simple	Simple model of a battery	
		Storage: Distribution	Introduces on-site electricity generators and/or storage	

The next chapter – Chapter 4, presents in detail all the simulations performed, with the description of the base project and the passive and active solutions implemented to optimize energetically the building, which will justify the parameters described. In Chapter 5, are displayed and analysed the outputs referred previously.

4

IMPROVE ENERGY PERFORMANCE OF SKY HOUSE

4.1. SKY HOUSE DESCRIPTION

The building energetically optimized is a single-family residential building named “Sky House” (Figure 4.1) of typology T3, located in Esposende. This building was designed by Ooty, a registered trademark that belongs to the Black Oak Company group, which works in prefabricated and modular structures with wooden substructure. Their buildings have a powerful and distinctive image, allied to a modern concept of prefabricated structures.

Figure 4.1 - Sky House [76]

The building has approximately 130 m^2 of gross area and just one floor, composed of a living room and kitchen in open space, two bedrooms, one bathroom, and a suite, with a bathroom and closet (see Figure 4. 2. - House Plan). There is also an outdoor space, with 18 m^2 of area.

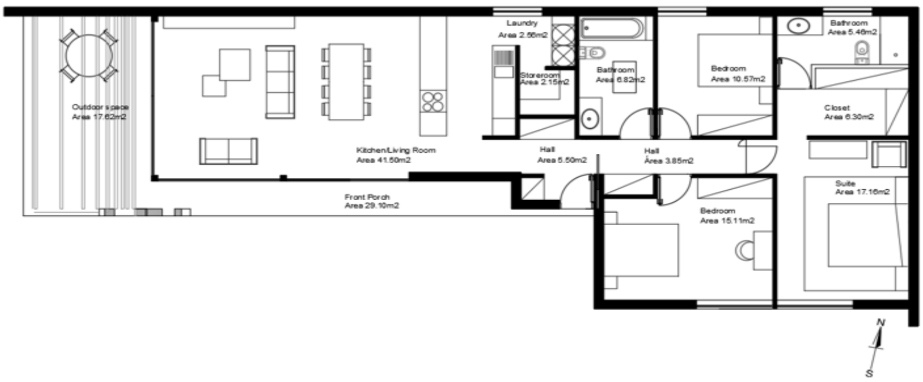


Figure 4. 2. - House Plan

The area of each compartment is represented in Table 4.1. and **Error! Reference source not found.**.

Table 4.1. - Compartment Area

	Area (m^2)
Kitchen/Living Room (Open space)	41,50
Laundry	2,51
Storeroom	2,15
Bathroom	6,82
Hall 1	5,50
Hall 2	3,85
Bedroom 1	10,57
Bedroom 2	15,11
Suite	17,16
Closet	6,30
Bathroom	5,46

The roof is flat, with no direct access. The plan of the roof can be observed in the following figure.

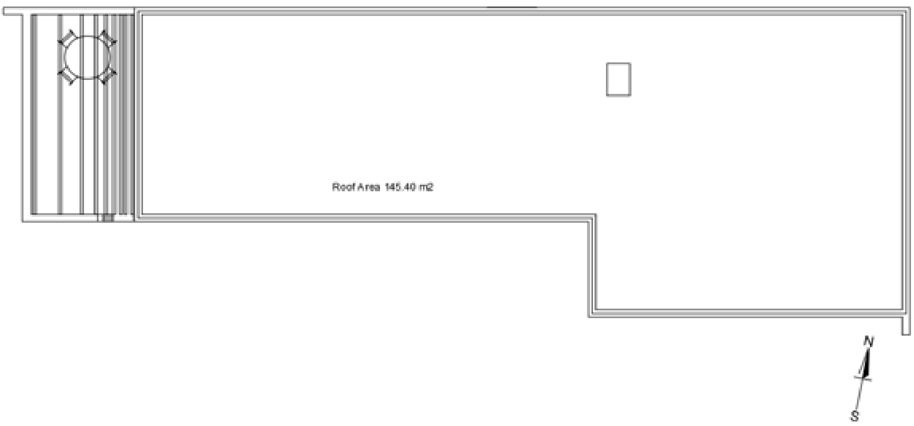


Figure 4. 3. - Roof Plan

4.2. Base Build Project

4.2.1. Building Envelope

One of the most essential factors for the hygrothermal and energy analysis is the building envelope and its constitution, responsible for the energy exchanges between the interior and exterior that need to be studied to optimise the energy efficiency. This subchapter presents the composition of the "Sky House" building envelope and the materials used in the base project, without the application of the passive or active solution, referred in Chapter 2.

4.2.1.1. Exterior Walls Constitution

The exterior walls are formed of a structure of lights wood profiles, locked with a structuralised wooden sheet of OSB – Oriented Strand Board (Figure 4.4), creating a composition capable of resisting vertical and perpendicular loads, transmitting them to the foundation. In the walls are used 12 mm plates of OSB.

Figure 4.4 – OSB [77]

There are two types of exterior walls being the difference in the wood structure and if this involves the whole wall (A) or just the interior part (B). The layout of each type of wall (A or B) is identified in the next figure.

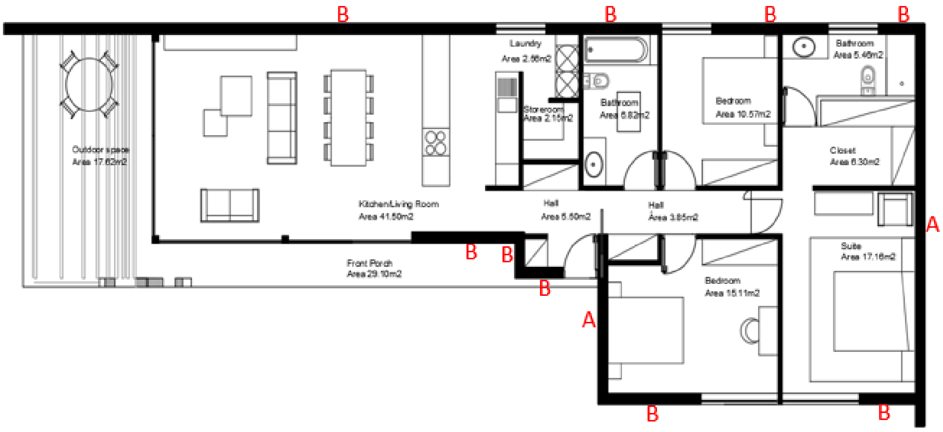


Figure 4.5 - Layout of each type of wall (A or B)

In the exterior wall type A between the wood structures are applicated the remaining materials: in the outside face expanded polystyrene as an exterior finish, UV protection membrane, OSB 12 mm, thermal and acoustic insulation, a waterproof membrane, and plasterboard as an interior finish (Figure 4.6).

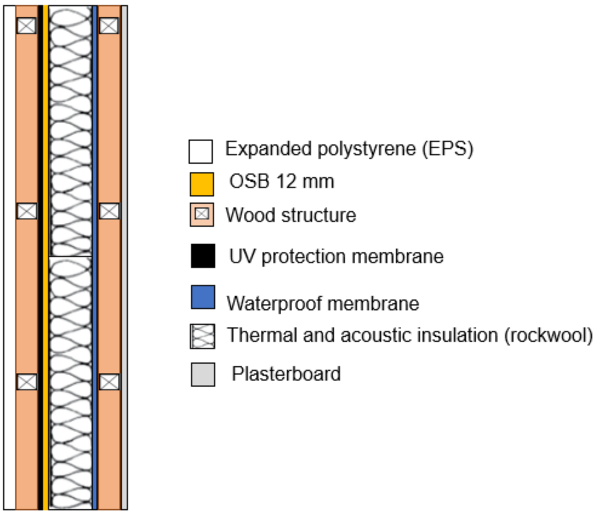


Figure 4.6 - Exterior Wall A System Composition

In the exterior wall type B, the wood structure is located after the waterproof membrane, as illustrated in the following figure.

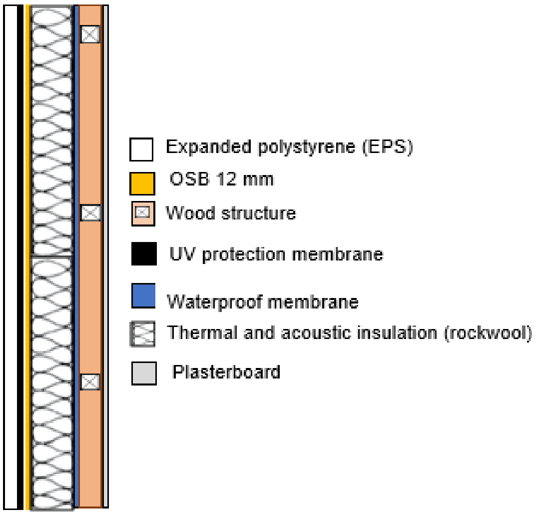


Figure 4.7 - Exterior Wall B System Composition

A part of the exterior walls B has also applied Thermowood (see Figure 4.8), operating as a ventilated façade. The Thermowood presents excellent durability and low maintenance costs.

Figure 4.8 - Exterior Wall with Thermowood [76]

For the thermal and acoustic insulation is used rockwool (Figure 4.9). This insulation material is capable of sustaining its initial physical characteristics throughout the life of the building. Moreover, rockwool presents great thermal resistance, performing a meaningful function in the reduction of energy demand.

Figure 4.9 - Insulation Material: Rockwool [78]

Table 4.2 presents the properties of the materials that compose the exterior walls:

Table 4.2 - Constitution of Exterior Walls

Material	e (m)	λ (W/m.K)	ρ(kg/m^3)	C_p (J/kg.K)
Expanded Polystyrene (EPS 100)	0,03 (A) 0,04 (B)	0,037	20	1550
OSB	0,012	0,12	600	1700
Rockwood	0,1	0,04	50	800
Plasterboard	0,013	0,35	750	840
Thermowood	0,032 (B)	0,15	485	1300

, e (m) represents the thickness, λ (W/m.k) the thermal conductivity, ρ (kg/m^3) the density, and C_p the specific heat.

For the Portuguese climate, a traditional wall usually has an insulation thickness that fluctuates between 4 to 8 cm, being the most usual 6 cm. However, as it is lightweight construction, the thickness is more considerable with 10 cm for both walls (A and B).

4.2.1.2. Floor Composition

The floor is in contact with the ground, and it is composed of a concrete base, followed by wood CL4, plastic sleeve, rockwool, OSB, and floating floor (Figure 4.10). The wood CL4 is a type of wood used when there is contact with the ground or water, thus being permanently exposed to moisture.

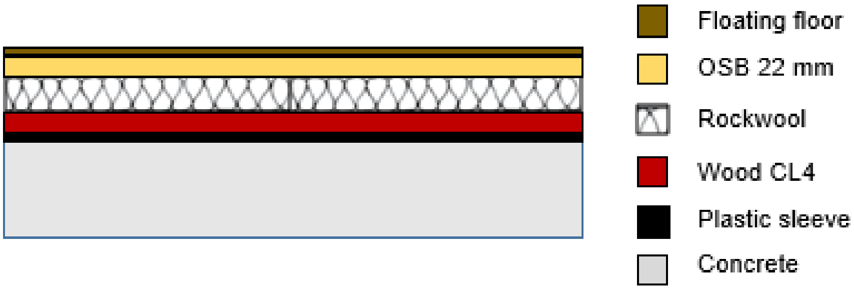


Figure 4.10 - Floor Composition

Table 4.3 presents the properties of the materials.

Table 4.3 - Constitution of the Floor

Material	e (m)	λ (W/m.K)	ρ(kg/m³)	C_p (J/kg.K)
Concrete	0,2	2	2400	940
Wood CL4	0,028	0,23	800	1500
Rockwood	0,05	0,045	25	800
OSB	0,022	0,12	600	1700
Floating floor	0,007	0,13	400	1300

4.2.1.3 Roof Description

As previously mentioned, the roof is flat and not accessible. Its constitution has as first layer pebbles, followed by a PVC waterproof, OSB 22 mm, ventilation zone, breathable protective, rockwool, a vapour barrier, and as interior finish a suspended ceiling system. In addition to the mentioned, the roof also has a parapet. Its composition is represented in Figure 4.11.

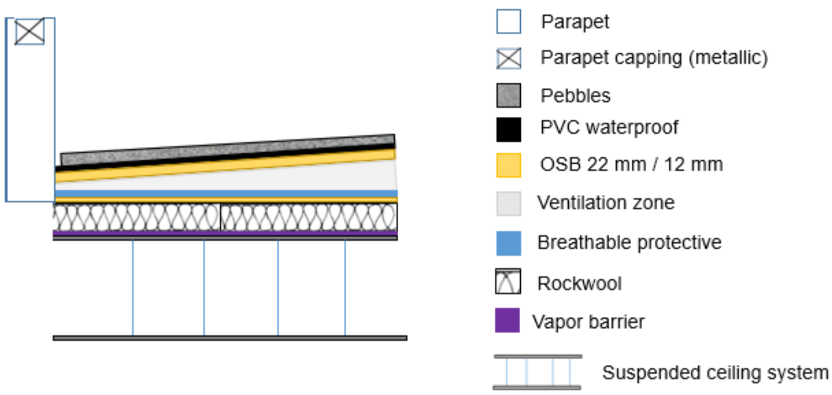


Figure 4.11 - Roof Composition

Table 4.4 presents the properties of the roof materials.

Table 4.4 - Constitution of the Roof

Material	e (m)	λ (W/m.K)	ρ(kg/m^3)	C_p (J/kg.K)
OSB	0,022	0,12	600	1700
Rockwood	0,2	0,04	70	800
Ceiling system	0,02	0,13	400	1300

As mentioned before, extremely thin materials are not considered for thermal resistance or heat capacity, so not all the materials have their properties presented.

4.2.1.4. Glazing, Windows and Shading Devices

The building has a large glass area, as is illustrated in Figure 4.12. The windows have the following arrangement: three in the living room, one in the kitchen, one in each of the bedrooms, and two in the suite.

Figure 4.12 – "Sky House" [76]

All the windows are double-pane, with 5 mm and 5 mm, plus a 6 mm air blade space and metal frame with thermal break. The shading devices are opaque interior curtains (Figure 4.13).

Figure 4.13 - Shading Device: Opaque Interior Curtains

Therefore, the thermal transmission coefficient has a value of 3,9 W/ (m^2.ºC) and a solar factor of 0,46.

The indicator values for the characteristics of the opaque interior curtains are represented in Table 4.5 and have as source ASHRAE (2001).

Table 4.5 - Characteristics of Opaque Interior Curtains

	Solar Transmittance	Solar Reflectance	Visible Transmittance
Opaque Interior Curtains	0	0,65	0,35

4.3. THERMO-ENERGETIC SIMULATIONS OF SKY HOUSE

4.3.1. SIMULATION 0: BASE PROJECT

The basic project information is described in Subchapter 4.2.1, and the inputs in Chapter 3. The inputs, along with the climatic file, allows the simulation to run. As for the results, the user can choose the ones that are more appropriate to the necessary conclusions.

In this case, it was decided to analyse only the operative temperature – a simplified measure of human thermal comfort derived from air temperature, mean radiant temperature, and airspeed, for the period of simulation of one year.

Since it is a T3, it is admitted as standard n+1 occupants: four residents. The operating hours of the house were defined for all days of the week by from 7 PM until 8 AM 100% occupation, and from 8 AM until 7 PM 0% of occupation (this example is presented in 3.5.3.2: Schedule: Compact). As the number of residents described here, the operating hours of the house are considered a general rule applied in all simulations, except those where the contrary is referred.

- Simulation 0.1: Base Project Uninhabited

For the first simulation was considered the uninhabited base project during the period mentioned previously – 1 year.

- Simulation 0.2: Base Project with Standard Occupation and Operating Hours

In this simulation, the only modification performance was the change of the occupation of the house from 0 to the standard occupation considered – four people, with the operating hours admitted as standard.

- Simulation 0.3: Base Project with Non-Standard Occupation/Operating Hours

  Simulation 0.3.1:

In this simulation, the number of residents remains the standard (4 people), but the operating hours are modified: for all days of the week by 7 PM until 8 AM, the occupation is 100%, and from 8 AM until 7 PM, the occupation is 50%.

  Simulation 0.3.2:

This simulation was considered a different occupation: instead of four residents, it was admitted that the number of occupants would double. So, there would be eight occupants. The operating hours remain the standards.

Simulation 0.3.3:

In the fifth simulation performing and following the previous logic, the number of residents is eight people , and the operating hours are also modified. So, it is considered that at least four residents are always in the house.

Table 4.6 presents a summary of the simulations of the base project – Simulations 0.

Table 4.6 - Simulations 0: Base Project - Summary

Simulation	Number of residents	Operating Hours
0.1	0	-
0.2	4	7 PM until 8 PM 100% occupation 8 AM until 7 PM 0% occupation
0.3.1	4	7 PM until 8 PM 100% occupation 8 AM until 7 PM 50% occupation
0.3.2	8	7 PM until 8 PM 100% occupation 8 AM until 7 PM 0% occupation
0.3.3	8	7 PM until 8 PM 100% occupation 8 AM until 7 PM 50% occupation

4.3.2. Simulation 1: Building Optimization with Passive Solutions

As introduced in Chapter 2, a multitude of passive solutions can be implemented in buildings, performing important improvements in the hygrothermal behaviour of the building. Thus, the passive measures proposed for the Sky House will be presented, with the primary purpose of obtaining an energetically autonomous building. Consequently, and to understand the impact of the different interventions proposed, diverse simulations were executed. The output analysed is the operative temperature since implementing these solutions aims to provide comfortable temperatures by minimizing solar gains in the summer and heat loss in winter.

- Simulation 1.1: Sun Control and Protection Device – Exterior Blinds

In the base project, the sun control is an interior protection (opaque interior curtains). However, the external shading devices are more efficient and adequate to reduce the solar gains since the glazing area is high. In this way, the interior protection was replaced by an exterior, more specifically, by exterior blinds, on horizontal wooden slats (Figure 4.14).

Figure 4.14 - Example of Exterior Blinds [79]

The exterior blinds can be composed of other materials, but it was considered that the choice of the wood fits in the building envelope. The width of the stripes is 3,0 cm, the distance between strips 2,5 cm, and the thickness 3 mm. The heat transfer coefficient of the wood in use is 0,9 W/m. °C.

- Simulation 1.2: Triple Glazing Window

The windows are double pane in the base project, with a 6 mm air blade space and metal frames. The proposed alteration would be the replacement of these windows by triple glazing windows. For this type of window, the value utilised for the u-factor is 0,13 W/ (m^2.ºC), and the SHGC (Solar Heat Gain Coefficient) is 0,25 [80].

- Simulation 1.3: Exterior Blinds and Triple Glazing Window

In this simulation, the exterior protection and the triple glazing window are used simultaneously.

- Simulation 1.4: Increase of Insulation Thickness of Exterior Walls and Roof

In the previous simulations, the performance of the non-opaque building envelope was improved through the implementation of exterior blinds and triple glazing windows. Subsequently, it is necessary to develop the thermal behaviour of the opaque envelope without modifying the character of the light-frame construction. Thus, the only correction performed is the increase of the thickness of insulation.

As in the construction are used elements such as wooden structures, the thickness increase must be plausible, adopting 20% for walls and roof. In this way, the rockwool thickness in walls goes from 10 to 12 cm and 20 to 24 cm in the roof.

- Simulation 1.5: Increase of Insulation Thickness of Exterior Walls, Roof and Floor

In another simulation was also increase the insulation by 20% on the floor, beyond the walls and roof — the thickness of the insulation increase from 5 to 6 cm.

- Simulation 1.6: Exterior Blinds, Triple Glazing Window and Thickness Increase of Exterior Walls and Roof

This simulation incorporates the more effective passive interventions to improve the building´s thermal performance: exterior blinds and triple glazing windows for the non – opaque building envelope and the thickness increase for exterior walls and roof for the opaque building envelope.

Table 4.7 presents a summary of the simulations of the base project with the implementation of passive solutions– Simulations 1.

Table 4.7 - Simulations 1: Building Optimization with Passive Solutions - Summary

Simulation	Passive Solution(s)
1.1	Exterior Blind
1.2	Triple Glazing Window
1.3	Exterior Blind and Triple Glazing Window
1.4	Increase of Insulation Thickness of Exterior Walls and Roof (in 20%)
1.5	Increase of Insulation Thickness of Exterior Walls, Roof and Floor (in 20%)
1.6	Exterior Blinds, Triple Glazing Window and Thickness Increase of Exterior Walls and Roof (in 20%)

4.3.3. Simulation 2: Building Optimization with Active Solutions

The starting point for these simulations is the building envelope optimized – Simulation 1.6. The active solution implemented is a Solar PV system with a battery for energy storage.

The solar panels will be located on the roof, and it is admitted four percentages of roof area occupation:

- 100%, which corresponds to 145 m^2 of photovoltaic panels;
- 75%, which corresponds to 109 m^2 of photovoltaic panels;
- 50%, which corresponds to 73 m^2 of photovoltaic panels;
- 25%, which corresponds to 36 m^2 of photovoltaic panels.

For each of these areas of photovoltaic panels, a simulation was displayed for a battery with unlimited storage capacity and also for a battery with a storage capacity of 16,64 kWh [81].

The efficiency value adopted for the photovoltaic cells was 20%; however, high-quality panels currently already reach higher values.

The simulation named 2.1 is the simulation for the occupation of 25% of the roof´s area and battery with unlimited storage capacity, followed by simulation 2.2 for the same percentage of the occupation, but in this time with the battery with limited storage capacity indicated previously. The designation of the simulations follows this logic until reach the last simulation – 2.8, percentage of roof´s occupation of 100% and battery with limited storage capacity.

The output considered in these simulations are Zone Ideal Loads Zone Total Heating Rate, Zone Ideal Loads Zone Total Cooling Rate, and Generator Produced DC Electricity Rate. The first two outputs are used to obtain the amount of energy needed to be produced by the PV Solar System for the operative temperature to remain in the ideal range. The last output mentioned is necessary to determine if the area of panels considered, allowing with the battery, is sufficient to satisfy the needs.

Thermal comfort depends on different aspects, such as air temperature, humidity, movement of air, thermal radiation - environmental factors, and physical activity and clothing - personal factors). So, does not exists a "one size fits all" recipe for thermal comfort [82]. In this way, the definition of the range for operative temperature that provides comfort for the residents is based on ASHRAE 55 (2010). The ASHRAE 55 standard defines the different combinations of indoor thermal environmental, and personal factors that provide comfortable thermal conditions for the residents. Figure 4.15 presents the parameters of this standard for thermal comfort [83]. This figure shows, for a metabolic rate of 1.1 met, the operative temperature range that provides comfort fluctuates between approximately 20 and 24 °C. However, the ideal range considered for the analysis described previously is a little more extensive: 18 to 24 °C .

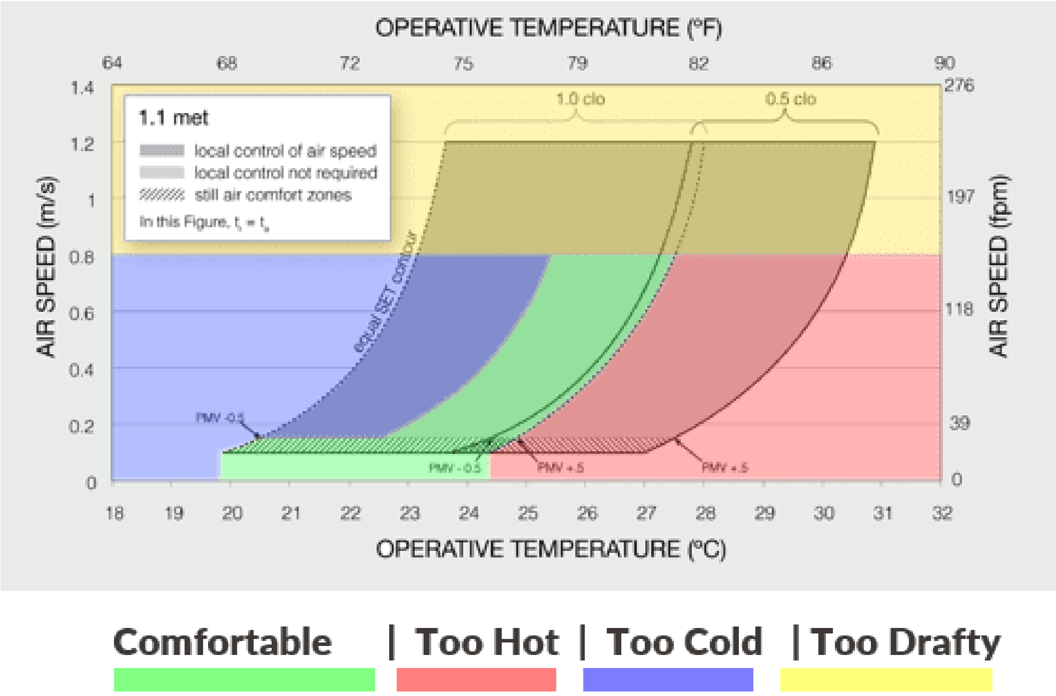


Figure 4.15 - ASHRAE 55 parameters for Thermal Comfort [83]

4.4. SYNTHESIS OF THE THERMO-ENERGETIC SIMULATIONS OF SKY HOUSE

The following figures are a synthesis of the simulations executed.

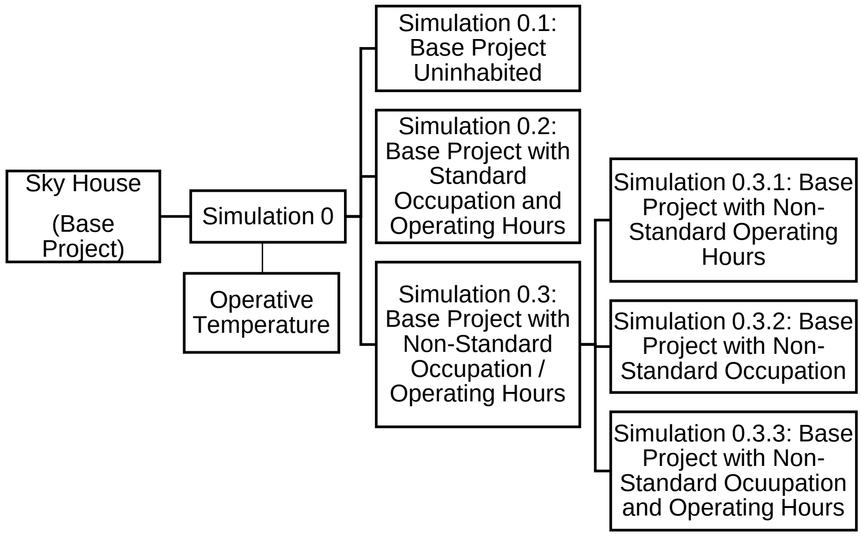


Figure 4.16 - Simulation 0: Base Project

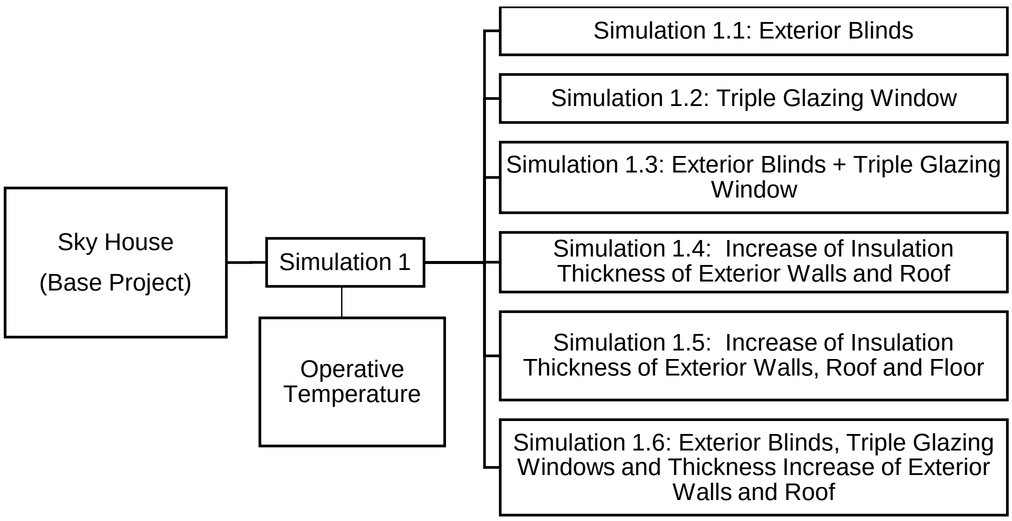


Figure 4.17 - Simulation 1: Building Optimization with Active Solutions

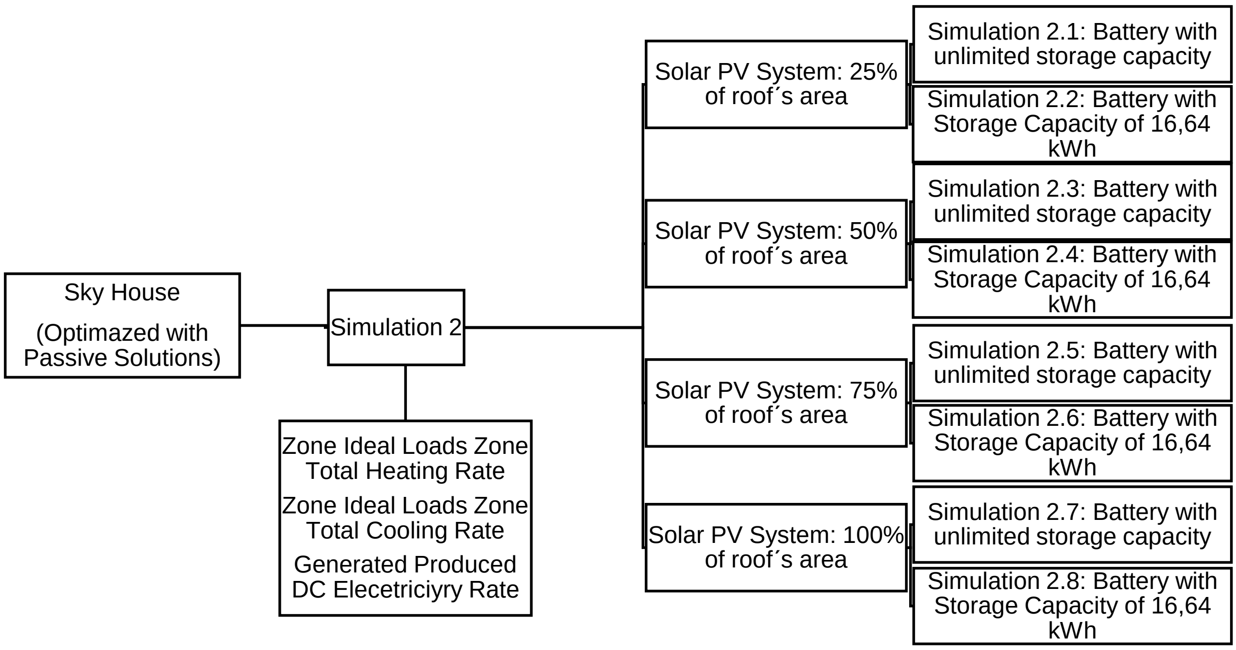


Figure 4.18 - Simulation 2: Building Optimization with Passive and Active Solutions

5
RESULTS AND DISCUSSION

5.1. INTRODUCTION

This chapter presents the results of various simulation scenarios described previously to achieve the best solution for energy autonomy of the residential.

5.2. RESULTS OF SIMULATION 0: BASE PROJECT

As mentioned before, for the base project, it was decided to analyse the operative temperature.

5.2.1. RESULTS OF SIMULATION 0.1: BASE PROJECT UNINHABITED

The following graphic (Figure 5.1) represents the operative temperature for the base project during one year of simulation, considering that the house remains uninhabited during this time interval.

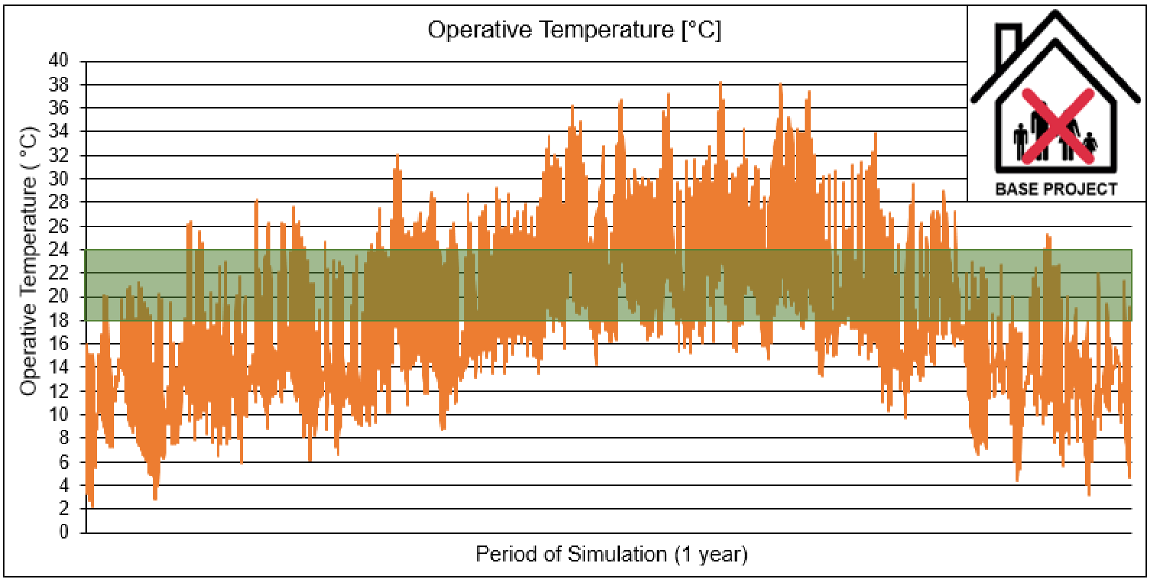


Figure 5.1 - Operative Temperature for Uninhabited Base Project

For this simulation, it is observed that the maximum and minimum temperatures are notably distant from the intended values, with the maximum temperature of 38,17 °C, and the minimum of 2,20 °C. In the summer, the large area of glazing, which in this simulation only has interior protection, results in excessive solar gains, reaching extremely high temperatures inside the house. In the winter, low temperatures can be sustained by the lack of solar gains and internal gains since the house remains unoccupied throughout the simulation.

5.2.2. Results of Simulation 0.2: Base Project with Standard Occupation and Operating Hours

In this simulation (Figure 5.2), it is expected that the maximum and minimum operative temperatures increase, due to the internal gains, generated by the occupation.

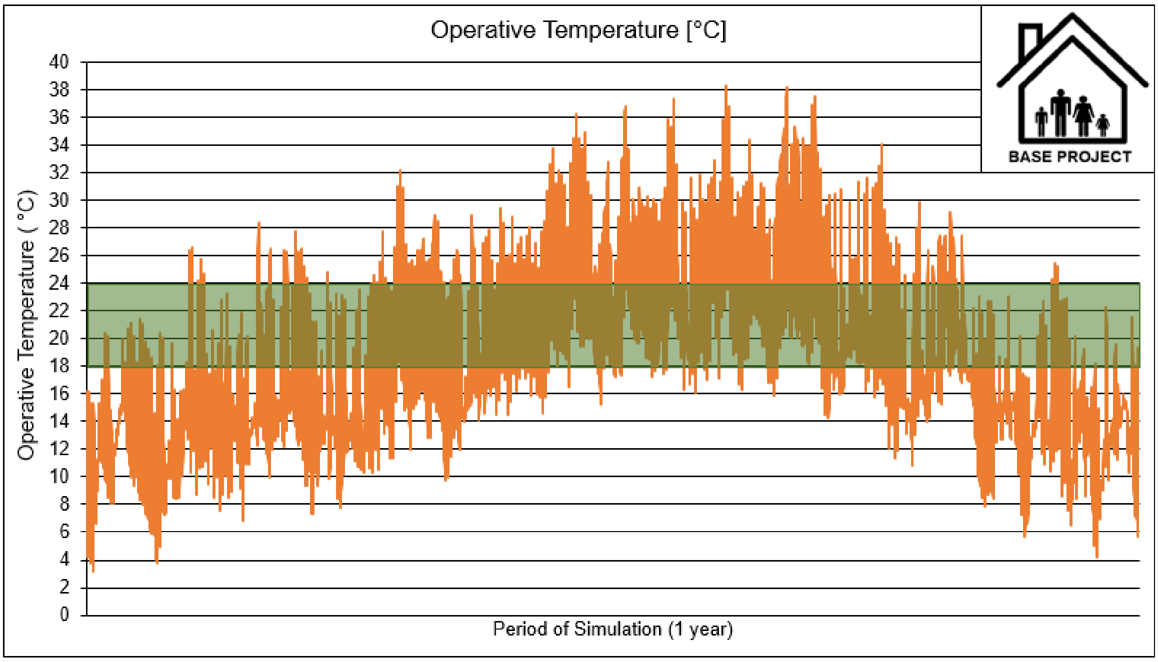


Figure 5.2 - Operative Temperature of Base Project with Standard Occupation and Operating Hours

As expected, there is an increase in the operative temperatures, even if very small: in the maximum temperature, it is barely perceptible, being less than 0,1 °C (increasing from 38,17 °C to 38,24 °C). The increase is a little more significant in the minimum operative temperature, changing from 2,20 °C to 3,21 °C.

In conclusion, it can be assumed that the internal gains generated through the occupation mainly influence the minimum temperatures, with a reduced impact.

5.2.3. Results of Simulation 0.3: Base Project with Non-Standard Occupation / Operating Hours

- Results of Simulation 0.3.1: Base Project with Non-Standard Operating Hours

In this simulation, and despite keeping the standard number of residents (4), the operating hours increased, keeping the house occupied at all hours by at least two residents. The operative temperatures for the year of simulation are represented in Figure 5.3.

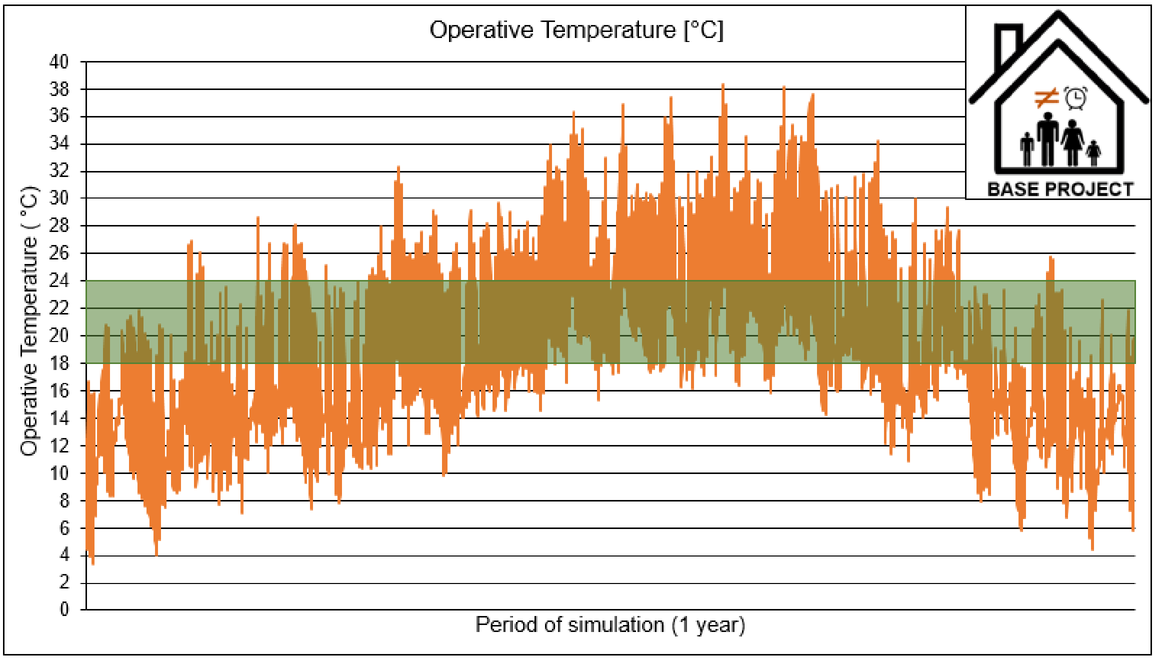


Figure 5.3 - Operative Temperature of Base Project with Non-Standard Operating Hours

By analysing Figure 5.3, the maximum operative temperature is 38,31 °C and the minimum 3,42°C. So, it is concluded that always having residents in the house increases the operative temperatures due to increased internal gains.

- Results of Simulation 0.3.2: Base Project with Non-Standard Occupation

In the fourth simulation run, the number of occupants double to eight residents. As previously, and for the same reasons stated, is expected a general increase in the temperatures.

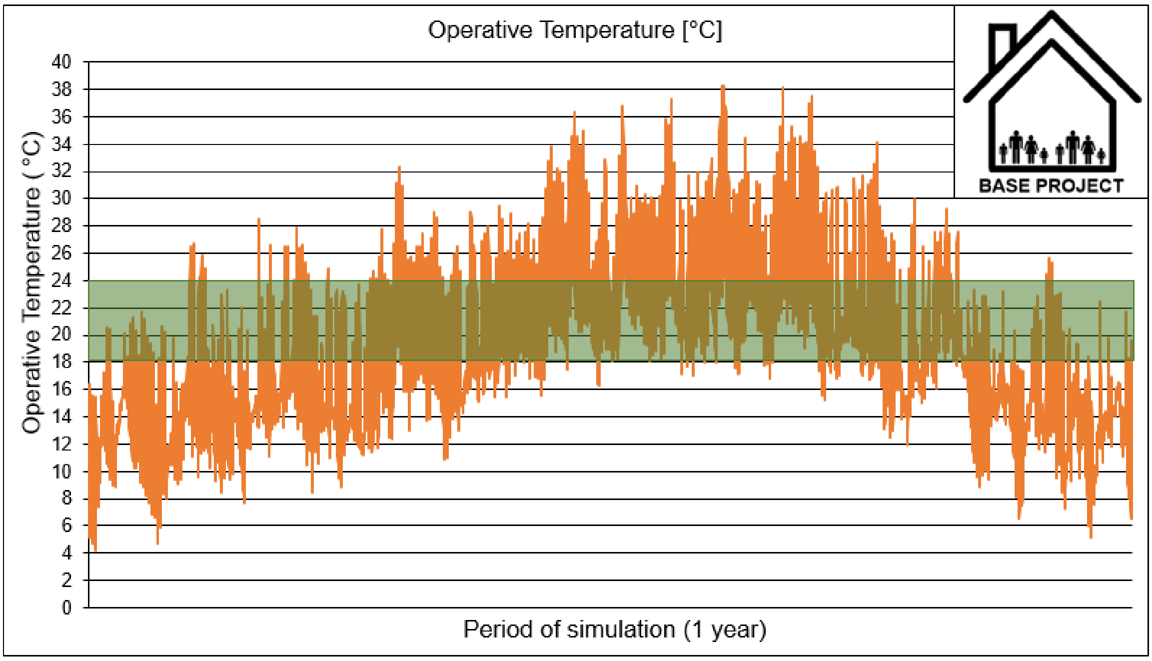


Figure 5.4 - Operative Temperature of Base Project with Non-Standard Occupation

As predicted and verified in Figure 5.4, there was an increase in the temperatures. The maximum operative temperature is 38,33 °C, and the minimum 4,16 °C, which constitute an increase of 0,16 °C for the maxim temperature, and 0,95 °C for the minimum (comparing with the occupation of 4 residents).

Thus, it can be concluded that despite the number of residents being double (from 4 to 8), the maximum operative temperatures remain almost equal, being noticed most accentuated change in the minimums. Even so, and although the internal gains from the occupation influence direct in the increase of operative temperature, the impact is not of a high order of significance.

- Results of Simulation 0.3.3: Base Project with Non-Standard Occupation and Operating Hours

The last simulation performed before implementing solutions that optimize the building from the energy point of view is the occupation increase (4 to 8) and the operating hours. Due to the inferences from the previous scenarios, it is presumed an increase in the temperatures.

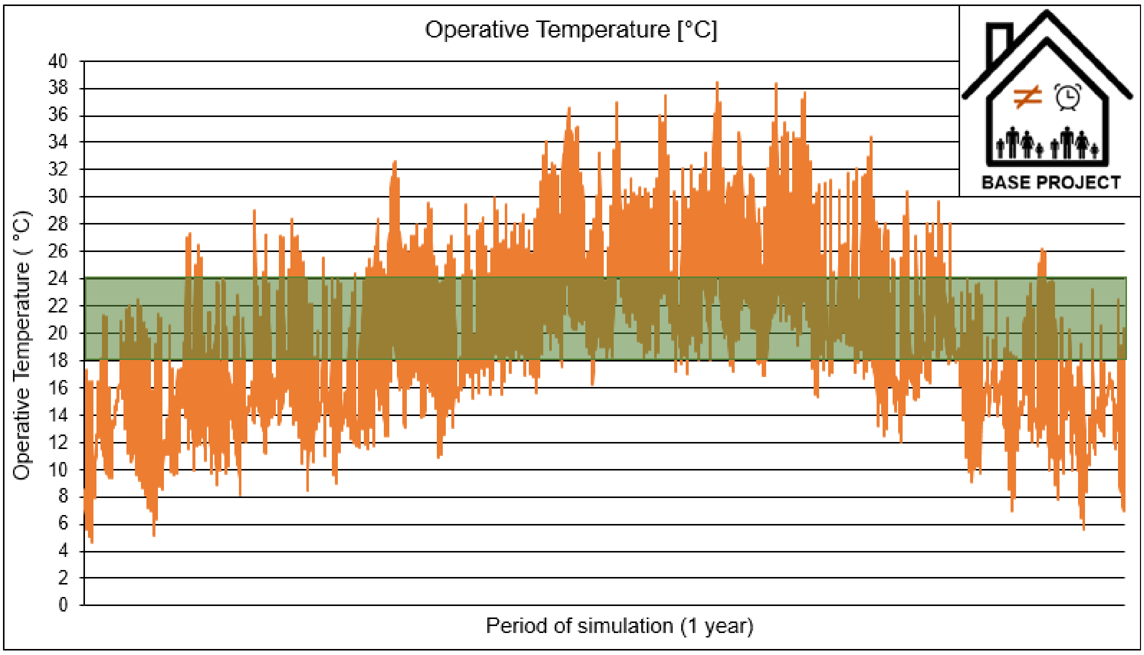


Figure 5.5 - Operative Temperature of Base Project with Non-Standard Occupation and Operating Hours

As expected, this simulation is the one that produces the highest operative temperatures values of all simulations made for the base project since the internal gains are superior for this scenario. Thus, the maximum operative temperature is 38,47 °C and the minimum 4,60 °C.

5.2.4. Synthesis Simulation 0: Base Project

Table 5.1 contains a summary of the results of the six simulations performed for the base project.

Table 5.1 - Synthesis of Simulation 0 Results

Simulation	Occupation (number of residents)	Operating Hours (Schedule)	Maximum Operative Temperature (ºC)	Minimum Operative Temperature (ºC)
0.1 	-	-	38,17	2,20
0.2 	4	7 PM until 8 AM 100% 8 AM until 7 PM 0%	38,24	3,21
0.3.1 	4	7 PM until 8 AM 100% 8 AM until 7 PM 50%	38,31	3,24
0.3.2 	8	7 PM until 8 AM 100% 8 AM until 7 PM 0%	38,33	4,16
0.3.3 	8	7 PM until 8 AM 100% 8 AM until 7 PM 50%	38,47	4,60

Simulation 0.2 is the starting point for energy optimization with passive solutions since this simulation contains the number of residents and operating hours considered conventional. From this simulation, all

the implemented solutions have as objective place the operative temperature in the band between 18 – 24 °C. It can also be concluded that the value of operative temperatures is very far from the desired range.

5.3. RESULTS OF SIMULATION 1: BUILDING OPTIMIZATION WITH PASSIVE SOLUTIONS

As seen and discussed previously, the operative temperatures sensed inside the residence are considerably distant from providing hygrothermal comfort to the occupants. For that reasons, it was necessary to implement some passive solutions. The results achieved are presented subsequently.

5.3.1. RESULT OF SIMULATION 1.1: SUN CONTROL AND PROTECTION DEVICE – EXTERIOR BLINDS

The following image presents the result of Simulation 1.1: operative temperatures of the building, with the implementation of exterior blinds as sun control device instead of the interior curtains of the base project.

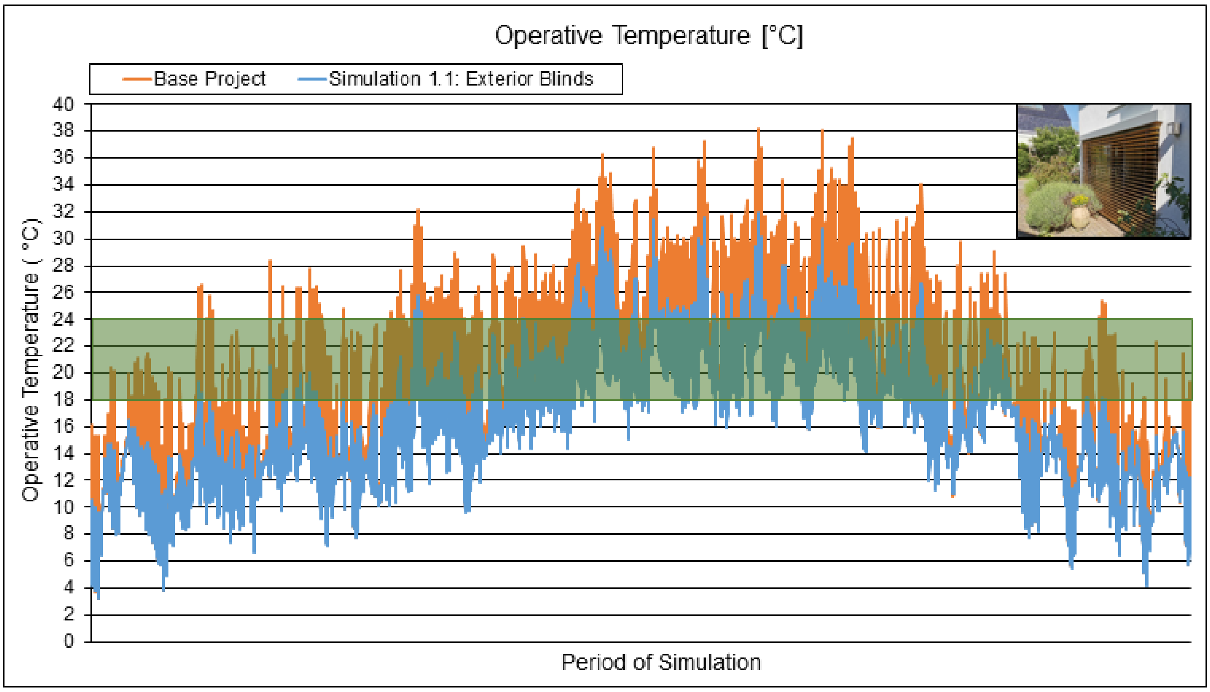


Figure 5.6 - Operative Temperature for Base Project with Exterior Blinds

This intervention (Figure 5.6) performs satisfying results, accomplishing the purpose of its implementation, decreasing the maximum temperatures. Thus, the maximum temperature decrease from 38,24 °C to 31,90 °C. The minimum temperatures remain approximately constant (minimum temperature is 3,20 °C).

5.3.2. RESULTS OF SIMULATION 1.2: TRIPLE GLAZING WINDOW

In this simulation, the double pane window is replaced by a triple glazing window. The next image shows the results.

In this simulation, and the previous one, the passive solutions are added individually to the base project in order to the formed conclusions not being influenced by another solution analysed before.

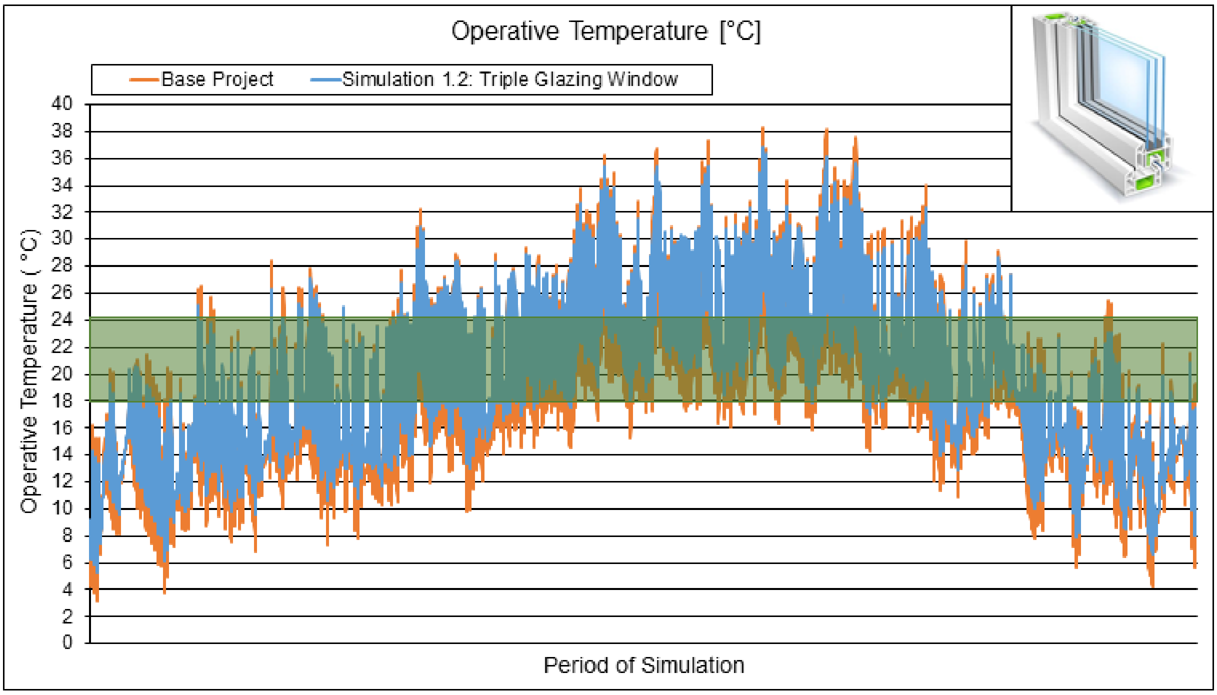


Figure 5.7 - Operative Temperature for Base Project with Triple Glazing Window

As observed in Figure 5.7, and comparing to the base project, the maximum operative temperature decrease from 38,24 °C to 36,89 °C and the minimum operative temperature increase from 3,21 °C to 5,26 °C. Thus, the triple glazing panel is an added value in the energy optimization of the house, decreasing the solar gains in the summer and the heat losses through the glass.

5.3.3. Result of Simulation 1.3: Exterior Blinds and Triple Glazing Window

Like how both exterior blinds and triple glazing window present satisfactory results, leaving the approach of the temperature for the ideal range of values, in this simulation, the exterior protection and the triple glazing window are used simultaneously. Thus, it is expected that the maximum temperatures decrease by the restriction of the solar gains and the control of the gains by conduction. The behaviour of the minimum temperatures is more uncertain because the exterior blind does not allow the heat by solar radiation, and at the same time, the glass decreases the heat losses, performing better insulation.

The results of the simulation are presented in Figure 5.8.

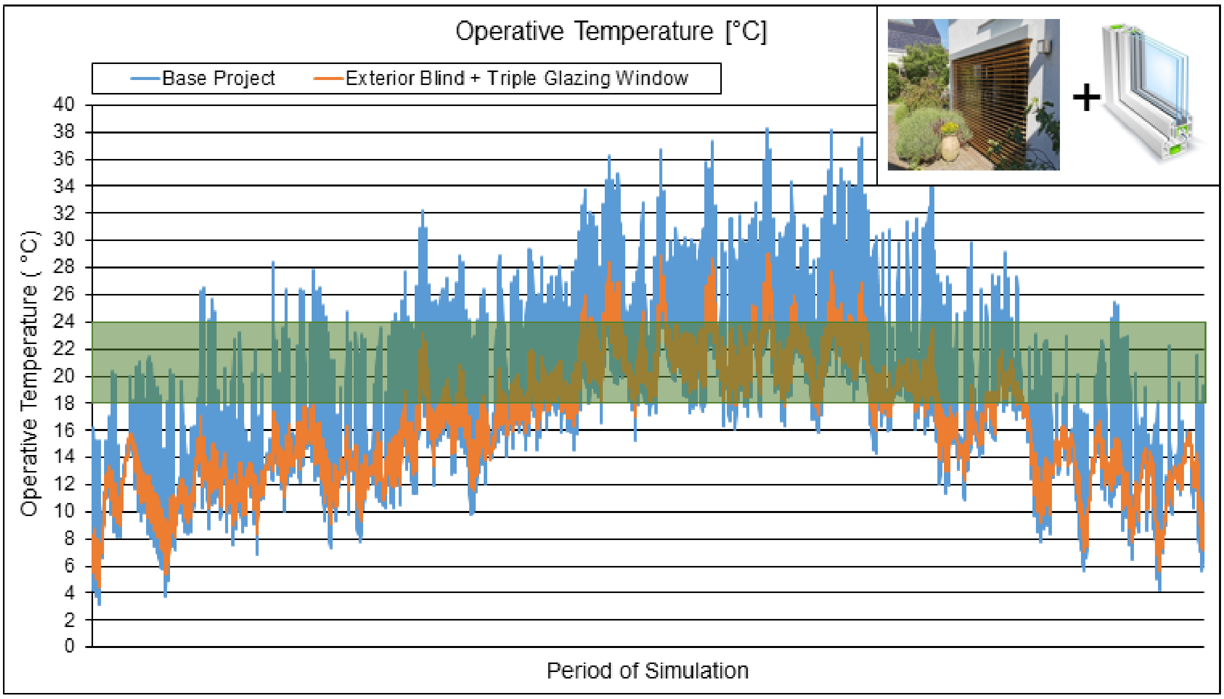


Figure 5.8 - Operative Temperature for Base Project with Exterior Blinds and Triple Glazing Window

It is observed that the maximum operative temperatures decrease, being the highest value of 28,42 °C. Compared the minimum operative temperature of the base project or just the implementation of exterior blinds, there is an increase, reaching 3,84 °C.

For the minimum temperatures, it is more beneficial not to use exterior blinds; however, it is necessary a more general analysis. Therefore, the use of exterior blinds, simultaneously with triple glazing window, constitute a significant improvement in the building thermal behaviour, especially for the higher temperatures (that decrease from 38,24 °C to 28,42 °C, almost 10 °C).

5.3.4. Result of Simulation 1.4: Increase of Insulation Thickness of Exterior Walls and Roof

In this simulation, the insulation thickness of exterior walls and roof is increased by 20%. Figure 5.9 presents the results.

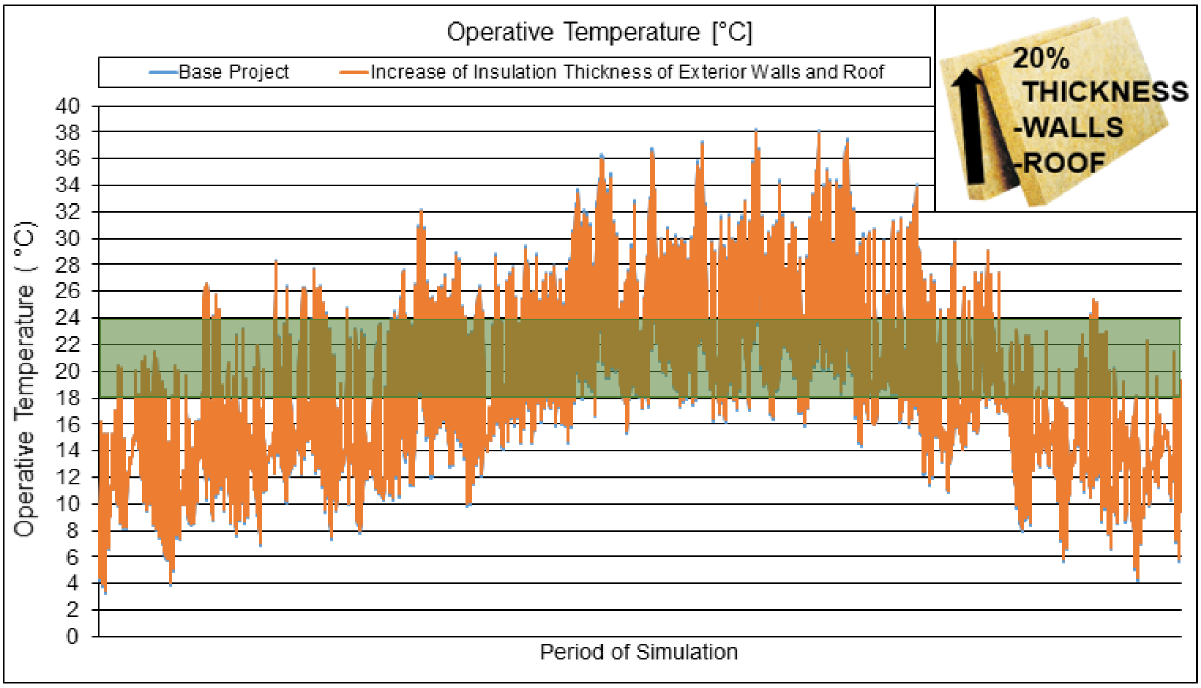


Figure 5.9 - Operative Temperature for Base Project with the Increase of Thickness Insulation for Exterior Walls and Roof

The difference in the operative temperature for the base project and this scenario is almost imperceptible. However, it has to be considered that the insulation increase adopted a moderate value for reasons already mentioned. Thus, the maximum temperatures go from 38,24 °C in the base project to 38°C, and the minimum temperatures increase from 3,21 °C to 3,46 °C. In this simulation are considered double-paned windows and interior curtain as shading device, which allied to the large area of glazing, results in significant gains and losses of energy through this element. Thus, the measure of increase the insulation is conditioned, presenting a minor influence on the operative temperatures.

5.3.5. Result of Simulation 1.5: Increase of Insulation Thickness of Exterior Walls, Roof and Floor

For this simulation was also increased the roof's insulation by 20%, beyond the walls and roof.

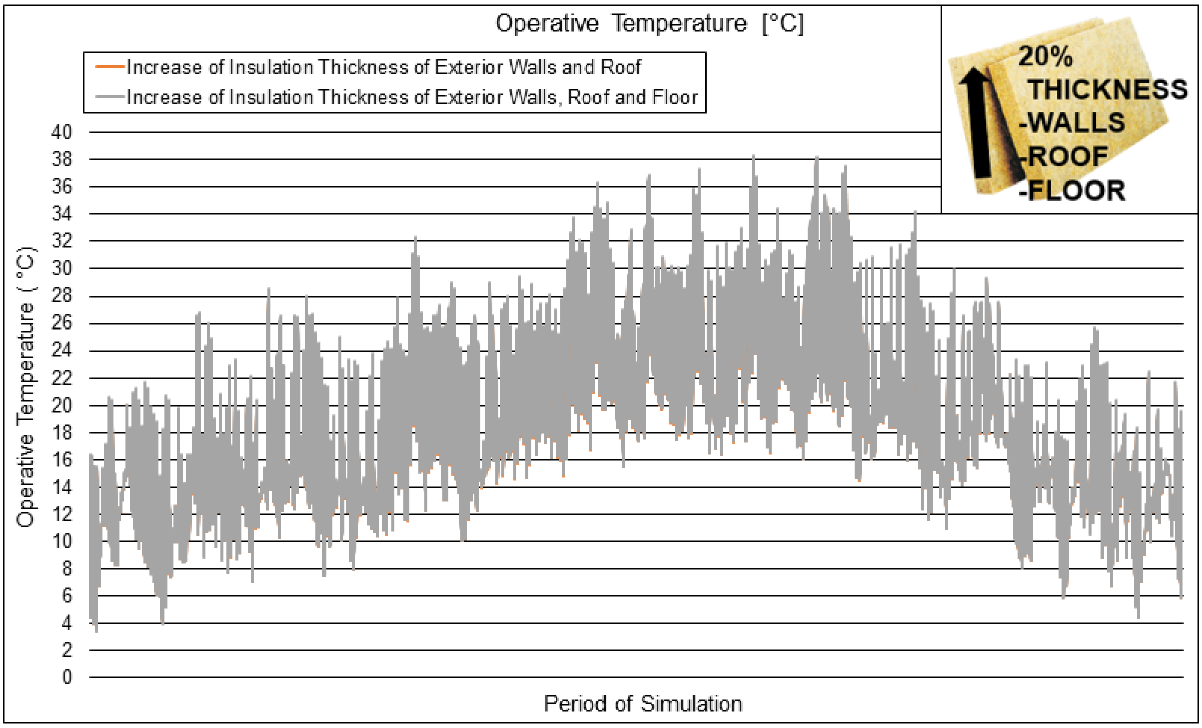


Figure 5.10 - Operative Temperature for Base Project with the Increase of Thickness Insulation for Exterior Walls, Roof and Floor

Although the differences between the two graphics presented above are almost undetectable, the results reveal that the maximum operative temperature increase – from 38 ºC to 38,33 ºC. The minimum temperature remains almost equal (an increase of 0,03 ºC). In this way, this intervention does not become manifest useful.

5.3.6. Result of Simulation 1.6: Exterior Blinds, Triple Glazing Window and Increase Of Insulation Thickness of Exterior Walls and Roof

The last simulation executed for the passive solutions includes the adjustments considerer beneficial for the energetic optimization of the building: exterior blinds, triple glazing window and increase of insulation thickness for exterior walls and roof. Therefore, the results of the simulation are represented in Figure 5.11.

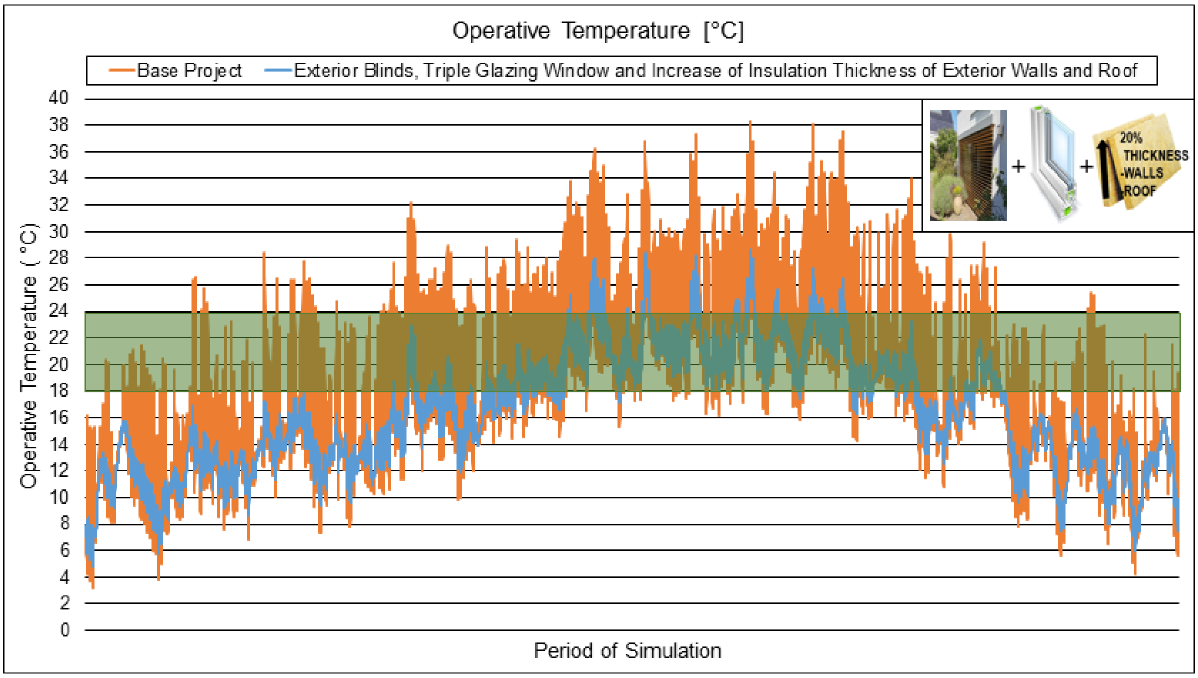


Figure 5.11 - Operative Temperature for Base Project with Exterior Blinds, Triple Glazing Window and the Increase of Thickness Insulation for Exterior Walls and Roof

With the implementation of these passive solutions, is observed a general decrease of the higher temperatures. However, although rise on a small scale, the lower temperatures are limited influenced by these solutions. Thus, after applying these solutions, the highest operative temperature is 28,61 ºC and the lowest 4,76 ºC.

5.3.7. Synthesis Simulation 1: Building Optimization with Passive Solutions

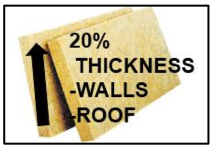
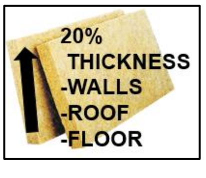
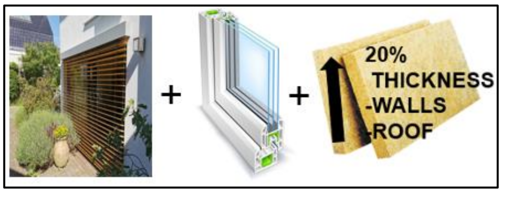
By analysing the simulations' results, it can be concluded that the passive solutions can effectively benefit the indoor comfort conditions, influencing mostly the higher temperatures.

The shading element (exterior blinds) minimize the extrasolar loads, and better insulation (thorough the triple glazing window and the increase of the insulation thickness) reduce the heat transfer from outside to inside, maintaining a cooler interior temperature.

Notwithstanding that, it is also necessary to use a renewable energy source to maintain the comfortable temperatures not yet reached. Thus, the PV Solar System will be fundamental to lowering the higher temperatures and raising the lower temperatures, which were limited affected by passive solutions.

Table 5.2 contains a review of the simulation performed, and Figure 5. 12 displays the temperature change by implementing the passive solutions.

Table 5.2 - Synthesis of Simulation 1- Passive Solutions Results

Simulation	Passive Solution	Maximum Operative Temperature (ºC)	Minimum Operative Temperature (ºC)
0.2 	-	38,24	3,21
1.1 	Exterior Blinds	31,90	3,20
1.2 	Triple Glazing Window	36,89	5,26
1.3 	Exterior Blinds and Triple Glazing Window	28,42	3,84
1.4 	Increase of Insulation Thickness of Exterior Walls and Roof	38	3,46
1.5 	Increase of Insulation Thickness of Exterior Walls, Roof and Floor	38,33	3,46
1.6 	Exterior Blinds, Triple Glazing Window and Increase of Insulation Thickness of Exterior Walls and Roof	28,61	4,76

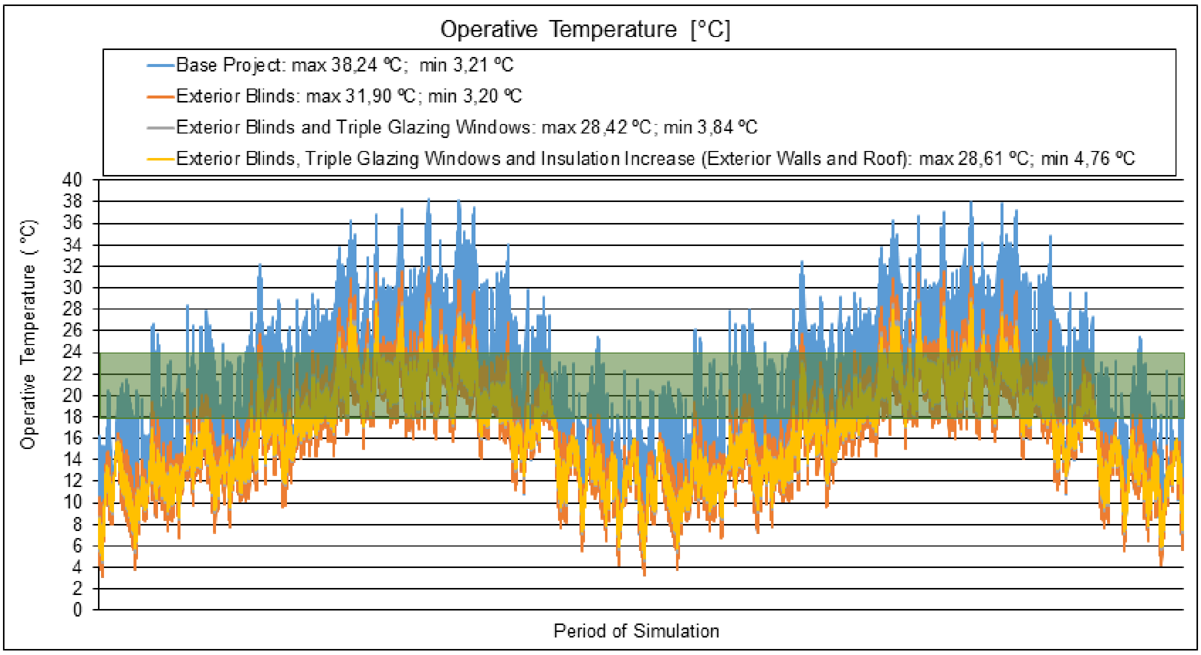


Figure 5. 12 - Operative Temperatures for the Passive Solutions

5.4. Results of Simulation 2: Building Optimization with Active Solutions

For the simulations performed with the PV Solar System, the outputs analysed are the Heating and Cooling Rate, plus the Generated Electricity Rate. For the house to be energetically autonomous, and the temperature range set between 18 – 24 ºC, it is necessary that the sum of the heating and cooling needs are less or equal to the energy produced or storage by the photovoltaic panels. The analysis of the energy needed, produced/stored, is done hourly.

5.4.1. Heating and Cooling Rate – Energy Needed

The heating and cooling energy needed to the range of operative temperature stand between the 18-24 ºC (for the base project optimized with the passive solutions – Simulation 1.6) is presented in Table 5.3, through the medium values for each month, summer, winter and year of simulation.

Table 5.3 - Energy Needed for Cooling and Heating - Monthly and Annual Average

<table>
<tr><th rowspan="3">Month</th><th colspan="7">Energy Needed for Heating and Cooling</th></tr>
<tr><th colspan="2">Monthly Average</th><th colspan="2">Summer Average (June, July, August)</th><th colspan="2">Winter Average (December, January and February)</th><th>Annual Average</th></tr>
<tr><th>kW</th><th>kWh</th><th>kW</th><th>kWh</th><th>kW</th><th>kWh</th><th>kWh</th></tr>
<tr><td>January</td><td>1307,6</td><td>1,8</td><td>-</td><td>-</td><td rowspan="2">3735,0</td><td rowspan="2">1,7</td><td rowspan="12">1,9</td></tr>
<tr><td>February</td><td>1211,6</td><td>1,8</td><td>-</td><td>-</td></tr>
<tr><td>March</td><td>1536,0</td><td>2,1</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>April</td><td>1716,6</td><td>2,4</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>May</td><td>1944,1</td><td>2,6</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>June</td><td>2336,9</td><td>3,2</td><td rowspan="3">6701,8</td><td rowspan="3">3,0</td><td>-</td><td>-</td></tr>
<tr><td>July</td><td>2453,7</td><td>3,3</td><td>-</td><td>-</td></tr>
<tr><td>August</td><td>1911,2</td><td>2,6</td><td>-</td><td>-</td></tr>
<tr><td>September</td><td>130,4</td><td>0,2</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>October</td><td>360,8</td><td>0,5</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>November</td><td>891,2</td><td>1,2</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>December</td><td>1215,8</td><td>1,6</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

5.4.2. Generated Electricity Rate – Energy Produced / Stored

Since the output data list is extensive, only the conclusions of each simulation will be presented: the percentage of time in which the dimensioned solar system cannot meet the energy needs (see Table 5.4).

Table 5.4 - Unmet Energy Demand

Roof´s Area of PV Solar System	Battery	Unment Energy Demand: % of total time of simulation
25% (36 m²)	Battery with Unlimited Storage Capacity	44,7
	Battery with Storage Capacity of 16,64 kWh	55
50 (73 m²)	Battery with Unlimited Storage Capacity	2,85
	Battery with Storage Capacity of 16,64 kWh	3,49
75 (109 m²)	Battery with Unlimited Storage Capacity	0,41
	Battery with Storage Capacity of 16,64 kWh	0,49
100 (145 m²)	Battery with Unlimited Storage Capacity	0,1
	Battery with Storage Capacity of 16,64 kWh	0,1

Interpreting the simulation results, it is concluded that the Sky House, with the proposed interventions, becomes energetically autonomous (for the occupation and operating hours standard considered) when photovoltaic panels occupy 100% of the roof area. The energy demand is unmet for 0,1% of the time (9 hours), corresponding to the first nine hours of the simulation – 24 PM to 08 AM of 1 January.

For the coverage of 75% of the roof´s area by photovoltaic panels, the results are also positive, since the 0,41% of the time of simulations in which energy needs are not satisfied corresponds to only 36 hours, throughout a whole year, and 0,49% to 43 hours. When the photovoltaic panels occupy 50% of the roof´s area, the results are also promising, since the 2,85% of the time the energy needs are unmet corresponds to 250 hours - approximately 10 days, and 3,49% to 13 days.

On the contrary course, for an area of 25% of the roof occupied by the photovoltaic panels, the results shown are not favourable since, for approximately half of the year of simulation, the energy produced/stored cannot meet the energy needed. Thus, for this area of photovoltaic panels, the house cannot be considered energetically autonomous.

5.5. Final Notes

The results for the energy needed are obtained for the standard occupation and operating hours. However, as demonstrated in Simulations 0 for the base project and for other options of occupation and operating hours, the operative temperatures are very similar. Thus, it can be considered that the photovoltaic system produces energy that will correspond to the energy needs (for the areas of PV Solar System: 145, 109 and 73 m^2).

For the simulations performed, the heat gains considered are only obtained from the occupation because it is difficult to predict what kind of equipments will be used. So, it is also essential to consider electrical equipments with low energy consumption and understand the relations between the internal heat loads and the temperatures that influence indoor comfort.

6
CONCLUSIONS

6.1. FINAL CONSIDERATIONS

As a conclusion of this work, it is necessary to reinforce the value of the design project, where the options considered should have as target reduce as much as possible the energy demand of the building. For that, exists numerous options of passive solutions, some of them presented in this work.

The study case – "Sky House", shows that with the implementation of passive solutions, which in this specific case includes the improvement of the thermal behaviour of windows, the use of more efficient shading devices, and the increase of insulation, it is possible to reach better levels of energy efficiency. For complementing the energetic optimization of the building envelope, the integration of a renewable energy source, which in the study case was a solar PV system, allows meeting the energy needs that remain, obtaining an energetic autonomous building, which constitutes the proposed objective.

It is also inevitable to highlight the value of tools, such as EnergyPlus, that allow the numerical study of the energetic behaviour of buildings, which allows not only to analyse the thermal behaviour of the building but also to predict the electrical energy consumption, constituting a way to validate the options made, still in the design phase.

6.1. FUTURE WORKS

As future work, it would be interesting to complement the simulations executed with the study and implementation of electrical equipment (by preference with low energy consumption) and assess if the photovoltaic system still meets the energy consumption for more these energy needs.

In addition, it would also be appealing, implement the suggested solutions on the constructed building and being made actual experimental measures of the studied parameters, so it would be possible to compare both results – the simulated and the measured values, working as a validation of the simulations performed in this work, where all the conclusions formed are based.

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