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Analysis of the Influence of Trombe Walls on the Thermal Behavior of Light Steel Frame Construction

Dissertação de Mestrado em Eficiência Acústica e Energética para uma Construção Sustentável, orientada pelo Professor Doutor Paulo Fernando Antunes dos Santos e apresentada ao Departamento de Engenharia Civil da Faculdade de Ciências e Tecnologia da Universidade de Coimbra.

Março de 2020

Faculdade de Ciências e Tecnologia da Universidade de Coimbra
Departamento de Engenharia Civil

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Análise da influência de paredes de Trombe no comportamento térmico de construções com estrutura leve em aço

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Fevereiro de 2020

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RESUMO

Em termos de eficiência energética, o setor da construção tem um grande potencial de melhoria, visto que 40% de toda a energia produzida é consumida por edifícios na Europa, e o setor segue em expansão (EU, 2010). Este grande potencial chama a atenção para estratégias passivas para se alcançar o conforto térmico interior. A energia solar é relevante devido a radiação gratuita que vem do sol, sendo uma alternativa sustentável aos sistemas de aquecimento à base de combustíveis fósseis. A parede de Trombe é um dispositivo solar passivo que pode estar presente na envolvente exterior dos edifícios, para acumular calor solar e auxiliar na ventilação, aquecimento e até arrefecimento dos ambientes interiores. O dispositivo pode reduzir o consumo de energia de um edifício em até 30%. Em relação a sistemas construtivos, a construção leve em aço (LSF) vem atraindo atenção globalmente. Porém, o sistema LSF apresenta alguns desafios, especialmente quanto ao seu comportamento térmico. Estratégias passivas são uma boa alternativa para mitigar estes desafios. Assim, este trabalho tem o objetivo de estudar os impactos de ganhos solares indiretos em construções leves em aço, através de uma parede de Trombe, visando melhorar o seu comportamento térmico e reduzir consumos energéticos. A pesquisa foi conduzida em dois módulos experimentais em LSF construídos no campus da Universidade de Coimbra. Os módulos experimentais são compartimentos cúbicos idênticos, onde a única diferença é a presença de uma parede de Trombe na fachada sul de um deles. Foram realizadas medições para se registar o comportamento térmico dos módulos em LSF. Um modelo destes módulos foi criado no software DesignBuilder, comumente utilizado para análises térmicas e energéticas de edifícios. Concluiu-se que a parede de Trombe traz benefícios para construções em LSF em termos de conforto térmico e eficiência energética, porém é necessário projetar-se medidas de controle para evitar sobreaquecimento no verão e perdas de calor durante a noite no inverno.

Palavras-chave: Construção leve em aço, eficiência energética, parede de Trombe, aquecimento solar, simulação térmica.

ABSTRACT

In terms of energy efficiency, the construction sector has a great potential for improvement, since 40% of all energy produced is consumed by buildings in Europe, and the sector is constantly expanding (EU, 2010). This high potential has drawn attention to the passive strategies for achieving indoor thermal comfort. Solar energy is relevant due to the cost-free radiation that comes from the sun, being a sustainable alternative to heating systems that run on fossil fuels. A Trombe wall is a passive solar device that can be present in a building’s external wall system to accumulate solar heat and aid in the ventilation, heating and even cooling of the interior space. The device can reduce the energy consumption of a building up to 30%. Regarding construction systems, the Light Steel-Framed (LSF) has been attracting attention worldwide. However, LSF construction also presents some challenges, especially related to its thermal behavior. Passive strategies are a good choice to mitigate the thermal challenges present on LSF construction. Thus, this dissertation has the objective to study the impacts of indirectly gains from solar energy in LSF construction through a Trombe wall, aiming to improve its thermal behavior and reduce energy consumption. Research was conducted on two LSF modules constructed in the University of Coimbra`s campus. Those experimental modules are identical cubic compartments, the only difference being the presence of a water Trombe wall in the south façade of one of them. Measurements was conducted in order to register the thermal behavior of the LSF modules. A model of these LSF modules will be created on the software DesignBuilder, commonly used for thermal and energy performance analyses of buildings. It was concluded that the Trombe wall is beneficial for LSF buildings in terms of thermal comfort and energy efficiency, but it is necessary to design solutions to avoid overheating during the summer and heat losses during the winter nights.

Key words: Light steel frame, energy efficiency, Trombe wall, solar heating, thermal simulation

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1. INTRODUCTION

1.1 Motivation

Sustainable development is currently the main aspect to consider in all major decision-making processes. The term, which first appeared in the Brundtland report, also known as Our Common Future, published by the United Nations in 1987, defines that *"humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs"* (UN, 1987). Based on this principle, nations have been more conscious about climate change, CO_2 emissions, and resources depletion/consumption, creating mitigation programs and orienting their development in that direction.

Energy usage is an important topic when addressing sustainable development, since the world's energy matrix is still very dependent on fossil fuels, such as coal and oil. The consumption of these fuels should be avoided not only because they are finite materials, but mostly due to the amount of CO_2 released from its combustion. The production of electrical energy from renewable sources, such as solar photovoltaic and wind, is a good replacement for fossil fuels due to the low impacts of their operation. According to the last report from the International Energy Agency (IEA), in 2017, about 25% of the electricity consumed worldwide was produced from renewable sources (IEA@, 2017).

In terms of energy efficiency, the construction sector has a great potential for improvement, since 40% of all energy produced is consumed by buildings in Europe, and the sector is constantly expanding. Aiming to improve the energy efficiency in buildings, the European Union (EU) has established the Directive 2010/31/EU, in which is defined the concept of a nearly Zero Energy Building (nZEB), as a building with a very high energy performance, and that covers its small energy needs with energy produced by renewable sources, on-site or nearby. The EU member states must ensure that by 31 December 2020 all new buildings are nearly zero energy buildings (EU, 2010).

The Annex 1 of the directive presents a common general framework for the calculation of the energy performance of buildings, on which each member state should base their own regulations, aiming to achieve the goals proposed. Although the directive foresees flexibility factors for the calculation of the primary energy needs for buildings in different climate zones, there are practical challenges among member states regarding the implementation of the nZEB concept. In northern countries, for instance, it is relatively easy to reach indoor comfort conditions during the summer due to the mild weather, so the effort on the design phase of the project can be focused on reducing the energy needs for heating, optimizing systems. On the other hand, for the southern countries, especially Mediterranean, it is harder to balance the indoor comfort conditions during summer and winter, due to the high temperatures and sun radiation during the summer, being necessary to install in buildings both systems for heating and cooling, increasing costs and energy needs (Attia *et al.*, 2017)

Given the potential of reduction in energy needs of buildings, passive strategies have been studied to enhance the indoor comfort conditions with no energy consumption. One of the most accepted methodologies concerning those passive strategies is the Passive House, originated in Germany in the early ’90s. It focuses on passive strategies as high insulation, avoiding thermal bridges, airtightness and heat recovery in the ventilation systems. It has been demonstrated that energy needs for heating can be decreased up to 90% in climates similar to Germany’s, at just a 5-10% increase in the building cost. Passive houses can make use of solar gains when it is possible, but it is not mandatory (Schnieders, Feist e Rongen, 2015).

Solar energy, however, is relevant due to the cost-free radiation that comes from the sun, being a sustainable alternative to heating systems that run on fossil fuels. The solar energy can be harnessed directly, through solar gains from windows and glazed areas, or indirectly, through architectural devices used in buildings, such as solar roofs, solar chimneys, Trombe walls, among others. The Trombe wall has a simple configuration and is designed to accumulate solar heat, that is later used for indoor heating. It is classically composed by a wall with high thermal inertia, painted black to increase radiation absorption. The surface of the wall is glazed, leaving an air gap between the wall and the glass. The system exploits the greenhouse effect that occurs in the air layer, where the cold air comes in from the indoor space through a lower vent on the wall. The air is heated by solar energy and flows upward, reaching an upper vent on the wall and re-entering the indoor space. This kind of system can reduce energy consumption in buildings by up to 30% (Hu *et al.*, 2017).

Regarding construction systems, the Light Steel-Framed (LSF) has been attracting attention worldwide. This system does not require water during the construction phase, being known as a dry construction system and is characterized by the utilization of three main components in walls and slabs: cold formed steel sections as structural component, for load bearing; covering materials as gypsum plasterboards and oriented strand board (OSB) panels; insulation materials as mineral wool. Some advantages of this light construction system opposing to traditional heavyweight systems are the speed of construction, easy prefabrication of components, high architectural flexibility, small weight, the capacity of recycling and reuse of the components, among others. However, LSF construction also presents some challenges, especially related to its thermal behaviour. Due to the lightweight of the structural elements, it has lower thermal mass and therefore lower thermal inertia, which can lead to problems related to indoor comfort, such as overheating. Besides that, the high thermal conductivity of the steel elements creates significant thermal bridges, areas in the building envelope where the heat losses are increased. Those characteristics of LSF construction can lead to higher energy demand for both heating and cooling, as the larger fluctuation of the indoor temperature during the day (Soares *et al.*, 2017).

1.2 Research objectives

Passive strategies are a good choice to mitigate the thermal challenges present on LSF construction. Thus, this dissertation has the objective to study the impacts of indirectly gains from solar energy in LSF construction through a Trombe wall, aiming to improve its thermal behaviour and reduce energy consumption, keeping the comfort level of occupants.

a) b)

Figure 1 - LSF modules: a) north facade; b) south facade.

Research will be conducted on two LSF modules constructed in the University of Coimbra`s campus, at the Department of Civil Engineering (DEC) during the PhD research work of Rosa (2018), in order to test the improvements of thermal performance due to the presence of a

Trombe wall in LSF construction. Those experimental modules are identical cubic compartments (inner dimensions of 2.75m x 2.75m x 2.8m), the only difference being the presence of a water Trombe wall in the south facade of one of them. Figure 1 displays the two LSF modules constructed on the University`s campus. On the left, it is shown the north facade of the modules and on the right the south facade, where it can be observed the Trombe wall in one of the modules.

From the main objective stated, the specific objectives of the research are:

- To understand the thermal behaviour of the LSF modules, by conducting measurements *in situ*.
- To analyse whether the results of internal temperature from the measurements taken *in situ* matches the data from simulations of models of the LSF modules developed on the software DesignBuilder.
- Quantify the benefits of the Trombe wall in terms of indoor thermal comfort and energy efficiency through simulations conducted on DesignBuilder.
- To conduct a parametric study on the efficiency of the Trombe wall in the LSF module, altering some parameters on the model developed in DesignBuilder and analysing how it affects its performance.

1.3 Structure of the dissertation

The first chapter of this dissertation is dedicated to introduce the motivation and objectives of this work, including the presentations of the study object, the LSF modules and the Trombe wall present in one of them.

The second chapter is a state-of-the-art research on key topics related to this work, being passive construction, Trombe walls and the Light Steel Framing (LSF) construction system.

Next, the third chapter explains the methodology used during the development of this dissertation, in terms of tasks related to the main objectives proposed.

Following, the fourth and fifth chapters are dedicated to the development of the DesingBuilder`s models of the modules, being the reference and the Trombe wall modules, respectively. These chapters present a detailed explanation of the parameters considered during the modelling phase, as well as the calibration / validation procedures for each model.

On sixth chapter the benefits of the presence of the Trombe wall are quantified, both in terms of indoor thermal comfort as in terms of energy efficiency. The seventh chapter contain a parametric study, conducted in order to assess the impact of changes in some of the parameters of the Trombe wall on its efficiency.

The eighth, and final, chapter shows the conclusions achieved from the development of this work, as well as propositions for future works on this topic.

2. STATE-OF-THE-ART

This section presents a research made on the main subjects related to this works` topic. The objective of this chapter is to reinforce the motivation for the proposed theme, through a literature review. The subjects approached are (1) passive construction; (2) Trombe walls, and; (3) light steel framing construction system.

2.1 Passive construction

2.1.1 The Passive House concept

People have started to raise awareness about the need to reduce our fossil fuels consumption since the 1970s, when a global energy crisis took place, and later with the 1990s environmental concerns. This reduction in fossil fuels consumption can lead to a less polluted environment and slow down global warming (Chandel e Sarkar, 2015). Since 2014, buildings are responsible for the consumption of over 30% of the world`s total energy supply, and this sector`s energy demands are predicted to increase by 50% in 2050, compared to 2013 (Harkouss, Fardoun e Biwole, 2018). This high potential of reduction in energy demands from buildings has drawn attention to the passive strategies for indoor thermal comfort, pointing out that heating is one of the top energy consuming systems in buildings.

From that, it has emerged in Germany during the 1990s the concept of passive construction, namely "*Passive house*", or "*Passivhaus*" in German. Defined as a building which provides comfortable indoor conditions at an extremely low heating and cooling load, these buildings focus on the usage of passive strategies, such as high thermal insulation, airtightness, mechanical ventilation with heat recovery, high-quality windows and the avoidance of thermal bridges on the building envelope (Schnieders, Feist e Rongen, 2015).

Regarding indoor comfort, these buildings achieve an almost constant temperature profile throughout the day, with low oscillation, due to its high thermal insulation and airtightness. It also has good indoor air quality, maintaining adequate humidity levels due to the controlled ventilation system, which assures the well-being of the residents. In terms of sustainability, the passive houses promote the reduction in CO_2 emissions, as it has a much smaller energy need than regular construction, about 75% smaller (Ferreira, 2015). Nevertheless, some projects of passive houses in Germany have achieved up to 90% in energy demand reduction, with an increase in construction cost of 5 to 10%, compared to a regular building (Schnieders, Feist e Rongen, 2015).

The Passive House Institute, a German independent institute responsible for the certification of passive houses, have developed a series of criteria for a building to be considered a passive house, as it follows (PASSIV@, 2019):

- Space Heating Demand - not to exceed 15kWh annually OR 10W (peak demand) per square meter of usable living space;

- Space Cooling Demand - roughly matches the heat demand with an additional, climate-dependent allowance for dehumidification;

- Primary Energy Demand - not to exceed 120kWh annually for all domestic applications (heating, cooling, hot water, and domestic electricity) per square meter of usable living space;

- Airtightness - maximum of 0.6 air changes per hour at 50 Pascal pressure (as verified with an onsite pressure test in both pressurized and depressurized states);

- Thermal Comfort - thermal comfort must be met for all living areas year-round with not more than 10% of the hours in any given year over 25°C.

Although this concept of a passive house is a concretized guideline in central Europe, the same is not observed in southern Europe, where the climate is warmer. Most professionals of the construction sector in this region consider as a passive house a building constructed according to the solar geometry, while in the German Passivhaus buildings make use of solar gains when it is possible, but it is not mandatory. Other concern of the southern Europe professionals is their disagreement with the term “passive” in the German standards, as it encourages the use of an active mechanical ventilation system (Gonçalves e Brotas, 2007).

Attia *et al.* (2017) identified in their work some of the main barriers that are faced in the southern Europe countries (especially Mediterranean) when trying to achieve high energy efficiency in buildings. The first barrier presented is the geography and climate of the region, where the summer is hot and associated with intense solar radiation. According to the study, the construction sector has failed to incorporate new materials and technologies with the consolidated bioclimatic design concepts already present in the region, as proper shading, high thermal mass of the construction elements and night ventilation.

The second barrier pointed out is methodological. The implementation of strategies to achieve high energy efficiency in southern Europe is based on generalist calculation-based design, with little focus on monitoring its performance after construction. The last barrier presented is related to local authorities in these countries, where they usually are not in contact with research centres to increase their understanding on the subject of high energy efficiency in buildings. As a result, little effort has been made to provide the construction sector with local guidelines to achieve high standards in energy performance, related to its own climate and geography (Attia *et al.*, 2017). Besides those technical discrepancies in the understanding of passive construction across Europe, it is commonly accepted that passive systems for heating and cooling should be used when possible, in order to obtain the best energy performance.

2.1.2 Passive solar systems for buildings

The sun provides a high amount of energy to Earth`s atmosphere, of $1.5x10^8$ kWh annually, which correspond to about 10000 times the annual global energy demand. This energy can be exploited to help achieve indoor thermal comfort conditions in buildings through the implementation of solar technologies, both active (as solar collectors and photovoltaic systems) and passive (Gomes, 2011).

Passive systems are devices integrated to the building`s structure that contribute to its natural heating or cooling, in other words, the thermal exchanges are made naturally. In terms of passive solar systems, they are usually used for heating purposes, and aim to maximize the harvesting of energy from the sun, through well designed glazing areas that could be associated to massive elements, that allow the storage of thermal energy, to be used later during the day, when it is required. Solar passive systems for heating can be classified in direct gains, indirect gains and isolated gains (Gonçalves e Graça, 2004).

Direct gain systems are the simplest of the solar passive systems, consisting in heat a space using direct sun radiation. Every window or glazed area in the building envelope can work as a direct gain system. The basic components of the systems are a capitation area oriented to south (in the north hemisphere, north in the south hemisphere), a space to be heated directly exposed to the sun radiation, and interior elements (walls, slabs and ceiling) used for thermal storage (Gomes, 2011). Among the advantages of this type of system are the high energetic efficiency, low cost and natural illumination. In the other hands, some disadvantages of the systems are the lack of privacy if big glazed areas are used, and the possibility of overheating during hot days, being necessary the prediction of a shading device (Ferreira, 2015). The representation of a direct solar gain system is shown in Figure 2.

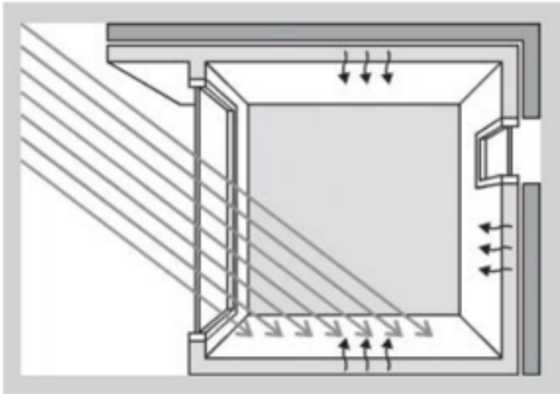


Figure 2 - Representation of a direct solar gain system (Gonçalves e Graça, 2004).

In the indirect gain systems, the heating of the interior space occurs indirectly, as the capitation of solar energy occurs in a storage wall interposed between the gain surface and the space to be heated. Examples of this type of system are Trombe walls, which are the study object of this work, high thermal mass walls, water columns wall and water roofing. Indirect gain systems require low maintenance and can help reducing the energy demands of a building. Moreover, in this system the lack of privacy is not an issue (Reaes Pinto e Dias, 2015). A scheme with indirect solar gain strategies is presented in Figure 3.

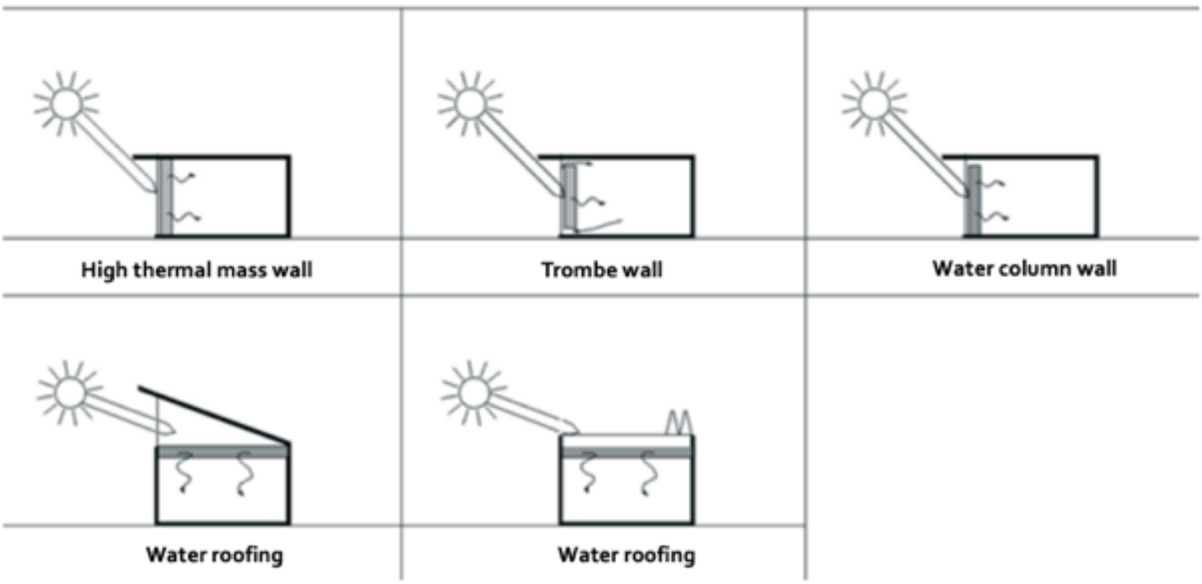


Figure 3 - Indirect solar gains strategies (Reaes Pinto e Dias, 2015).

Finally, in isolated solar gain systems, the capitation and storage of solar energy are located separated from the occupied zone of the building. Greenhouses and air collectors are examples of isolated gain systems, in which direct and indirect gains are combined (Reaes Pinto e Dias, 2015). The inner space of the greenhouses is heated directly by the incident solar radiation (direct gain) and the heat may be transmitted to an adjacent space through conduction by a storage wall, and through convection, if there are vents on this wall allowing air circulation between spaces (Reaes Pinto e Dias, 2015). The representation of an isolated solar gain system is shown in Figure 4.

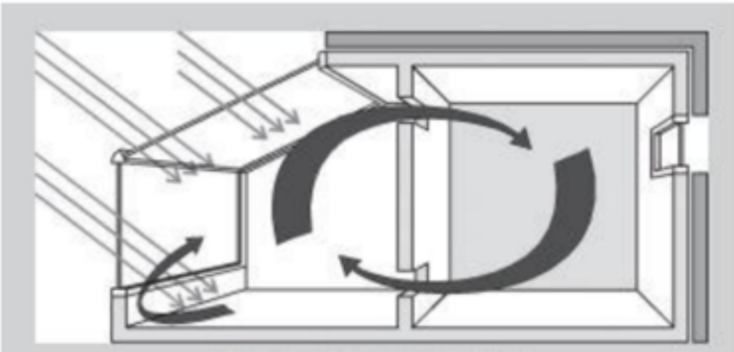


Figure 4 - Representation of an isolated solar gain system (Gonçalves e Graça, 2004).

2.2 Trombe walls

2.2.1 System overview

A Trombe wall is a passive solar device that can be present in a building's external wall system to accumulate solar heat and aid in the ventilation, heating and even cooling of the interior space. The concept was first referred in 1881, when American engineer Edward Morse patented his design of a black painted wall behind a glazing area and an air gap, containing vents in which the air flux could be regulated. Nevertheless, the system was developed and popularized in 1957 by French engineer Felix Trombe and French architect Jacque Michel, that is why nowadays the configuration is known as Trombe wall. The first house containing a Trombe wall was built in 1967, in France (Ferreira, 2015). The device is an important green architecture feature, in which the climate of the building`s implementation place is considered to adapt it through passive strategies. A Trombe wall can reduce the energy consumption of a building up to 30% (Saadatian *et al.*, 2012). Figure 5 shows a simple scheme of a typical Trombe wall.

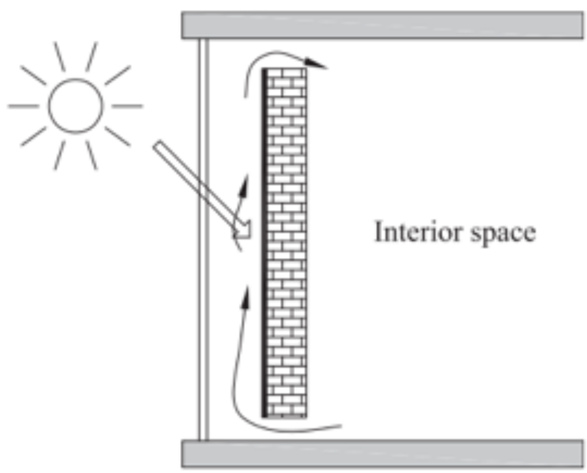


Figure 5 - Scheme of a typical Trombe wall (Hu et al., 2017).

The operation of the Trombe wall is based on heat transfer principles. It absorbs solar heat in its high thermal inertia storage wall and transfers part of this heat to the interior space of the building through conduction, radiation and convection. The device stores heat during the day and release it during the late afternoon and night times, when the occupants require it (Saadatian *et al.*, 2012). Meanwhile, the solar radiation heats up the air in the space between the glass and the storage wall exploiting the green-house effect, allowing the colder air from the indoor space to enter the heated cavity by its lower vent, due to the buoyancy effect. As the air that enters the cavity is heated by the incident solar radiation, it flows upwards, returning to the indoor space through the upper vent in the storage wall. So, the heat exchange between the Trombe wall and the indoor space occurs in part due to the transmission of the heat stored in the high thermal inertia wall, and in part due to the ventilation in the heated air gap (Hu *et al.*, 2017).

The design of a Trombe wall and the optimization of its performance has to account the properties of each of its constituents, as well as the system as a whole. A typical Trombe wall is composed by a storage wall, a glazing area, an air gap between those two elements, and shading and ventilation devices. In terms of storage wall, the key property to be considered is the thermal inertia of the element, as it has a direct impact in the quantity of heat that can be stored in it and then released to the indoor space. The thermal inertia can also control the temperature fluctuation in the indoor space throughout the day, decreasing the energy needs for heating and cooling. When the room temperature is lower than the storage wall, it gradually releases the stored heat to the room. This is especially interesting during the winter when the heat stored during the day is released during the night, when it is colder inside (Sá, 2011). Figure 6 presents the effects of the thermal inertia in the control of the temperature fluctuation inside the building. The peak temperature is delayed and decreased by the high inertia of the wall, which creates a damping effect.

Figure 6 - Demonstration of the effect of the thermal inertia in the control of indoor temperature fluctuation (Ferreira, 2015).

The glazing area is located in the exterior face of the Trombe wall, at a certain distance from the storage wall, creating an air gap. The glazing plays an important role in the system, as the greenhouse effect depends on its capacity to retain the heat in the air gap. This capacity depends on the thickness and type of the glass, its orientation and localization on the building facade, and the geometry of the sun trajectory during the day in the given location (Sá, 2011).

Regarding glass properties, when designing a solar passive heating device, the solar factor must be high, so it allows the passage of the maximum amount of solar radiation as possible. The solar factor of a glass is expressed in a scale of 0 to 1, in which a value of 0,7 means that 70% of the solar radiation is transmitted to the interior space. The sun trajectory also has an influence on the thermal performance of a Trombe wall, as the solar gains take in consideration the angle of incidence of direct solar radiation, as well as the shadows projected on the glazing area. The ideal orientation for the system during the winter is South, as in this season the sun runs almost perpendicularly in this direction during part of the morning and the early afternoon, allowing direct solar radiation during a larger amount of time (Sá, 2011).

The Trombe wall must also be equipped with shadowing devices, to avoid overheating during the summer, but also to cover the glazing area during the night, to reduce unwanted heat losses. There is currently a large variety of shadowing devices, that can be classified according to its position (exterior or interior), as well as to its handling (fixed or mobile). In this kind of system, the most used are shutters (interior and mobile), and horizontal flaps (exterior and fixed) (Ferreira, 2015). The flaps are structures projected from the wall or prolonged from the roof that have the purpose to allow the maximum amount of solar radiation during the winter, at the same time as it restrict the solar gain during the summer, avoiding overheating. Figure 7 presents an example of a shadowing flap during summer and winter seasons.

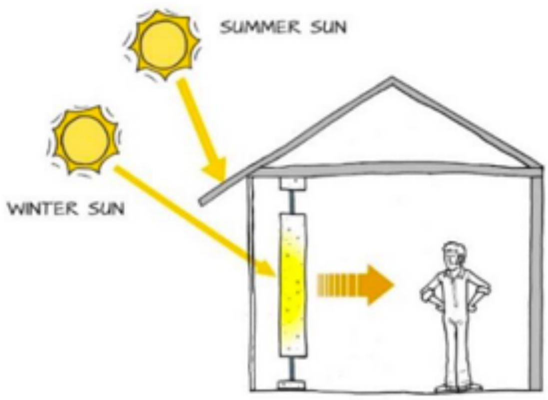


Figure 7 - Example of a shadowing flap during summer and winter seasons (Ferreira, 2015).

Trombe walls can also be classified by the presence and kind of ventilation devices. If the system does not feature any vents it is called a non-ventilated Trombe wall. It is called a ventilated Trombe wall if there are vents in the storage wall (typical configuration) and called a double-ventilated Trombe wall if there are vents both in the storage wall and in the glazing area. In the non-ventilated kind, there is no air circulation inside the device, so the space heating is only due to the transmission from the storage wall. On the ventilated Trombe wall the indoor heating is faster, as it happens both by transmission from the storage wall as by the air heating in the wall air gap. Lastly, the double-ventilated Trombe wall makes the system more versatile, as the implementation of vents in the glazing area makes it possible to capture hot air from the indoor space and release outside, acting as a cooling device, or to cool off the air gap of the system, preventing overheating (Ferreira, 2015). Figure 8 presents different configurations of vent opening, for different purposes or seasons.

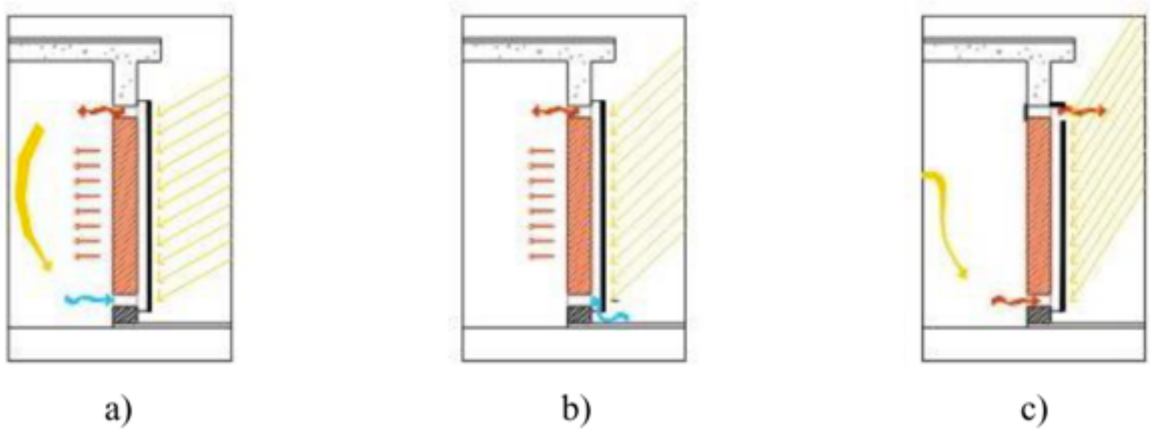


Figure 8 - Different configurations for double-ventilated Trombe walls – a) winter; b) spring/fall; c) summer (Ferreira, 2015).

2.2.2 Types of Trombe walls

After the characterization of the Trombe wall system's components and operation, it is important to acknowledge that over the years different configurations were designed to adapt the device to different climates and purposes. It can also incorporate new technologies such as photovoltaic cells or phase change materials. This section presents some of the different configurations of the Trombe wall system, as well as its particularities.

Firstly, the classic Trombe wall (presented in the past section) can already be divided in two different types, the non-ventilated Trombe wall and the ventilated Trombe wall. The first is the simplest configuration of the system, composed by a storage wall with no openings for ventilation, an air cavity and an external glazed area. On this kind of system, the solar heat is stored in the air cavity and progressively heats up the storage wall, which later releases the heat to the interior space. The heat transfer occurs through conduction only, and the time for the heat to reach the interior space is related to the thickness and choice of material for the storage wall. The non-ventilated Trombe wall is recommended for spaces with a nocturnal occupation, as the heat stored from the sun can take several hours to reach the interior space (Gomes, 2011).

For the ventilated Trombe wall, the difference is the presence of vents on the bottom and the top of the storage wall, which enables the heat stored in the air cavity to be transferred to the interior space through conduction and convection, making this configuration more complex than the non-ventilated. The ventilated Trombe wall is recommended for spaces with a diurnal occupation, as the heat is transferred to the interior space faster than on the non-ventilated configuration (Gomes, 2011).

Another type of configuration is the composite Trombe wall, also known as the Trombe-Michel wall. It is similar to the classic configuration, but it has another air cavity after the storage wall (usually non-ventilated), separated from the interior space with an insulated panel. The heat absorbed by the storage wall is transferred through conduction to the interior air cavity, which is then transferred to the interior space through convection. This configuration was developed to diminish heat losses during cold seasons, as the storage wall tends to have low thermal resistance. Nevertheless, the composite Trombe wall has the disadvantage of having higher thickness and construction cost when compared to the classic configuration (Martins, 2010). A scheme of the composite Trombe wall is displayed in the Figure 9.

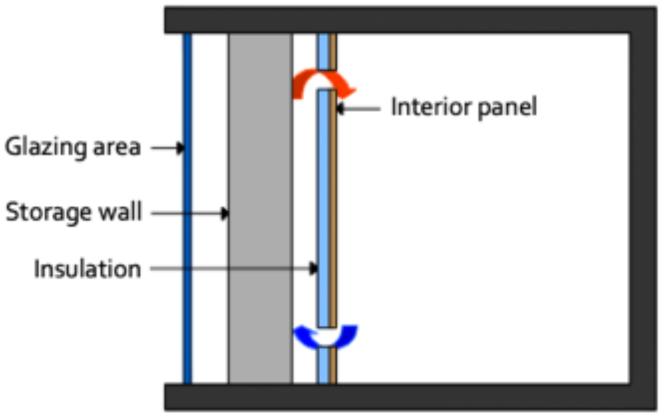


Figure 9 - Scheme of the composite Trombe wall (Adapted from Martins, 2010).

The water Trombe wall is another configuration possible. It uses a water container in the shape of a wall instead of masonry as a heat storage unit. The water performs better than a masonry wall in indirect heat gains, as the surface temperature of the water does not rise as much as in heavy walls, therefore less heat is reflected back through the glazing area (Saadatian *et al.*, 2012). Also, the water has a higher specific heat than other construction materials as concrete and bricks, which enables it to store a higher amount of heat. Another advantage of the usage of water as a storage wall is that, as a fluid, convection occurs inside of the container, which makes the heat to be transferred to the interior space faster in comparison with a classic Trombe wall, in which the heat passes the storage wall only through conduction (Saadatian *et al.*, 2012).

In terms of innovation, the photovoltaic Trombe wall can be cited as a more technological approach to the device. This configuration is similar to the classic Trombe wall, but the front side of the glazing area is composed of photovoltaic panels. In this system part of the incident solar radiation is accumulated on the panels on the glazing, and part is absorbed by the storage wall, therefore the efficiency of the Trombe wall is reduced (Ferreira, 2015). This configuration, however, produces electricity, which is a benefit. Also, the photovoltaic Trombe wall has an aesthetic please when compared to other configurations, as the patterns of dark blue cells can add visual appeal to a building (Saadatian *et al.*, 2012). An example of photovoltaic Trombe wall installed in a test cell is shown in Figure 10.

Figure 10 - Example of a photovoltaic Trombe wall (Saadatian et al., 2012).

One of the latest Trombe walls approaches to arise is the one that incorporates the usage of phase change materials (PCM), such as phase eutectic salts or salt hydrates, that can store higher amounts of calorific energy, as well as release it when changing phase. These materials can store more energy in a smaller volume when compared to regular construction materials, and are much lighter (Saadatian *et al.*, 2012). PCM can be incorporated in two different manners, energy can be absorbed by PCM capsules incorporated in regular construction materials as concrete or plasterboards, or by adding non-encapsulated PCM directly on the materials, as in the production of glass bricks or in the usage of PCM panels. The operation of this configuration of Trombe wall is simple, when the sun radiation reaches the storage wall the heat is stored by the PCM as it changes phase from a solid to a liquid state, and when the temperature decreases it releases the calorific energy while changes phase back to a solid state (Martins, 2010).

2.2.3 Advantages and disadvantages of Trombe walls

As demonstrated in the previous sections, the Trombe wall is a passive solution that is congruent with the sustainable construction principles. Nevertheless, its usage presents both conveniences and challenges. Some of the advantages and disadvantages of the Trombe wall system are listed below.

Advantages:

- Passive, low maintenance systems;
- Reduces energy consumption for heating;
- Protect the interior space against ultraviolet rays;
- Control the temperature fluctuation in the indoor space throughout the day, increasing thermal comfort;
- Increases air circulation in the indoor space;
- Increases privacy in the indoor space.

Disadvantages:

- The thickness of the storage wall may limit the indoor space;
- Storage walls restrict natural illumination and exterior view;
- It requires south orientation to increase its performance;
- Can lead to overheat during summer season if a shading device is not predicted;
- May increase heat losses during the night time if the system is not correctly isolated.

2.3 Light Steel Frame construction system

2.3.1 System overview

The lightweight framing construction system was the most traditional system in the United States since the XIX century, but it used wood as its main structural element. The steel began to appear as an efficient option during the second world war, in 1945, whereas the material was used to build military bases outside American territory. The use of steel as the main structural element was seen as a good system once it was light enough to be transported in planes, and as the assembly of the structure was relatively easy (Ferreira, 2014).

Nevertheless, the first code for lightweight steel framing (LSF) construction was published only in the ’90s by the National Association of Home Builders (NAHB) associated with the American Iron and Steel Institute (AISI). The need for a code came after a hurricane passed through the United States in 1992, destroying thousands of houses. Therefore, it was necessary to seek for alternatives to rebuild them. The lightweight steel framing was seen as a good option due to its structure’s smaller risk of collapse and smaller construction costs. The publication of this first code has contributed to the acceptance, promotion, and development of the LSF construction system, as it began to be seen as a professional technical system. Nowadays the United States are world leaders in this kind of construction, in Europe, we highlight the United Kingdom, Denmark, and Sweden as the countries with this construction system more developed (Fereira, 2014).

As stated before, the main structural elements in LSF construction are steel sections. These steel sections are cold-formed and usually galvanized to increase its durability and avoid corrosion. They are used in all the building components, both for the envelope (external walls and roof) and the interior partitions (internal walls and slabs), except or the ground floor slab, where is often used reinforced concrete (Santos, 2017). Figure 11 presents an example of module constructed in LSF, in which the structure in steel sections can be observed.

Regarding construction materials in the LSF system, material layers could be divided into three distinct groups: i) exterior layer; ii) inner layer, between the steel sections and iii) interior layer. The exterior layer is commonly composed by an External Thermal Insulation Composite System (ETICS) for thermal insulation, bonded with an Oriented Strand Board (OSB) for mechanical resistance. The inner layer is composed of an air cavity and mineral wool, used between the steel sections. Mineral wool is a fundamental part of the system, as it ensures thermal insulation, acoustic insulation, and fire resistance, but other materials can be used in the inner layer for check these requirements, like fiberglass or injected polyurethane. Lastly, the inner layer is composed by a plasterboard, that can be fixed to steel sections or glued to an OSB panel. The plasterboard is a gypsum board, that may contain various additives, between two outer layers of paper. Those boards also help with the thermal and acoustic insulation, as with the fire resistance (Rosa, 2018). Figure 12 presents a cross-sections of a typical LSF wall.

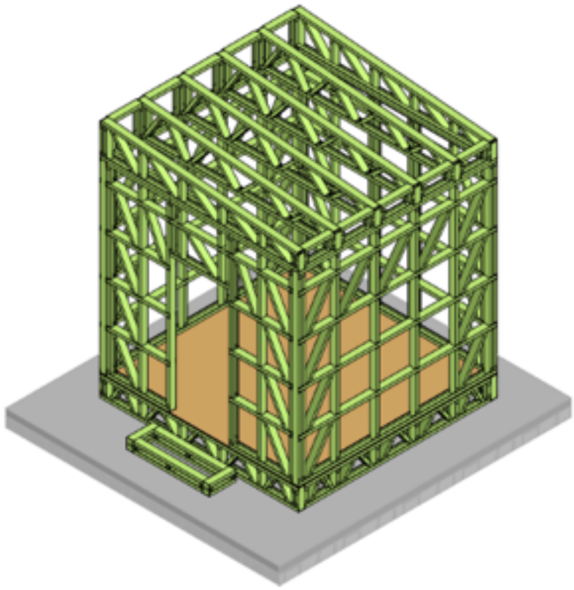


Figure 11 - Example of steel section structure in LSF construction (Rosa, 2018).

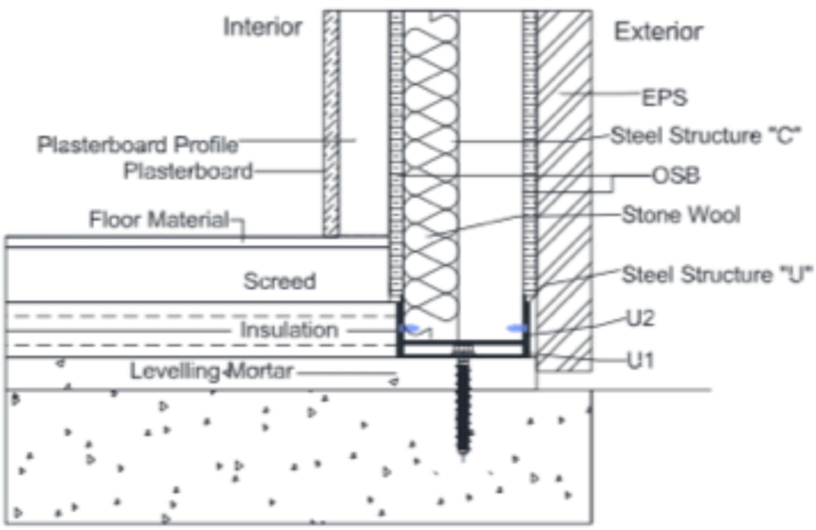


Figure 12 - Cross section of a typical LSF wall (Rosa, 2018).

Construction elements in LSF can be classified according to the position of the thermal insulation materials. It is called "cold frame construction" when the insulation material is all concentrated in the inner layer of the wall, placed between the steel sections. This configuration leads to higher heat loss due to the steel thermal bridge, and has a higher risk of interstitial condensation, as the steel temperature decreases. When besides the inner insulation, there is also a continuous layer of ETICS on the outside of the building, it is called "hybrid frame construction". This is the most common configuration in LSF construction. When all the thermal insulation is located in the exterior, outside the steel sections, it is called "warm frame construction", as the steel frame is warmer. The warm construction is seen as the best option in terms of thermal behavior, as the outer continuous insulation reduces the effect of the steel thermal bridges, lowers the thermal transmission value of the construction element (*U*-value), and reduces the risk of interstitial condensation. In the other hand, when using this configuration, often the walls are thicker, reducing the interior floor area (Santos, 2017).

Figure 13 shows examples of the three different kinds of frame construction in LSF, regarding the temperature distribution in each one.

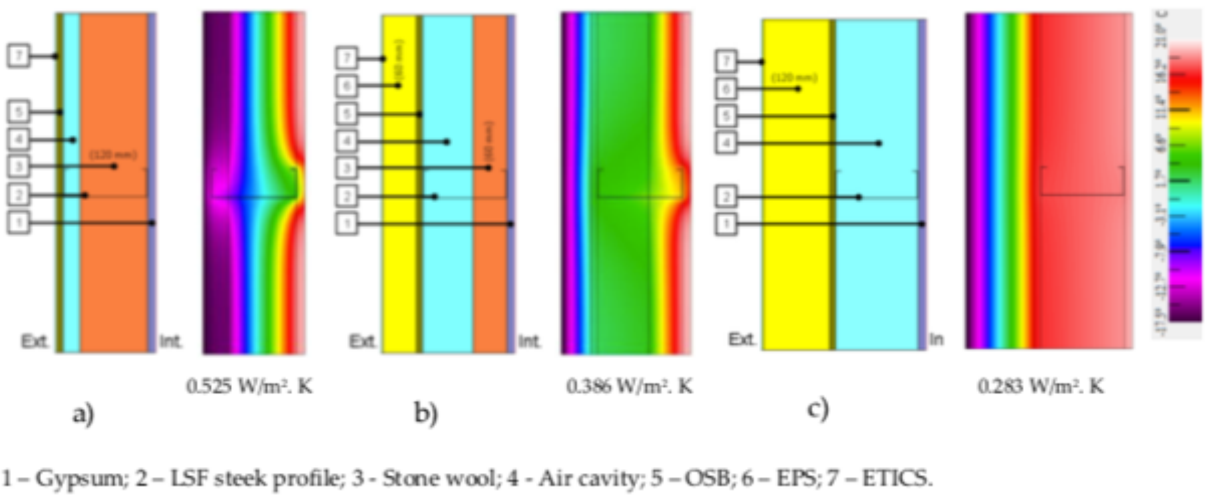


Figure 13 - Classification of LSF walls and interior temperature distribution. a) cold frame construction; b) hybrid frame construction; c) warm frame construction (Santos, 2017).

In terms of construction, there are three framing methods in LSF: (1) stick-built (or stick-framing); (2) panelized, and; (3) modular. The first method, stick-built, is the most common for LSF construction. It consists of the assembly of the structural elements in situ, whereas the steel sections can come to the construction site already with the desired measures and perforated according to the project, or not. The steel sections are joined and fastened with specific elements. Some advantages of this method are the ease of transport of the components to the construction site, the assembly of the structural elements is simpler, and it is easier to make modifications or adjusts in the project after the construction has started (Ferreira, 2014).

The second method, panelised or 2D, consists in the assembly of panels in conditions of industrial prefabrication. The structural panels formed with steel sections can be already attached to internal and/or external panels in the industry, with insulation. Advantages of this method include better quality control of the products, due to the industrialization of the assembly process, reduction of the costs in the construction site and the higher speed of construction. The last method, modular or 3D, consists in the assembly of whole modules (in three dimensions) in industrialized conditions, including all layers and finishing options. This method has the same advantages as the panelised, but it has a few inconveniences, as the difficult to transport the modules, and the need for a place to store them (Ferreira, 2014). Figure 14 presents a schematic representation of the three different framing methods.

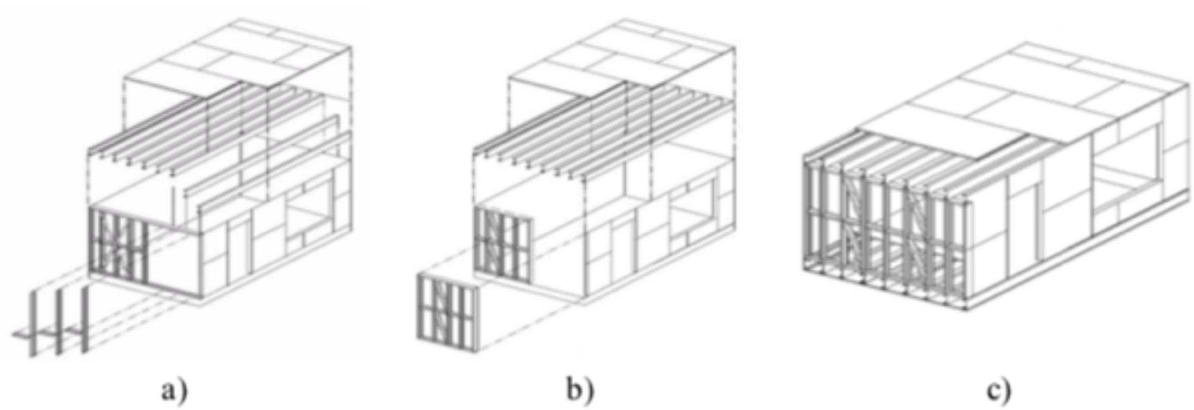


Figure 14 - Schematic representation of the three different framing methods: a) stick-built; b) panelised and c) modular (Ferreira, 2014).

The LSF construction system has been promoted and developed over the years and nowadays it is a competitive solution, especially in economically developed countries. The system presents many advantages in comparison with other construction systems, as higher construction speed, better quality control of the products, high structural stability and safety due to the lightweight of the structure and the elevated number of steel sections in the construction elements, sustainability (high recyclability of the steel elements), among others. In the other hand, there are a few limitations about the LSF construction, as in the height of the buildings (usually two or three floors), in the dimensions of openings, and in the thermal performance of the building, once it has a low thermal inertia, and is susceptible to the effect of thermal bridges due to the steel structure (Ferreira, 2015).

2.3.2 Thermal performance of LSF buildings

The thermal performance of a building can be addressed as how well it responds to changes in the outdoor climate in order to maintain thermal comfort conditions in the inside space. Regarding LSF construction two main possible drawbacks are highlighted, given the specificities of the system: influence of thermal bridges and low thermal inertia, which can affect the thermal performance of buildings.

A thermal bridge is a preferential heat path through the building envelope, resulting in a reduction of the effectiveness of the thermal insulation. In LSF construction the thermal bridges are related to the steel elements, that have a high thermal conductivity, which can lead to higher thermal losses to the exterior (Soares *et al.*, 2017). However, there are some strategies that can be used to mitigate the effects of the thermal bridges in LSF construction. One of these strategies is the usage of external continuous thermal insulation (ETICS) systems, avoiding interruptions of the insultation layer. At junctions of building elements, the insulations must join in full width. Also, the building geometry should be kept as simple as possible, as corners and elements junctions are considered geometrical thermal bridges (Santos, 2017). Moreover, there are some thermal bridges mitigation strategies that are linked directly to the steel studs, as pointed out by Santos, Martins e Simões Da Silva (2014) (demonstrated in Figure 15):

a) Increasing the heat flux path, by reducing the area of the steel profile through the insertion of gaps.
b) Reduction of the contact area of the steel stud`s flange with the surface of the panels of the wall, adopting steel sections with a special geometry.
c) Introduction of thermal breaks for building components, which create a barrier and cuts the thermal transmissions between external elements and the indoor space.
d) Application of thermal break strips locally along the steel studs, which are insulation materials that can be attached using button screws or adhesive.

Thermal inertia is a bulk material property that measures its capacity to store and release heat over time. In buildings, the term is related to the capacity to store heat in its elements and provide inertia against outdoor temperature fluctuation. This property allows the retarding of the indoor temperature peak in relation to the external temperature peak. During the winter season, a high thermal inertia can store heat from solar gains during the day and release it during the night, when it is colder, helping to decrease energy use for heating. During the summer season, a high thermal inertia can delay the temperature peak in the indoor space during the day, helping decrease energy use for cooling (ROSA, 2018).

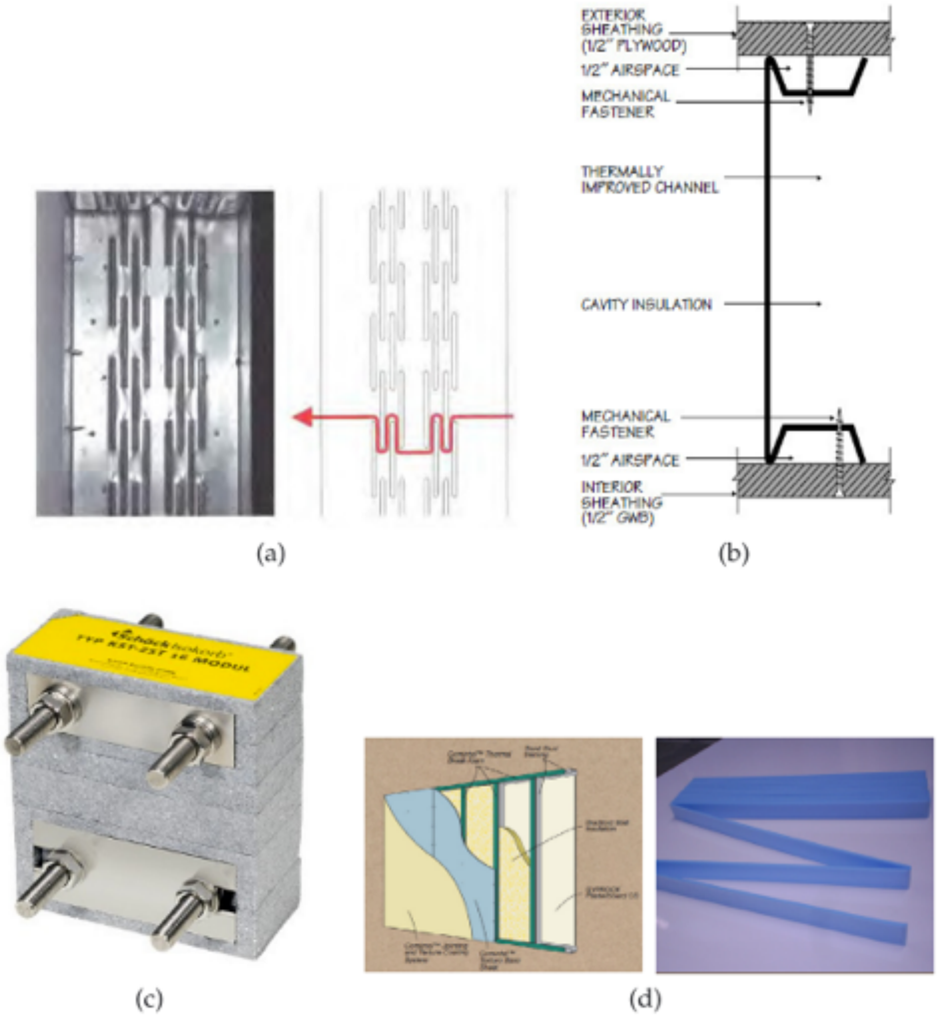


Figure 15 - Thermal bridges mitigation techniques: a) increase heat flux path; b) reduce flange contact area; c) thermal breaks for building elements; c) thermal break strips (Santos, Martins e Simões da Silva, 2014).

One of the drawbacks of the LSF construction system is its low thermal inertia, which can cause a higher indoor temperature fluctuation and, consequently, higher energy consumption to achieve thermal comfort in the inside space. However, there are some strategies that can be adopted to increase thermal mass in LSF construction, such as the use of massive construction materials (such as Trombe walls), the use of ground thermal mass as in geothermal energy systems, and the use PCM incorporated in the LSF construction elements, in order to increase its thermal mass with little increase to its weight (Santos, 2017).

3. ASSESSMENT OF THE REFERENCE LSF MODULE

The first task for the development of this work is to conduct measurements in order to register the thermal behaviour of the LSF module that does not have a Trombe wall installed. This module was selected to be the first due to the least complex nature of its heat exchanges, in comparison with the one that has a Trombe wall. For the measurements, a datalogger to analyse air temperature and humidity inside the module was installed.

A model of the LSF module without the Trombe wall was created on the software DesignBuilder, commonly used for thermal and energy performance analyses of buildings. The thermal behavior from the simulation of the module will then be compared with the data obtained from the measurements taken, aiming to calibrate and validate the model developed.

In order to obtain the most realistic results from the simulation, weather data was collected from two meteorological stations to be inputted in the software, one located in the university's campus, at the Department of Mechanical Engineering (DEM), and another one located at Coimbra iParque, about 7 km away from the modules. From de DEM station data of air temperature, dew point, relative humidity and air pressure are collected. Since this station does not record solar parameters other than total solar radiation, data of total solar radiation, infrared radiation and diffuse solar radiation are collected from the CoolHaven station. The data was added to the weather file of Coimbra, present in the DesignBuilder`s database. This weather file is in the International Weather for Energy Calculation (IWEC) format, developed by ASHRAE, which represents a "typical" year based on a historic mean value for its parameters (EPLUS@, 2019) .

3.1 Modelling the LSF module 1 on DesignBuilder

The first step for the creation of the model for the LSF module 1 (reference module) on DesignBuilder was the geometry input. For that, the assemble manual of the module was consulted, where all the geometry specifications could be found, including the positioning of the door, step and the roof inclination. The experimental module is a cubic structure with inner dimensions of 2.75m x 2.75m x 2.80m, constructed in LSF. The external dimensions as well as constructions details of the module are displayed in the Figure 16.

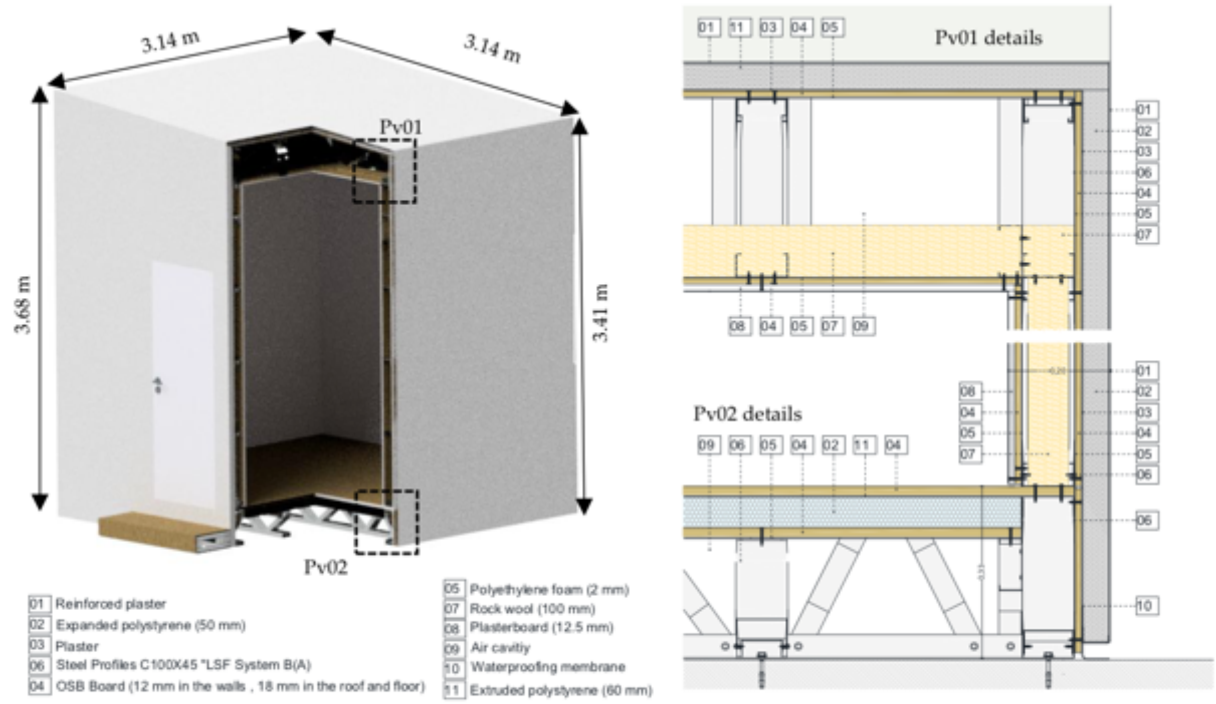


Figure 16 - Construction details of the LSF modules (Rosa, 2018).

As the roof system is composed of a flat internal slab and an inclined outer slab, creating an air gap between them that is not constant in thickness, the roof was modelled in two parts, an inclined roof and a flat ceiling, which makes the software interprets the air gap as a different zone inside the module, non-ventilated. For the air gap that exists between the ground and the floor pavement the same was not done because it is constant in thickness. Instead, the floor element was modelled considering the thickness of the air gap as one of its layers. The model geometry created on DesignBuilder is shown in the following Figure 17.

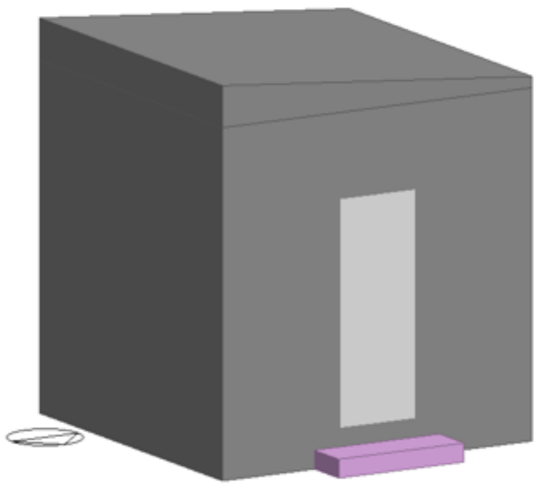


Figure 17 - Model of module 1 developed on DesignBuilder.

Next, the construction elements of the module were assessed. The specification of the construction elements, such as number of layers, materials and thicknesses could also be found on the module's assemble manual (Rosa, 2018). The thermal properties of the materials were taken from the technical brochure of the actual materials used in the module's construction, provided by the manufactures. A resume of the materials used and its thermal properties is given in the Table 1, that follows.

Table 1 - Properties of the materials used in the module's construction.

Materials	Thickness [mm]	λ [(m^2.K)/W]
Reinforced plaster	05	0.720 (DesignBuilder database)
EPS	50	0.036 (Saint-Gobain, 2019)
OSB	12	0.130 (Norbord, 2019)
Mineral wool	100	0.037 (Termolan, 2019)
XPS	60	0.035 (Danopren, 2019)
Vinyl flooring	3.4	0.250 (Sarlon, 2019)
PVC mantle	1.5	0.170 (Danopol, 2019)
Wooden door	44	0.143 (Vicaima, 2019)

The construction elements were modelled on DesignBuilder following the module`s assemble manual (Rosa, 2018), and the thermal properties of the materials present in the software`s database were changed to equal the ones of the materials used in the module`s construction. The Table 2 presents the cross sections of the elements modelled on the software, as well as a description of its layers and the *U*-value calculated for each element by the software.

Table 2 - Cross sections of the construction elements modelled on DesignBuilder.

Element	Cross section	Materials (outer to inner surface)	Thickness [mm]	*U*-value [W/(m^2.K)]
External walls		Reinforced plaster EPS OSB Mineral wool OSB	05 50 12 100 12	0.226

Floor pavement		Air gap OSB XPS OSB Vinyl flooring	234 18 60 18 3.4	0.408
Ceiling		Mineral wool OSB	100 12	0.333
Roof		PVC mantle EPS OSB	1.5 50 12	0.599
Door		Reinforced plaster EPS Wood	05 50 44	0.524

All the construction elements were modelled in the “Construction” tab of the DesignBuilder model. Still in this tab the parameter “Airtightness” was set to a constant rate of 0,05 ac/h, as the module was built to be airtight but there are slits alongside the junction of the door with the walls, that lead to infiltrations. As the air infiltration is constant, the “schedule” selected for the “Airtightness” parameter was “On 24/7” which maintain the constant rate of 0,05 ac/h during all time. A study of the air infiltration on the module was undertaken by Rosa, 2018.

As the module does not have natural or mechanical ventilation, in the “HVAC” tab of the software the HVAC template was set to “No heating/cooling” and the parameters “natural ventilation” and “mechanical ventilation” were both set off. Also, as the module is kept empty, the activity of the space was set as "None" in the "Activity" tab, and the occupancy parameter was set off.

The simulation was conducted for the period of 27th of July until the 16th of October, as the data loggers used for the calibration of the models were installed in the module in the 26th of July and its data of internal air temperature were collected for the first time in the 17th of October. The internal air temperature was measured until the 19th of January, but there was a problem with the CoolHaven weather station, which stopped recording data of solar radiation since the 4th of November, making it unfeasible to compare the results of the simulation with the data recorded inside the modules from this date. The results of internal air temperature over time of the simulation were compared with the data collected from the equipment installed inside the module 1. Graphs with the comparison among data from the simulation and data collected from the measurements inside the module are presented below, in Figure 18 and Figure 19. It is possible to observe that the curves are similar in format, but the peaks of temperature are different. The temperature data from the simulation shows that the model has a smaller variance in temperature throughout the day, with a smaller difference between the daily peaks of higher and lower temperature. That smaller fluctuation in temperature might indicate that the heat losses in the model are smaller than in reality, which might be linked to the small *U*-values of the construction elements. It is also possible to identify a difference in time of the peaks of temperature from the model and the module. There is a difference of about 3 hours in the temperature peaks recorded from the peaks simulated, which shows that the model has a higher thermal delay than the module.

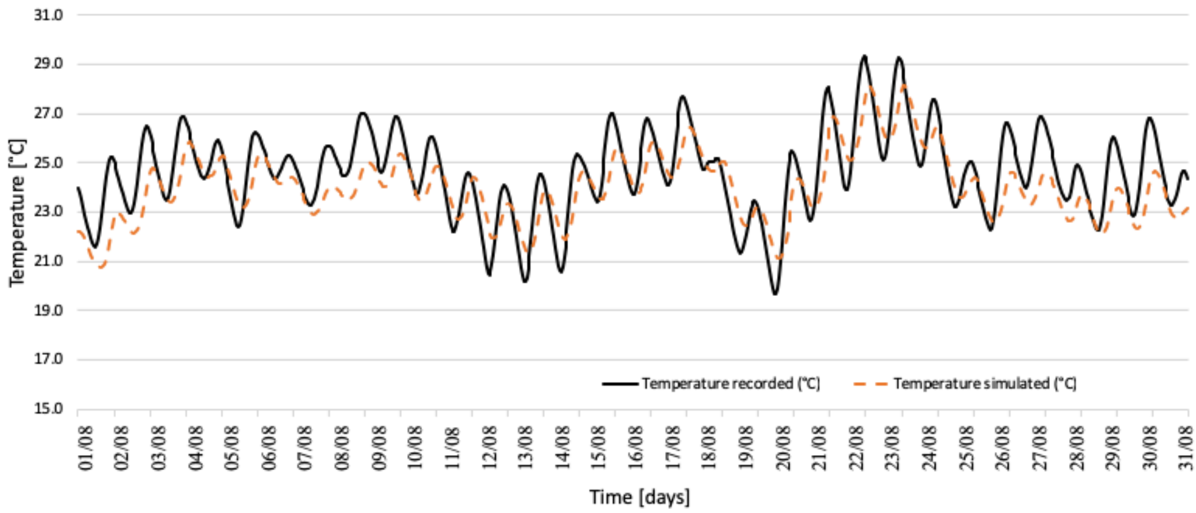


Figure 18 - Comparison of temperature data recorded and simulated – August.

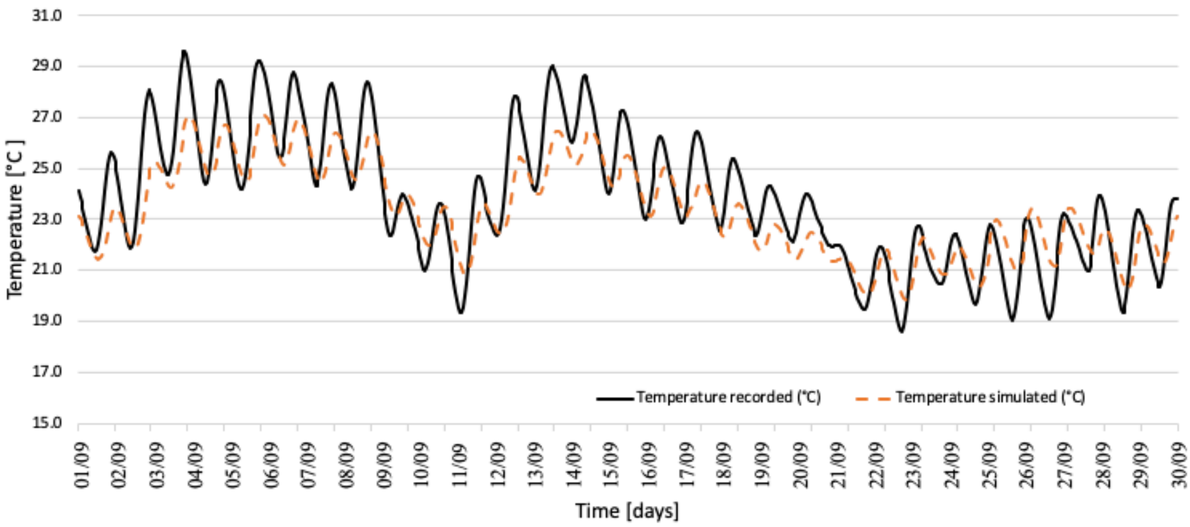


Figure 19 - Comparison of temperature data recorded and simulated – September.

Aiming to improve the quality of the model, a sensibility analysis will be conducted to approximate the data from the simulation to the data recorded inside the module 1, to calibrate the model. For that, some parameters are to be changed in the model created on DesignBuilder, and then new simulations will be conducted, to understand the impact of this parameters on the inside air temperature.

3.2 Calibration of the reference model on DesignBuilder

In order to approximate the results of the simulation from the air temperature data measured inside the module by the data logger, a sensibility study was carried to assess the impact of some parameters in the simulated indoor temperature. These parameters are related in majority to the accountability of the thermal bridges created by the steel sections in the construction elements, which is not taken in consideration on the first model developed. Two construction elements are in this situation, the ceiling and the external walls, as these elements has steel sections bridging its inner thermal insulation layer, composed of mineral wool. For the ceiling, as the steel sections are placed only in one direction, a 2D model was developed on the software THERM, to assess the influence of the steel element in the *U*-value of this element.

For the walls, as there are steel sections in the vertical, horizontal and diagonal planes, the ASHRAE zone method was used to calculate the *U*-value taking in consideration the effects of the steel sections. Briefly, this method assesses the global *U*-value for an assembly element with materials that have a high difference in conductivity, such as those with steel structures. The global *U*-value for the assembly element is given by the sum of the equivalent *U*-value by the steel sections times its area of influence and the equivalent *U*-value by the area without the effect of the thermal bridge times its area of influence, all divided by the total area of the element (ASHRAE, 2017). A formula that can be used for the calculation of the global *U*-value is given in the equation 1, below.

$$U_{global} = \frac{U_{stud} . A_{stud} + U_{cavity} . A_{cavity}}{A_{global}} \quad (1)$$

where,

U_{global} = Thermal transmittance of the assembly element [W/(m^2.K)]
A_{global} = Total area of the element [m^2]
U_{stud} = Thermal transmittance on the area under the influence of the steel section [W/(m^2.K)]
A_{stud} = Area of influence of the steel section on the element [m^2]
U_{cavity} = Thermal transmittance on the area that is not under the influence of the steel section [W/(m^2.K)]
A_{cavity} = Area of influence without the effect of the steel section on the element [m^2]

The first step to assess these values was to obtain the *U*-value of the element both under the influence of the steel section region as in the called opaque zone, where the steel has less influence. For that, a model of the external wall was also created in the software THERM.

Both the models of the wall and the ceiling have a width of 600mm, being that the distance between the steel sections in the construction elements of the module, and the C section is positioned in the middle of the model. Two sensors were simulated in the wall THERM model, one right under the steel section and another one in the edge of the model, in order to obtain the *U*-value of these different regions. These sensors were modelled with the width of the correspondent steel length that influence the heat flux, being 45mm for the external walls (influenced by the flange of the section). Moreover, in the ceiling model the mineral wool was considered only between steel sections, and not inside of them where it was considered an air gap, as that is how the module was constructed.

The Figure 20 show the models developed on the software THERM and the *U*-values obtained, being already the global value for the ceiling and for the frame region and the edge region for the wall.

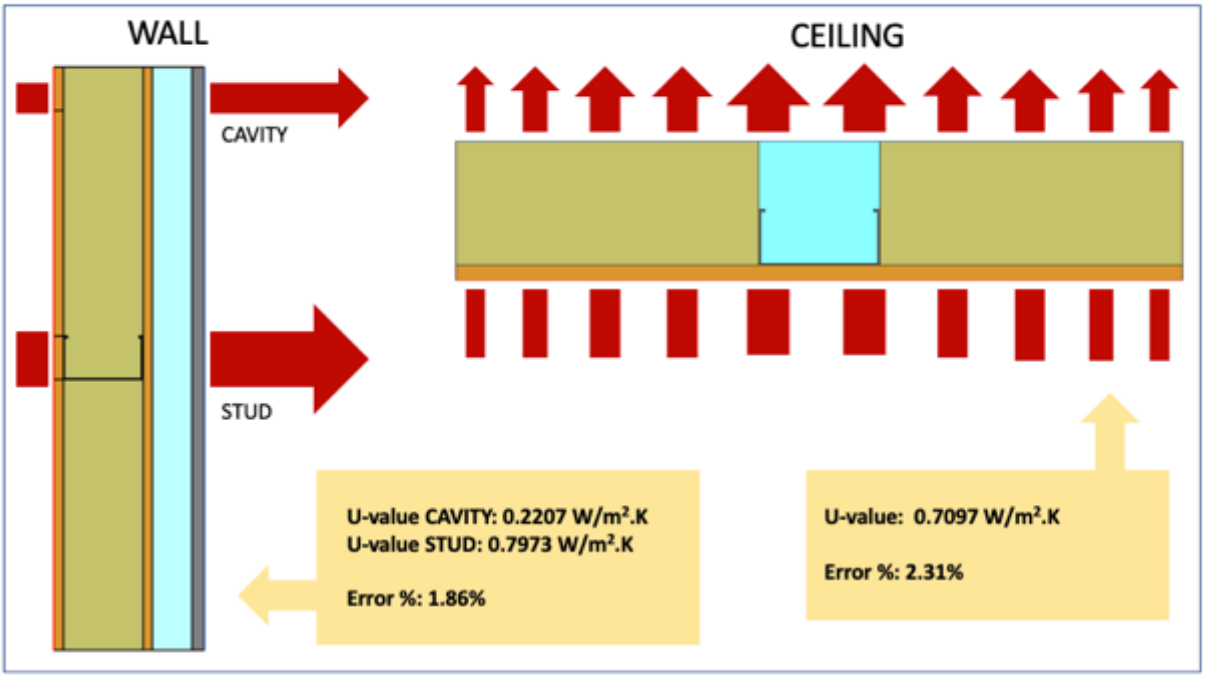


Figure 20 - THERM models of the external wall and of the ceiling.

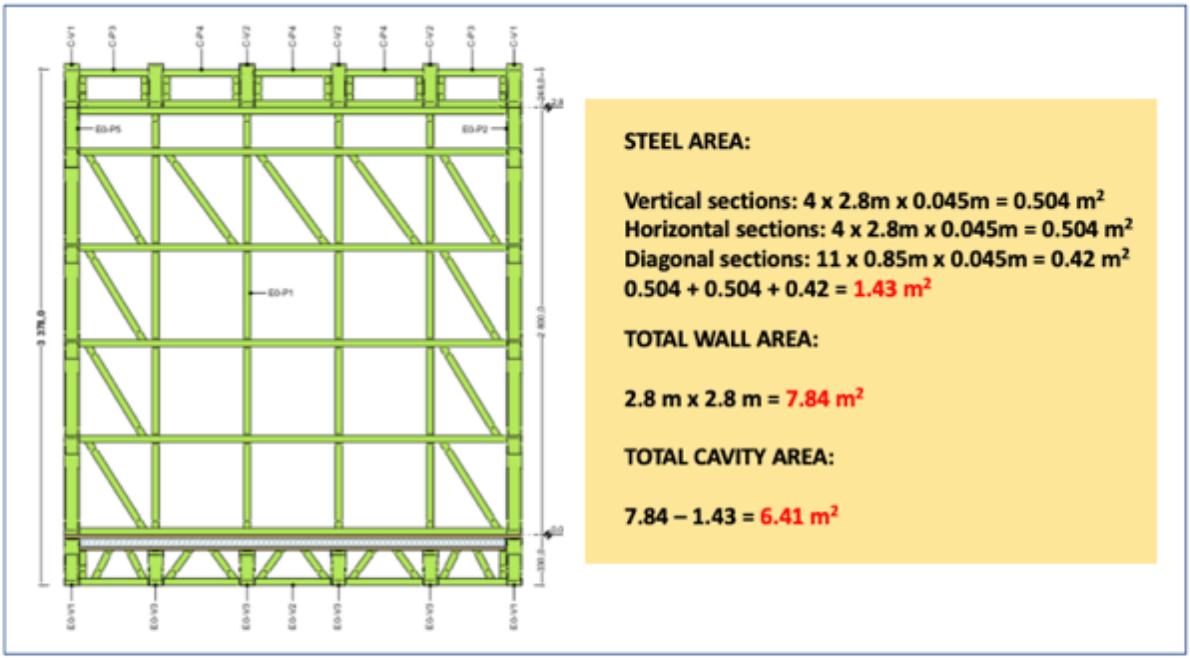


Figure 21 - Calculation of areas of influence for the external wall.

The next step is to calculate the percentage of the total area of the wall that is influenced by the steel sections. For that, the area of steel was calculated based on the structural schemes present in the assemble manual of the modules, then the total area of the element was calculated by its external dimensions, and at last the called cavity area is given by the total area minus the area of steel. The , presents a scheme of the steel sections in the walls and the calculation of the areas of influence necessary for the ASHRAE zone method, it is noteworthy that the steel sections of the perimeter of the walls was not consider for these calculations, as it could represent more of a linear thermal bridge of the module.

The final step is to calculate the global *U*-value for the assembly element using the equation stated in the beginning of this section. From the equation 1, the global *U*-value for the external wall is 0.3254 W/(m^2.K). For the ceiling the global *U*-value was taken straight from the THERM model, being 0.7097 W/(m^2.K). Without considering the steel elements the *U*-value was 0.241 W/(m^2.K) (26% smaller) for the walls and 0.333 W/(m^2.K) (53% smaller) for the ceiling. The new values were inputted in the DesignBuilder model using the “set *U*-value” tool on the “construction” tab, which caused a reduction in the insulation material to achieve the desired value. This method of considering the effects of thermal bridges in the simulations is presented in the DesignBuilder user`s guide (DSB@, 2013).

Moreover, another parameter studied regards how the crawl space present beneath the floor of the module was modelled. This space was firstly modelled as an air layer on the floor pavement, but the model might work closely to reality if it is considered as a different thermal zone. For that, the thickness of the crawl space should be stated in the “floor void depth” parameter in the “construction” tab of the software. When this scenario was studied, the air layer was deleted from the floor pavement construction element, the ground pavement was set to a concrete slab, and the “floor void depth” parameter was set to 0.234 m, the thickness of the air gap (DSB@, 2015). After the selection of the parameters to be analysed, the scenarios for the calibration study were set. Table 3 shows the scenarios created, as well as what are the changes in relation to the default model.

Table 3 - Presentation of the scenarios for the calibration of the model.

Scenario	**Modifications**	***U*-value of the walls [W/(m^2.K)]**	***U*-value of the ceiling [W/(m^2.K)]**
Scenario 0	Default model	0.2260	0.3333
Scenario 1	Altered the *U*-value for the walls	0.3254	0.3333
Scenario 2	Altered the *U*- value for the ceiling on Scenario 1	0.3254	0.7097
Scenario 3	Altered floor void gap on Scenario 1	0.3254	0.3333
Scenario 4	Altered floor void gap on Scenario 2	0.3254	0.7097

The simulations were carried for the total period of time present in the first data set collected from the data logger installed inside of the module, being from 27th of July to 15th of October 2019. It is important to state again that there was a problem with the CoolHaven weather station, which stopped recording data of solar radiation since the 4th of November, making it unfeasible to compare the results of the simulation with the data recorded inside the modules from this date.

Two statistical methods were used to assess the proximity between the data measured from the data simulated, the data correlation and the root square mean error (RSME). The first one is a tool that measures, in percentage, the linear relation between two sets of data, in other words it indicates the extent to which the variables fluctuate together, if when one increases the other decreases, and vice versa. The RSME measures how well a model performed, comparing the difference between simulated data with the real values. For this analysis, the smaller the value, the closer the simulation is to the reality. Table 4 present the correlation of data and RSME from each scenario with the data from the recorded temperature inside the module.

Scenario 4 shows the best correlation percentage for the whole period, however, all of the scenarios studied have high correlation with the recorded data, and the same can be observed regarding the RSME. From all models studied, scenario 4 best represent the real module regarding construction aspects, besides, although all the scenarios show high correlation values and small RSME values, the results from scenario 4 are especially high. From that, it is considered the best fit scenario in this study.

Table 4 - Correlation and RSME between data simulated from each scenario and data recorded inside the module 1.

Scenario	**Whole period**		**August**		**September**		**October**	
	Correl.	**RSME [°C]**	**Correl.**	**RSME [°C]**	**Correl.**	**RSME [°C]**	**Correl.**	**RSME [°C]**
Scenario 0	90.3%	1.19	80.3%	1.19	91.6%	1.28	82.5%	1.03
Scenario 1	95.4%	0.73	92.1%	0.74	96.0%	0.75	92.6%	0.69
Scenario 2	95.3%	0.74	92.1%	0.75	95.8%	0.75	92.4%	0.73
Scenario 3	96.1%	0.68	94.1%	0.70	96.5%	0.73	93.1%	0.69
Scenario 4	96.0%	0.67	94.1%	0.67	96.4%	0.72	92.9%	0.70

To visualize the impact of each scenario in the model, a graph with the evolution of indoor temperatures for the period of 02nd of September to 08th of September is presented below. This week was chosen because during it was recorded high sun radiation and external air temperature of above 30°C, which could represent a typical summer week in Portugal.

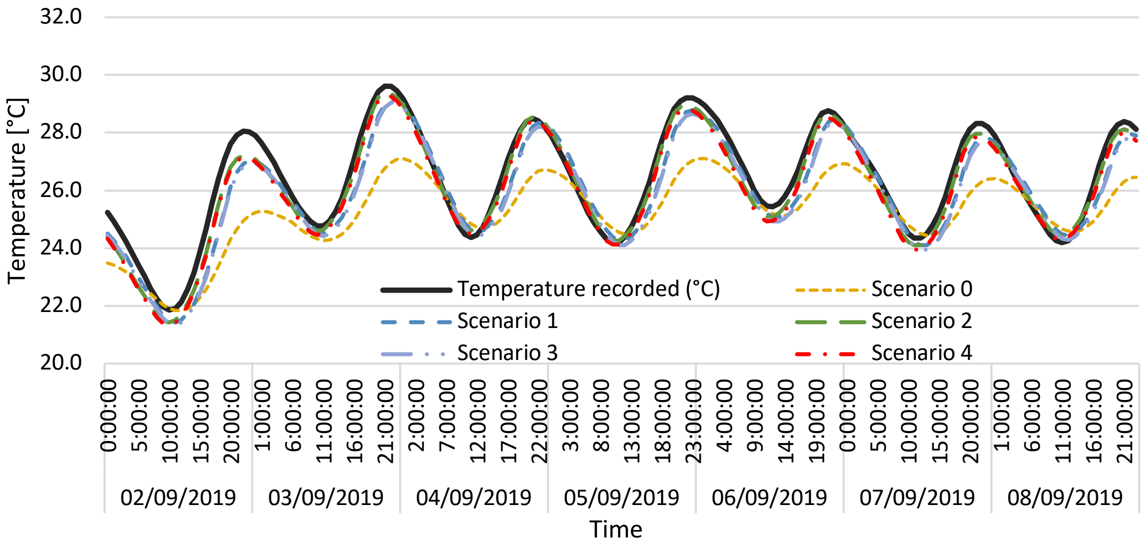


Figure 22 - Evolution of temperature - 02 to 08/09/19 (All scenarios).

Figure 22 presents a graph showing all the scenarios studied during the referred week, while Figure 23 presents a graph for the same period containing only the best fit scenario (Scenario 4), shown in comparison with data from the recorded temperature inside the module. For this particular week the correlation of data between recorded and simulated temperature is 98.85% and the RSME is 0.5°C.

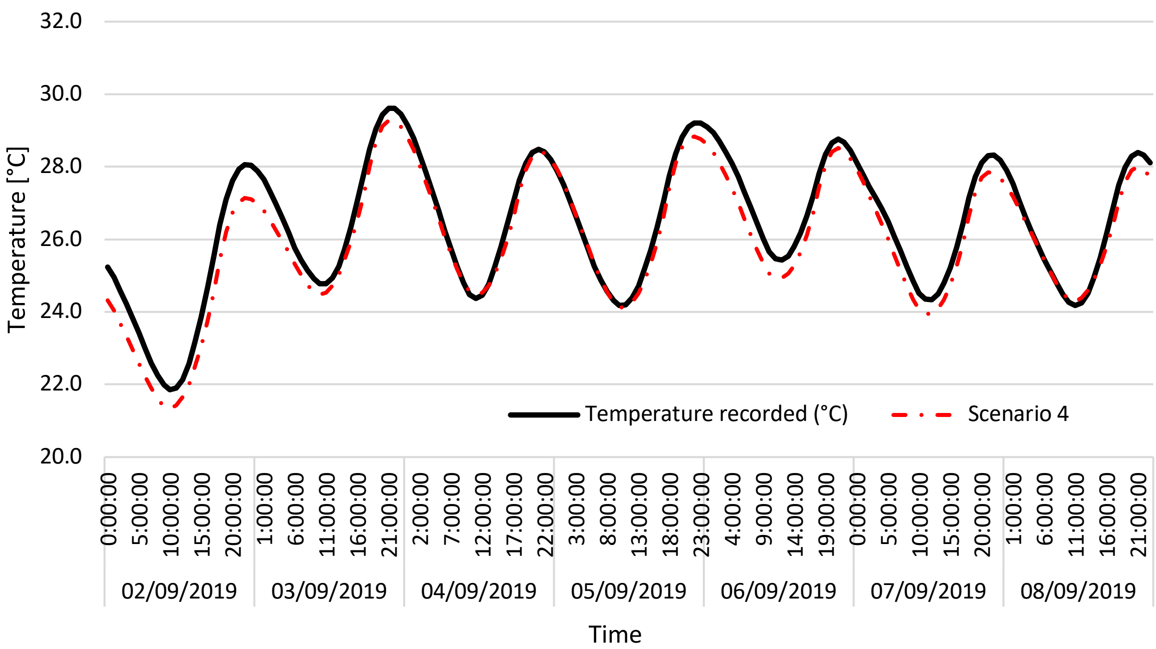


Figure 23 - Evolution of temperature - 02 to 08/09/19 (best fit scenario).

The scenario 1 approximated the simulated temperature curve from the recorded temperature curve, both in the y-axis (temperature peaks) and x-axis (thermal delay). The scenario 2 maintained the same curve, however it increased the maximum temperature peaks in about 0.5°C from the scenario 1, while the minimum peaks were maintained. These changes were expected, as the increase in the *U*-value of the construction elements represent a greater thermal loss for the module, increasing temperature fluctuation inside of it, and diminishing the thermal delay by the building envelope, which is linked to its thermal insulation.

Scenarios 3 and 4, where the floor void gap was altered in the previous scenarios caused similar results. When performed a correlation between the data, both scenarios had a good influence in the approximation of results when compared to the scenario 1.

In conclusion, scenario 4 best represent the real module regarding construction aspects and it is considered the best fit scenario in this study. This scenario is chosen to be used to further develop this project considering the results for temperature values simulated and the correlation of data from those to the measured values.

4. ASSESSMENT OF THE LSF MODULE WITH A TROMBE WALL

The second task is to repeat the activities from the first step for the LSF module with the Trombe wall installed. The measurement equipment is the same, and the results obtained from its data will be compared to the results from another model (with a Trombe wall) also created on the software DesignBuilder.

The main challenge at this point is to model the Trombe wall in the most accurate manner as possible, to correctly simulate its operation and thermal performance. A CFD analysis is carried to check if the simulated device works coherently.

4.1 Modelling the LSF module 2 on DesignBuilder

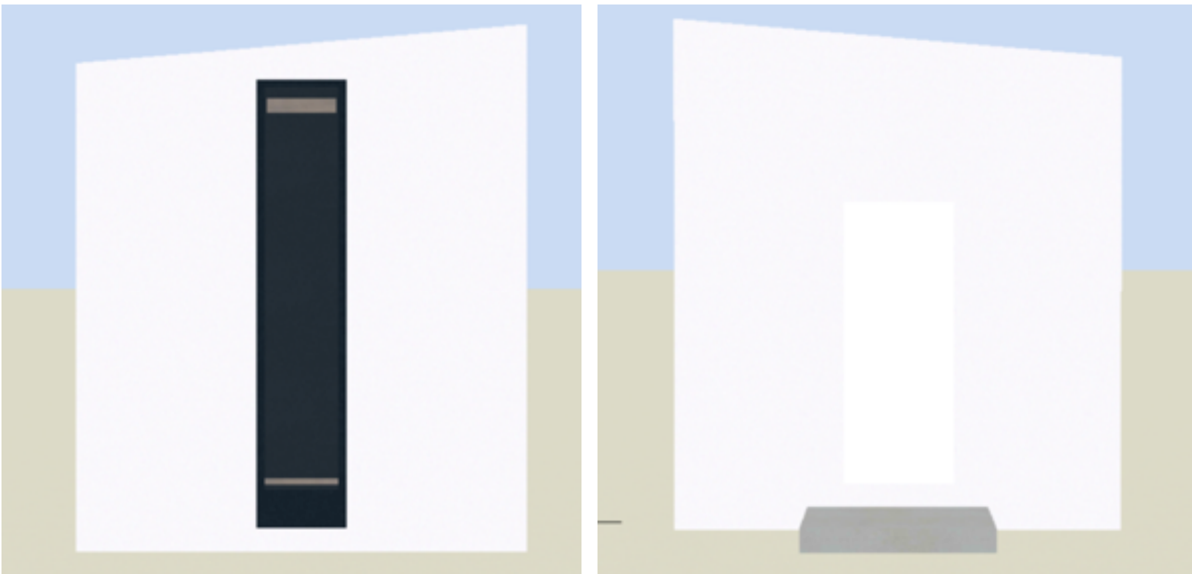
After completing the model of the reference LSF module (module 1), the next stage of this work is to develop a model of the LSF module that has a Trombe wall on its south facade (module 2). For that, the DsB file where the first model was created is used as a reference for the Trombe wall to be modelled on its south facade.

The water Trombe wall is 2.80 m high and 0.60 m wide, being a steel structure composed of an outer glazing, which is double glass with 4 mm + 16 mm of argon + planistar 6 mm, an air cavity of 70mm, a steel thermal storage wall with 0.05m of thickness filled with water, and a layer of 0.10 m of mineral wool on its inner surface. There are two air vents on the Trombe wall, the upper air vent is a rectangle with dimensions of 0.50 m x 0.10 m, while the bottom vent is a rectangle with dimensions of 0.50 m x 0.05 m (Rosa, 2018).

On the model created for the module 2, the steel used for the structure of the Trombe wall had its surface properties altered to simulate the dark paint used in the real device. The parameter "Solar absorptance" was set to 0.9, as the "Visible absorptance" altered to the same value (ASHRAE, 2005 apud Ferreira, 2015). The air cavity had to be set to 10 cm instead of the 7 cm of the real device, as the software did not perform the simulations when the air cavity was smaller than that. Figure 24 presents rendered images of the model developed for module 2.

In terms of simulation criteria there are a few differences between the one undertaken for the model of the module 1 and the module 2, regarding internal calculation algorithms. The parameter “Inside convection algorithm” is now set to “5 - cavity”. This algorithm was created to model the effects of convection between the outer surface of the thermal storage wall and the glazing area, allowing to a correct assessment of the convection coefficients according to the international standard ISO 15099. The “Outside convection algorithm” was set to “6 – DOE-2”, based on a component of forced convection and other of natural convection (Pinto, 2015).

For the software DesignBuilder to correctly calculate the natural ventilation and infiltrations on holes and air vents on walls, it is necessary to set the parameter “Natural ventilation and infiltration” to “Calculated”. It ensures that the assessment of these parameters due to the difference in air pressure, wind and flamboyance through this type of openings (Pinto, 2015). It is important to state that DesignBuilder does not have any built-in algorithm validated for the calculation of a naturally ventilated Trombe walls, only for sealed Trombe walls, which had been validated with experimental data by Ellis, 2003 (apud DSB@, 2014).



a) b)

Figure 24 - Rendered model of the module 2: a) south facade; b) north facade.

Similarly to the module 1, the simulations were carried for the total period of time present in the first data set collected from the data logger installed inside of the module, being from 27th of July to 15th of October 2019. As shown in Figure 25, the curve for the simulated temperature has the same format of the one for the temperature measured inside the module, with temperature peaks that are similar to each other during the majority of the period, although its peaks are more angular, with the maximum point being reached before. Table 5 presents the percentage of correlation and the RSME between the simulated data and the data measured inside module 2.

Table 5 - Correlation and RSME between data simulated and data recorded inside the module 2.

Whole period		**August**		**September**		**October**	
Correl.	**RSME**	**Correl.**	**RSME**	**Correl.**	**RSME**	**Correl.**	**RSME**
94.3%	0.89°C	95.2%	0.81°C	95.7%	0.86°C	95.4%	0.90°C

The graph presented in the Figure 25 shows the evolution of indoor temperatures for the period of 02nd of September to 08th of September, in order to allow comparison of thermal behaviour between module 1 and 2. The data correlation for this particular week is 97.45% and the RSME is 0.6°C.

It is possible to notice the effects of the Trombe wall on the modules, while the high temperature peaks inside module 1 was about 29°C (Figure 23), inside module 2 the high temperature peaks are about 34°C for the same week. That was expected, as this Trombe wall is configured as a heating device. Further comparisons among the behaviour of both modules are made in the following chapter 6.

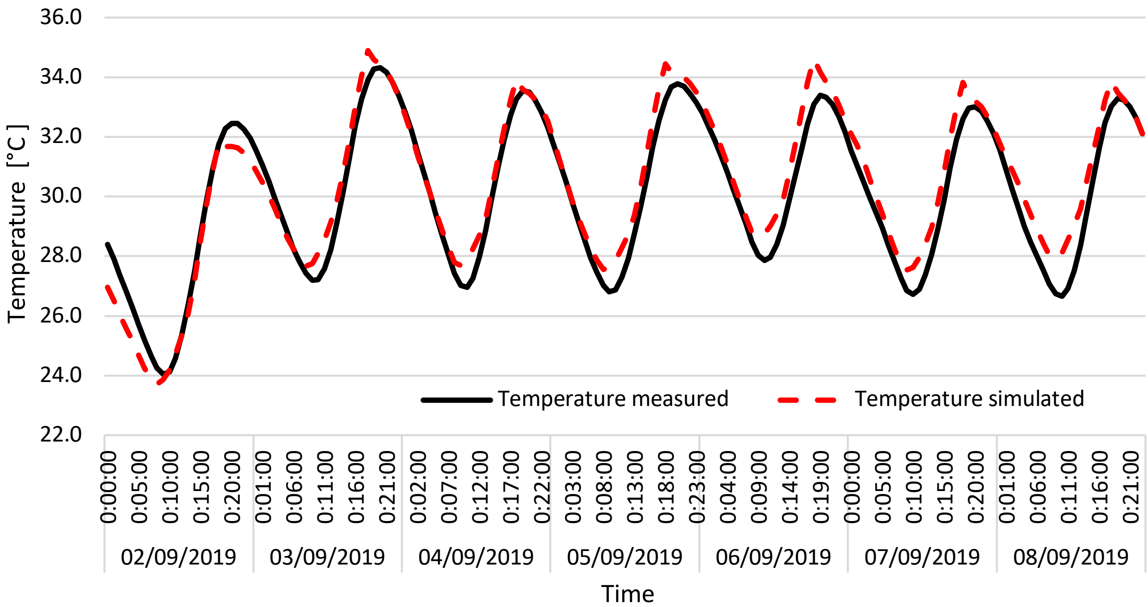


Figure 25 - Evolution of temperature inside module 2 (Trombe wall) - 02 to 08/09/19.

4.2 Computational Fluid Dynamics Analysis of the Trombe wall

The computational fluid dynamics (CFD) is a computational tool that allows the user to resolve and analyse problems involving fluid flows. The simulation is based on calculations that consider the finite elements method, with which a software can determinate the flow concentration, velocity, pressure and temperature of a fluid, such as the air inside the Trombe wall's cavity or inside of the module 2. In order to verify if the modelled Trombe wall is operating coherently, a CFD analysis is conducted on DesignBuilder, which has a built-in CFD tool.

For that, first it is necessary to stablish CFD boundary conditions to the model created. That can be done defining manually wall and window temperatures for all the surfaces present in the zone to be analysed or importing this data from a simulation already performed on the software (Ferreira, 2015). In order to import these parameters from a simulation is important to ensure that the boxes "Airflow In", "Airflow Out", "Inside surface temperature" and "External surface temperature" are checked in the "Outputs" tab of the model before performing it. The simulation is not dynamic, the data imported has to refer to a point in time of a full hour if the simulation is performed in an hourly basis or 30 minutes if the simulation is performed in a sub-hourly basis. For the simulation performed on this model the time chosen was 16:00 of the 4th of September, as the correlation of data between measured and simulated temperatures are high at this point, and the temperature is almost at the daily peak during this hour.

When performing a CFD analysis to the desired zone of the model, a grid volume is created, as the finite elements method is used for the calculations. The grid spacing for this analysis is 10 cm. After the calculations are finished and congruence is achieved, it is possible to create sections panes in the zone to visualize graphically the air velocity and the temperature in selected areas. The temperature is displayed in a scale of colours, from blue (colder) to red (hotter). The air velocity is displayed in vectors, being arrows that point out the direction of the flow, while also show the speed in a colour scale, from blue (slower) to red (faster).

The expected results for the model, to ensure that it is operating coherently, is that colder air enters the air cavity of the Trombe wall through its lower vent, while it flows upwards as it gets heated and return to the inside space of the module 2 through the upper vent. To assess this air flow the CFD analysis was performed for two zones, the air cavity of the Trombe wall and the inside space of the module 2.

The first CFD analysis performed was from the Trombe wall, and the results are shown in Figure 26. Two section panes were set for this analysis, one to create a front view of the air flow inside the air cavity and other to create a lateral view of the air flow. The air cavity of the Trombe wall presents high temperatures in its interior, from a minimum of 43°C up to a maximum of 51°C. It is perceptible through the colour scheme that the air enters the cavity in a lower temperature and gets heated up as it flows upwards, highlighting that the temperatures are higher at the borders of the Trombe wall, which are composed of steel sections. In terms of air velocity, the vectors show that the air is in fact flowing upwards, and that the air enters the lower vent faster than it leaves the upper vent, which can be explained by the influence of both the different size of the vents and the changes in temperature. The lower vent is smaller than the upper vent, creating a higher flow rate for the same volume of fluid. Also, it is possible to see in the results the relation between the air velocity and temperature, as the flow is faster at the borders of the Trombe wall, where the temperature is higher.

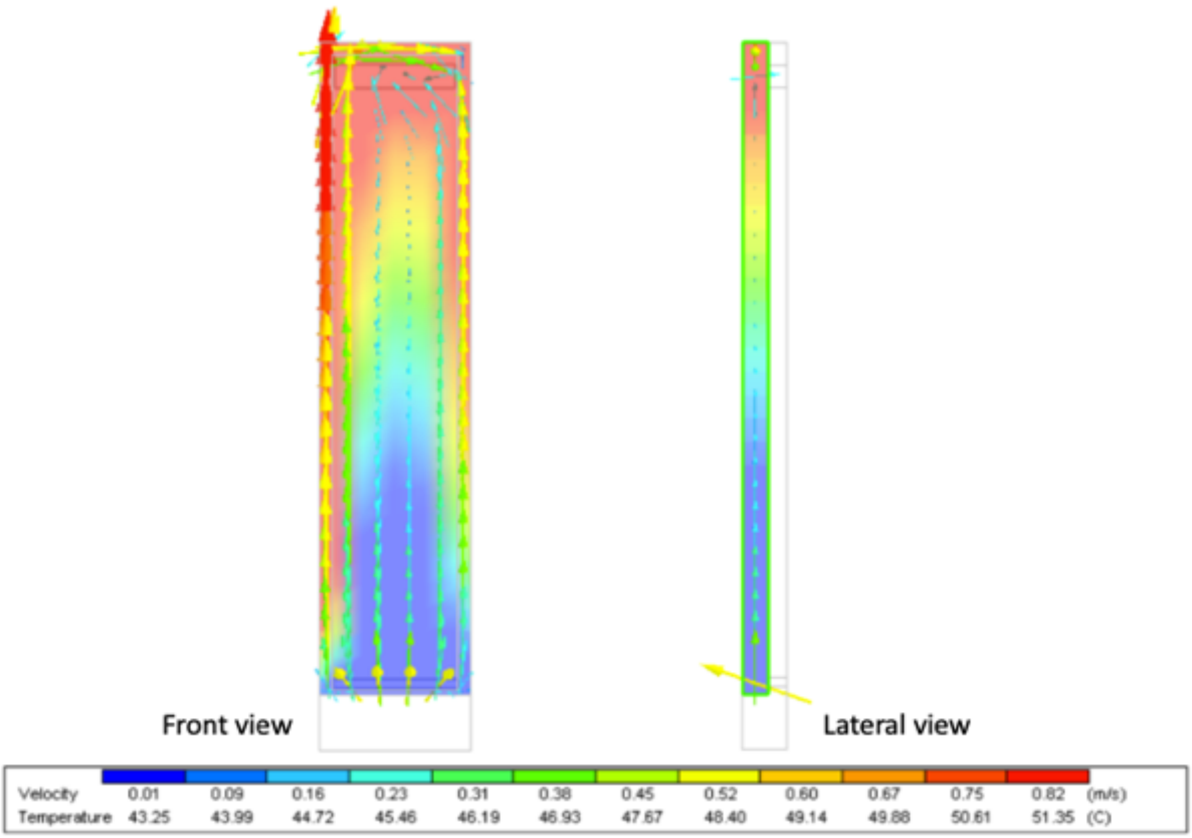


Figure 26 - CFD analysis of the Trombe wall.

The second CFD analysis performed was from the inside space of the module 2. Two section panes were set for this analysis, one at the height of the lower vent of the Trombe wall and another one at the height of its upper vent. The results are displayed in the Figure 27.0

From the results it is possible to conclude that the air is much hotter inside the air cavity of the Trombe wall than inside of the module, in which the temperature range is from 33°C to 36°C. The lower section pane shows that the air in the bottom of the module is more static and colder, while in the upper portion of the module the air is hotter and has more movement, as shown in the upper section pane. This section pane placement showed that it might have an air stratification inside the module 2, with higher temperatures at the top than at its bottom.

To better visualize how the air flows inside the module a third section pane was set, cutting it vertically from the door to the Trombe wall and creating a lateral view.

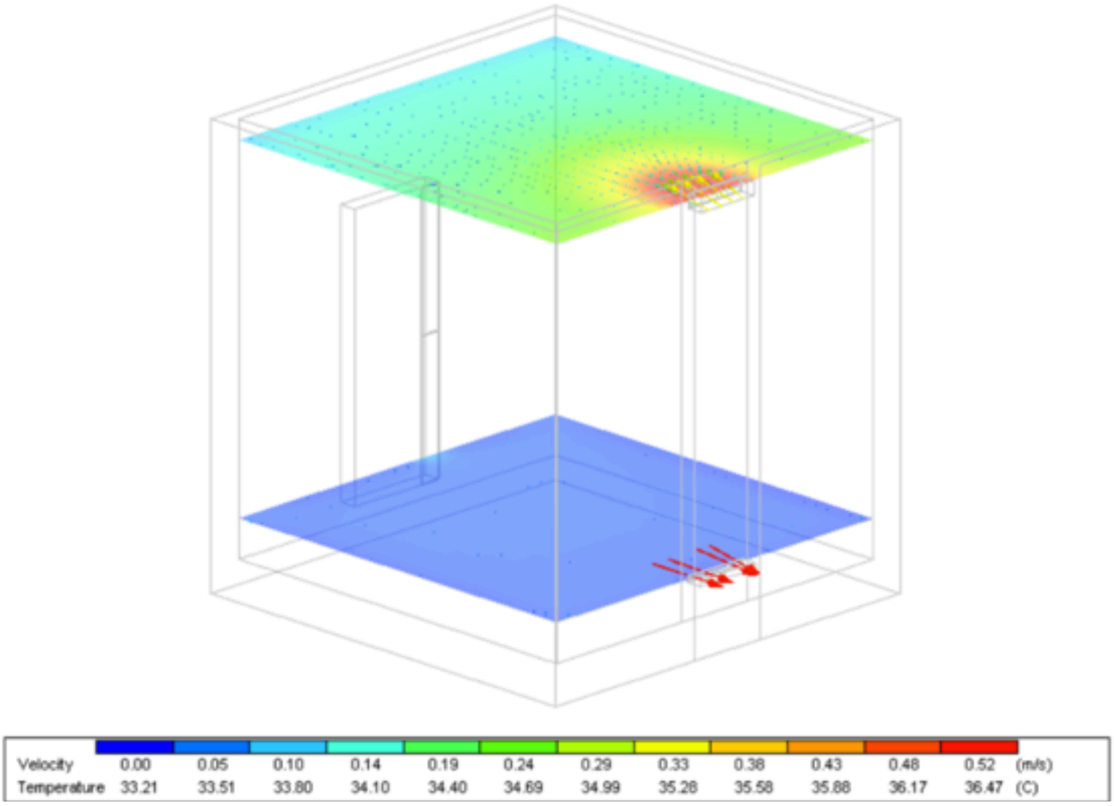


Figure 27 - CFD analysis of the module 2 – vents level.

The results of this new CFD analysis are displayed in Figure 28. The results show that the air enters from the upper vent and is directed to the opposite wall of the module and after to the bottom of it, making the air circulate. Nevertheless, it is perceptible that there is some air stratification. From this analysis is also perceptible the heat gains through conduction by the Trombe wall.

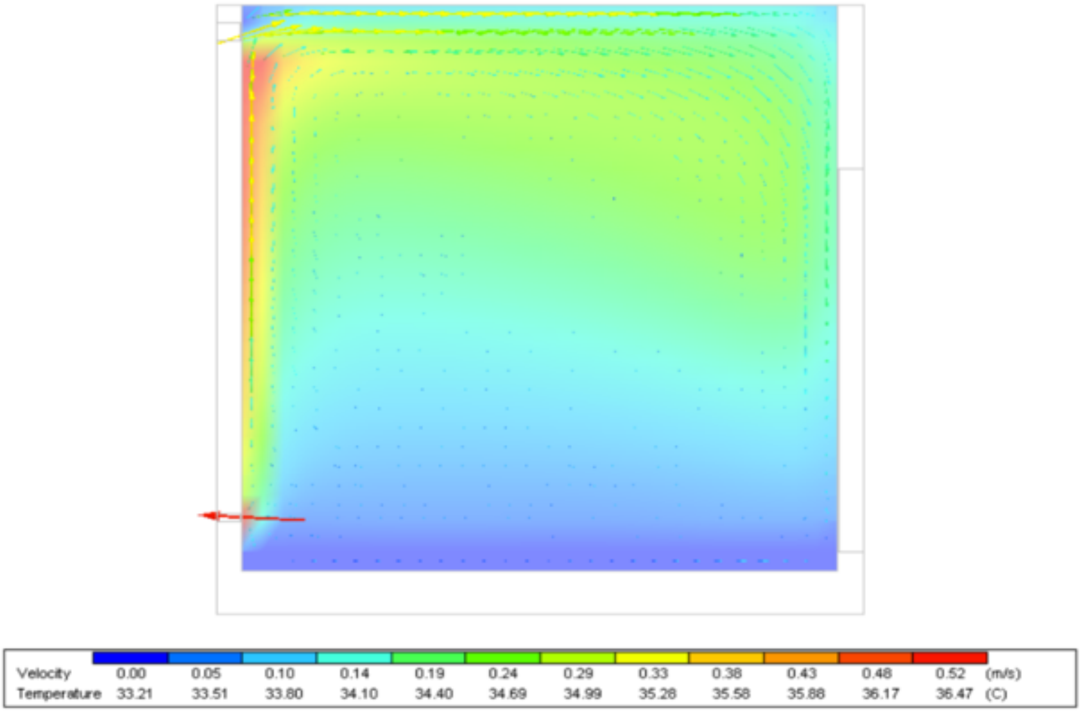


Figure 28 - CFD analysis of the module 2 – lateral view.

In conclusion, the CFD analysis have shown that the model of the Trombe wall created is operating coherently, as well as the results obtained in the thermal behaviour simulations showed results with high correlation with the data measured inside of the module 2.

5. QUANTIFICATION OF THE TROMBE WALL BENEFITS

After the calibration and validation of the DesignBuilder model of both LSF modules, the next task is to compare the results from the model of the LSF module without the Trombe wall with the one that has the device installed, in terms of indoor thermal comfort and energy performance.

That way it will be assessed the improvement in performance due to the Trombe wall. The comparisons are made using simulations from the models created on the software DesignBuilder, as well as the data from measurements taken simultaneously on both modules (with and without the Trombe wall).

5.1 Comparison of indoor temperature between modules

Measurements of internal temperature were conducted inside both modules 1 and 2 during the total period of 26th of July until 19th of January. Hence, it is possible to analyse the thermal behaviour of both modules during the summer and during the winter. The first analysis presented in this section is a comparison between the thermal behaviour of both modules in terms of internal temperature. For that, 4 distinct weeks are chosen to demonstrate the behaviour of the modules under different circumstances:

- Sunny summer week – from 2nd to 8th of September;
- Cloudy summer week – from 3rd to 9th of August;
- Sunny winter week – from 28th of December to 3rd of January;
- Cloudy winter week – from 16th to 22nd of December.

Graphs with the evolution of internal temperature for both modules during the sunny summer week and cloudy summer week are displayed in Figure 29 and Figure 30.

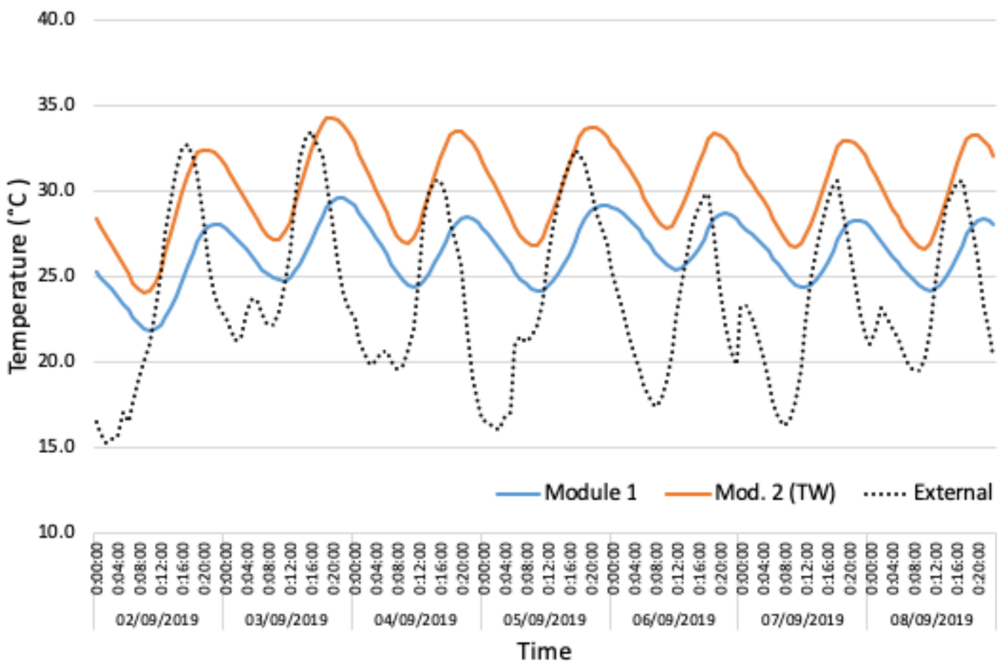


Figure 29 - Comparison of internal temperature between module 1 and module 2 – sunny summer week.

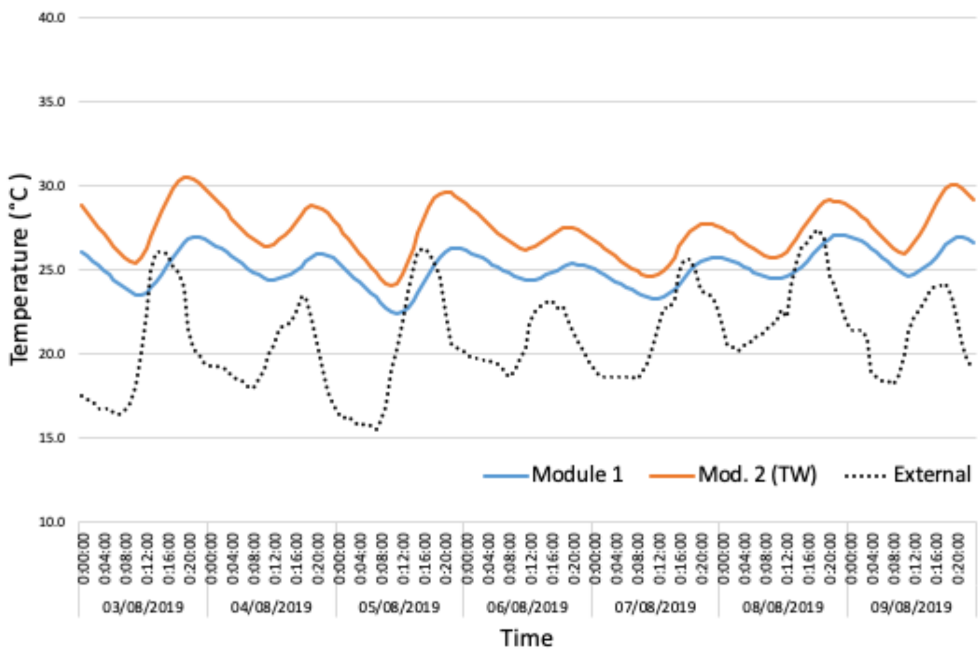


Figure 30 - Comparison of internal temperature between module 1 and module 2 – cloudy summer week.

From the graphs, it is possible to observe the influence of the Trombe wall on the air temperature of module 2, which is hotter than module 1 both during the sunny and the cloudy week. However, the difference between temperature in the modules is higher during the sunny week, as the Trombe wall exploits the sun radiation to heat the air on its cavity space. For the sunny summer week (Figure 29), the average temperature inside module 1 was 26.4°C, as for module 2 it was 30°C, a difference of 3.6°C. Meanwhile, for the cloudy summer week (Figure 30), the average temperature inside module 1 was 25.1°C, as for module 2 it was 27.3°C, a difference of 2.2°C.

It is important to highlight that the effects of the Trombe wall observed during these weeks is not beneficial to module 2 in terms of indoor thermal comfort, as it causes overheating. If the device was installed on an occupied building, shading devices would be necessary to avoid this excess of heat, or the external top vent present in the glazing area should be open, and the internal top vent sealed, in order to allow the heated air to scape to the outdoor (Ferreira, 2015), as demonstrated in Figure 8. This strategy would also help increase the ventilation of the module.

As the Trombe wall was conceived as a solar heating device, its behaviour during the winter season is the most important to be assessed. Figure 31 and Figure 32 show graphs with the evolution of internal temperature for both modules during the sunny winter week and cloudy winter week.

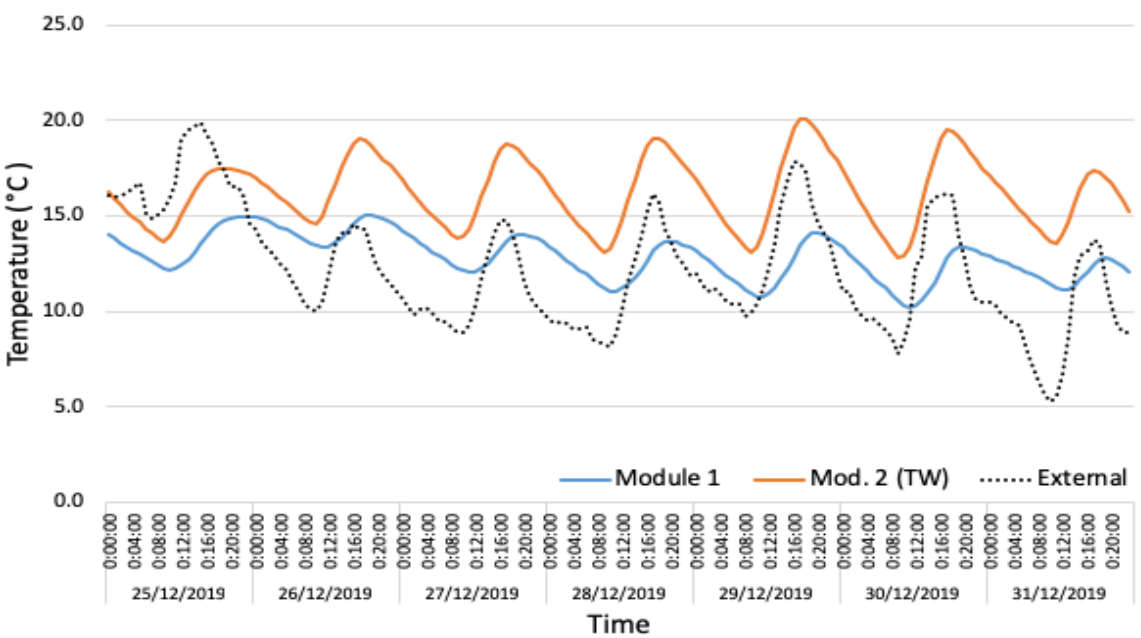


Figure 31 - Comparison of internal temperature between module 1 and module 2 – winter sunny week.

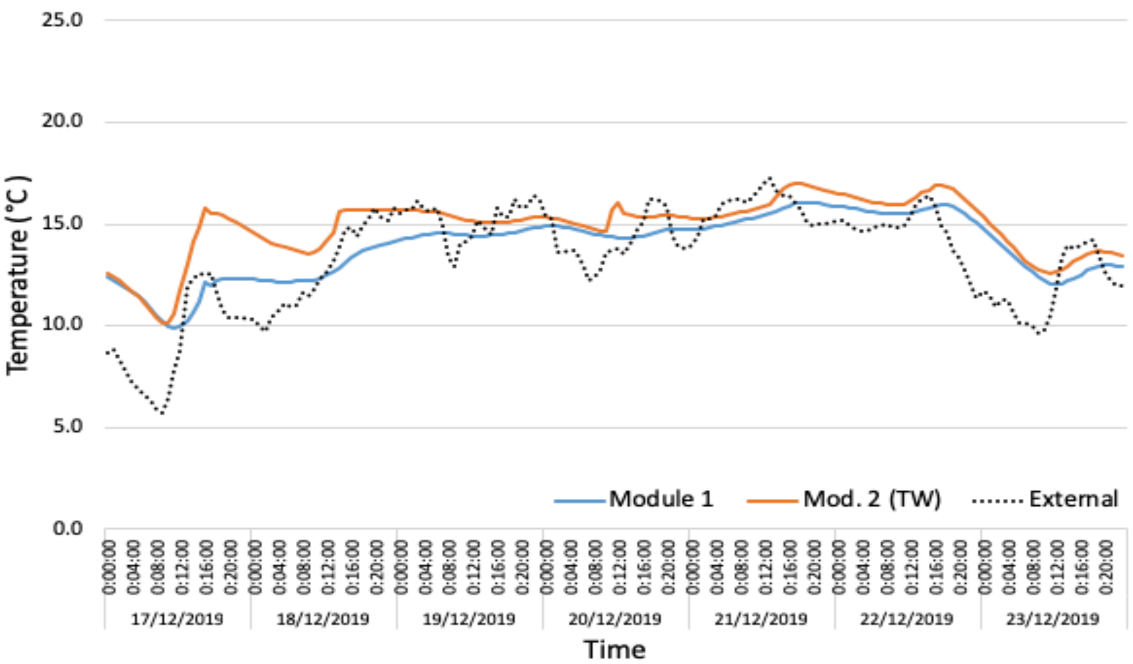


Figure 32 - Comparison of internal temperature between module 1 and module 2 – winter cloudy week.

For the sunny winter week (figure 31), the average temperature inside module 1 was 11.4°C, as for module 2 it was 15°C, a difference of 3.6°C. Meanwhile, for the cloudy winter week (figure 32), the average temperature inside module 1 was 14°C, as for module 2 it was 15°C, a difference of 1°C. Again, the greater influence of the Trombe wall was during sunny days. Although the difference between average temperatures between module 1 and 2 was of 3.6°C during the whole sunny week, the difference of maximum temperatures during the day is considerable. During the 29th of December the difference in maximum temperature between modules got to 6.6°C, while during the 3rd of September (sunny summer week) it got to 4.9°C.

During the cloudy week the temperature did not fluctuate much inside of the modules during the day, and the effects of the Trombe wall were the lower of the four weeks studied. However, on the 17th of December it is possible to observe a difference in maximum temperature between modules of 3.6°C, which must be linked to a period of higher sun radiation.

From that analysis it is possible to stablish a link between solar radiation and efficiency of the Trombe wall, as during the sunny weeks the difference between average temperatures of the modules were higher. Moreover, the difference between maximum temperature peaks were higher during the winter week (6.6°C) when compared to the sunny summer week (4.9°C), although, as stated before, the heating effects of the Trombe wall are not beneficial during the summer season and should be avoided.

5.2 Indoor thermal comfort and energy efficiency

In possession of a validated and calibrated model of both modules 1 and 2, it is possible to assess the benefits of the Trombe wall in terms of indoor thermal comfort and energy efficiency. For that, simulations were conducted for both models for the period of 22nd of December until the 20th of March, as it was observed in the previous section that the effects of the Trombe wall are more beneficial during the winter season.

It is important to highlight that for this simulation the weather data collected from the weather stations (which was used for the calibration of the modules) was not used, since the solar parameters, key for this analysis, were not recorded by the CoolHaven station since the 4th of November due to malfunctions. Instead, the IWEC weather file for Coimbra was selected on DesignBuilder`s database.

The temperature for thermal comfort inside of buildings during the winter season used to be indicated as 20°C by the Portuguese Regulation of Thermal Behaviour Characteristics of Buildings (RCCTE, in Portuguese) published in 2005 (RCCTE, 2005). However, with the publication of the Directive 2010/31/UE of the European Union (EU) regarding new parameters for the assessment of the energy performance of buildings, the Portuguese legislation had to be revaluated. The EU directive was, then, transposed to the national regulations through the law number 118/2013, in 2013. The regulation changed the value considered for internal comfort temperature from 20°C to 18°C for the winter season, value that is currently used to calculate the energy demand for heating (Jacinto, 2014).

To evaluate the indoor thermal comfort during the winter season inside the modules, the results from the simulations of the models are graphically compared with the mark of 18°C, to evaluate if any of the modules are able to achieve comfort with no heating system, and if the Trombe wall is capable of guarantee thermal comfort as the only heating system. Figure 33 displayed the comparison of the simulated indoor temperature inside the modules with the temperature of indoor comfort established by the Portuguese regulation.

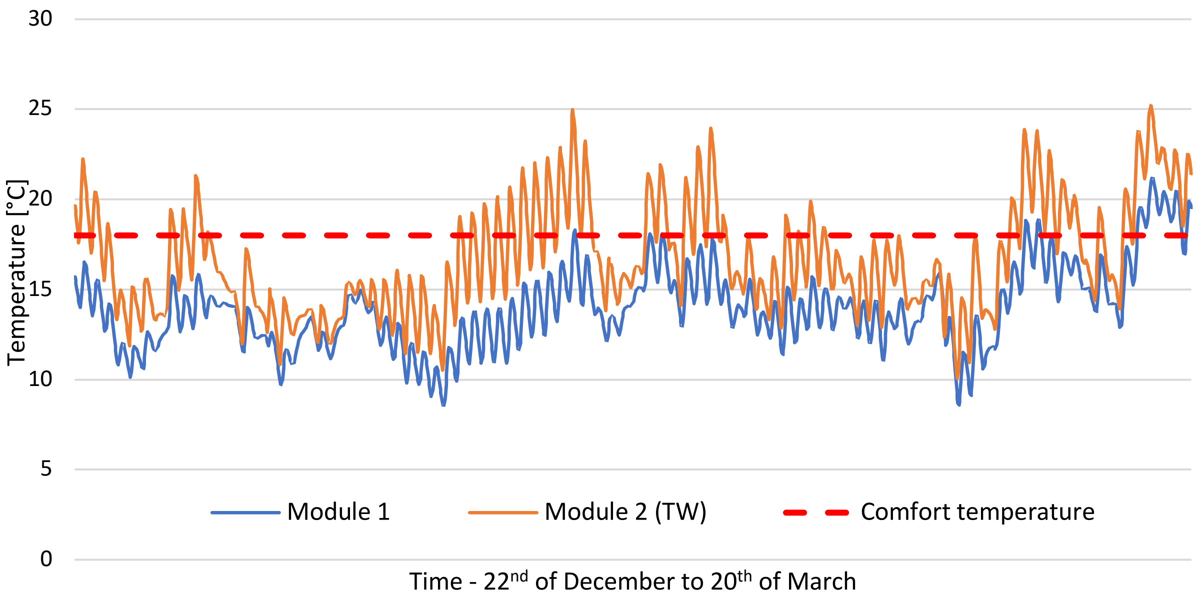


Figure 33 - Comparison of the indoor temperature simulated inside of modules 1 and 2 with the comfort temperature for the winter season.

From the image it is possible to observe that module 1 does not reach the temperature indicated as thermal comfort during the majority of the winter season, only surpassing the mark of 18°C on the last weeks of winter. Module 2 also does not reach indoor comfort during the majority of the winter; however, the inside temperature surpasses the mark of 18°C on 7 weeks. Moreover, the overall temperatures inside module 2 are closer to the mark of the comfort temperature during the whole period. Quantitatively, the software DesignBuilder can assess the hours in which the indoor thermal comfort is not met, based on the ASHRAE standard 55-2004. For the total period of simulation, of 2136 hours, module 1 did not met the requirements for thermal comfort in 2134 hours, while module 2 did not met the requirements in 2115 hours (+19 hours of comfort). The reason why these numbers seems small in comparison with the graph exposed in Figure 33 is that the ASHRAE standard consider not only the indoor air temperature to assess comfort, but also parameters as radiant temperature, air speed and humidity, which are not ideal inside the modules studied since there is no ventilation system designed nor even natural ventilation.

The analysis of indoor thermal comfort has shown that neither module 1 nor 2 is capable of reach comfort without another kind of heating system, as although the Trombe wall approximated the temperatures from the comfort line, the system alone does not guarantee comfort throughout the winter season. Hence, the next analysis aims to evaluate how the Trombe wall can help reduce the energy demand for heating, considering an air conditioning system as support.

For that, in the “HVAC” tab of the DesignBuilder`s models of the modules the parameter “No heating/cooling” was set to “Split no fresh air”, to simulate the presence of a split air conditioning system, with a coefficient of performance (COP) for heating of 2.35. The energy source was set to “Electricity from grid”. The heating setpoint was set to 20°C (previous temperature considered for calculating heating energy needs) and after to 18°C (current temperature considered for calculating heating energy needs), in order to analyse the difference in total energy demand for the winter season to elevate the inside air temperature in 2°C.

Two different scenarios were simulated for the “Schedule” parameter. The first scenario simulated an office space, that needs heating from 08:00 to 18:00, from Monday to Friday. The second scenario simulated a residential space, that needs heating from 19:00 to 07:00, during all days. Those scenarios were templates already present in the DesignBuilder`s database. The outcome of the simulations is the energy demand for heating, given in total energy for the whole period (winter season, from 22nd of December until the 20th of March) and energy per conditioned building area, in kWh and kWh/m², respectively. Table 6 presents the results of energy demand for heating from the simulations of modules 1 and 2 (where the Trombe wall is installed), on the scenarios studied.

Table 6 - Results of electric energy demand for heating the LSF modules during the whole winter season.

	Office space – heating during the day				**Residential space – heating during the night**			
	For 18°C		**For 20°C**		**For 18°C**		**For 20°C**	
	Total Energy [kWh]	**Energy per area [kWh/m²]**	**Total Energy [kWh]**	**Energy per area [kWh/m²]**	**Total Energy [kWh]**	**Energy per area [kWh/m²]**	**Total Energy [kWh]**	**Energy per area [kWh/m²]**
Module 1	82.17	4.52	121.65	6.69	110.13	6.06	165.48	9.1
Module 2 (TW)	56.98	3.13	100.13	5.5	101.82	5.59	171.6	9.42

The results indicate that, for the scenario where the heating needs occur during the day, the Trombe wall can help reduce the energy demand in 17.7% when climatizing the space until 20°C, and in 30.6% when climatizing the space until 18°C. That reduction is demand due to the fact that the device exploits the sun radiation to heat up the air inside of its cavity, and consequently the indoor space of the module, which decreases the need of heating from the split system. Moreover, according to the results it is necessary to use 43% more energy to climatize the module 2 to 20°C instead of 18°C, which confirms that the decrease in the reference temperature to calculate the energy needs for heating on the regulations can help to decrease the energy consumed by buildings in the country.

For the scenario in which the heating needs occur during the night, however, the module where the Trombe wall is installed actually required more energy to heat the module 2 to 20°C, 3.7% more. That increase in energy demand for heating inside module 2 is explained by two factors: first, the device requires solar radiation to work properly, which is not available during the period that requires heating in this scenario. Second, the Trombe wall has a higher *U*-value than the LSF walls, which causes a higher heat loss during the night, and increases the energy demand for heating. Therefore, it is important to design strategies to control these heat losses during the night, such as close the vents on the storage wall, incorporate blinds on the glazing area, or incorporate materials that could store heat during the day and transfer it to the interior space during the night, such as phase change materials (Saadatian *et al*., 2012).

6. PARAMETRIC STUDY OF THE TROMBE WALL

In this section a parametric study is conducted in order to assess the impact of changes in parameters of the Trombe wall on its efficiency. For that, simulations are carried for the reference model of module 2, already calibrated, and for different scenarios, in which some changes in parameters are proposed. The reference Trombe wall has an air cavity of 10 cm, vents dimensions of 50x5 cm (lower) and 50x10 cm (upper), and a 5 cm thick water storage wall. Table 7 presents the different scenarios studied.

Table 7 - Description of the scenarios studied.

Reference	Reference model of the module 2
Scenario 1	Air cavity changed from 10 cm to 20 cm
Scenario 2	Air cavity changed from 10 cm to 30 cm
Scenario 3	Vents dimensions changed to 50x8cm (lower) and 50x13cm (upper)
Scenario 4	Vents dimensions changed to 50x11cm (lower) and 50x16cm (upper)
Scenario 5	Thickness of the water storage changed from 5 cm to 10 cm
Scenario 6	Thickness of the water storage changed from 5 cm to 15 cm
Scenario 7	Storage wall changed to a 10 cm thick black painted concrete wall
Scenario 8	Storage wall changed to a 10 cm thick basalt wall

The simulations were conducted for the period of 22nd of January to the 29th of January, being a sunny week of the winter station. The analysis is made in terms of temperature evolution inside the module 2, while the impact of each scenario is given in terms of increment or decrement of the average temperature in relation to the reference model.

The first parameter analysed is the air cavity. The air cavity of the reference model is 10 cm thick, and the scenarios proposed change the thickness of the cavity to 20 cm (scenario 1) and 30 cm (scenario 2). The Figure 34 presents a graph with the evolution of inside air temperature of module 2 for the reference scenario, scenario 1 and scenario 2. From the graph it is possible to observe that the increase in thickness of the air cavity makes the temperature inside the module decrease. While the reference model has an average temperature of 18.2 °C for the studied period, for the scenario 1 it is 17.4°C (-0.8°C), and for scenario 2 it is 17.0°C (-1.2°C). This decrease in performance is linked to the fact that the increase in thickness of the cavity also increases the volume of air to be heated, and, as the results show, given the incident solar radiation and vent dimensions, higher volumes of air cannot be heated as effectively as smaller volumes. From that, it is perceptible that the best option is to have a smaller air cavity for this configuration of Trombe wall, as it has a better performance, and it keeps the device more compact.

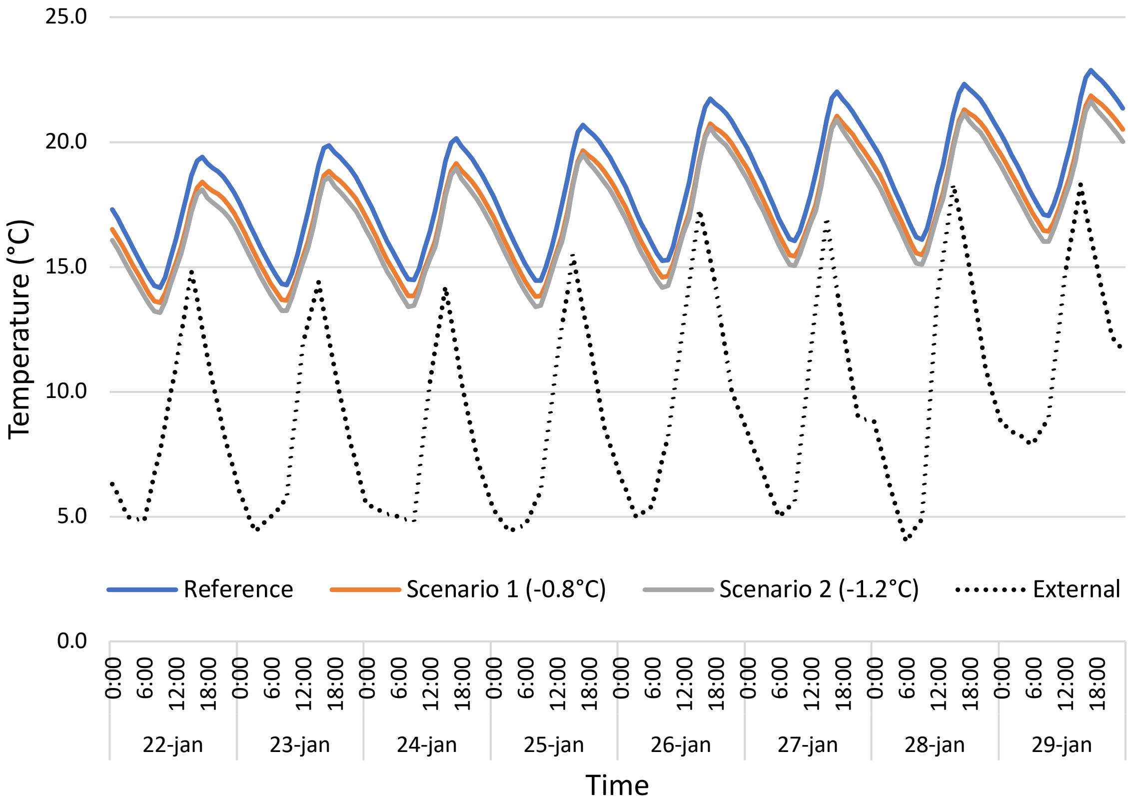


Figure 34 - Impact of changes in the thickness of the air cavity.

The second parameter analyzed was the dimension of the vents present on the storage wall in order to allow air convection. The reference model has an upper vent with dimensions of 50x10 cm and a lower vent with 50 x 5 cm. The Figure 35 presents a graph with the evolution of inside air temperature of module 2 for the reference scenario, scenario 3 and scenario 4.

According to the Figure 35, the increase in the vents` dimensions increased slightly the maximum peak of temperature during the studied period. For the scenario 3, where the vents were increased to 50x8cm (lower) and 50x13cm (upper), the average temperature was 18.7°C (+0.5°C), and for the scenario 4, where the vents were increased to 50x11cm (lower) and 50x16cm (upper), the average temperature was 18.8°C (+0.6°C). The results may indicate that the potential of heating due to solar radiation is not being fully tapped by the reference Trombe wall, as a slightly increase in the air flux caused an increase in the performance of the device.

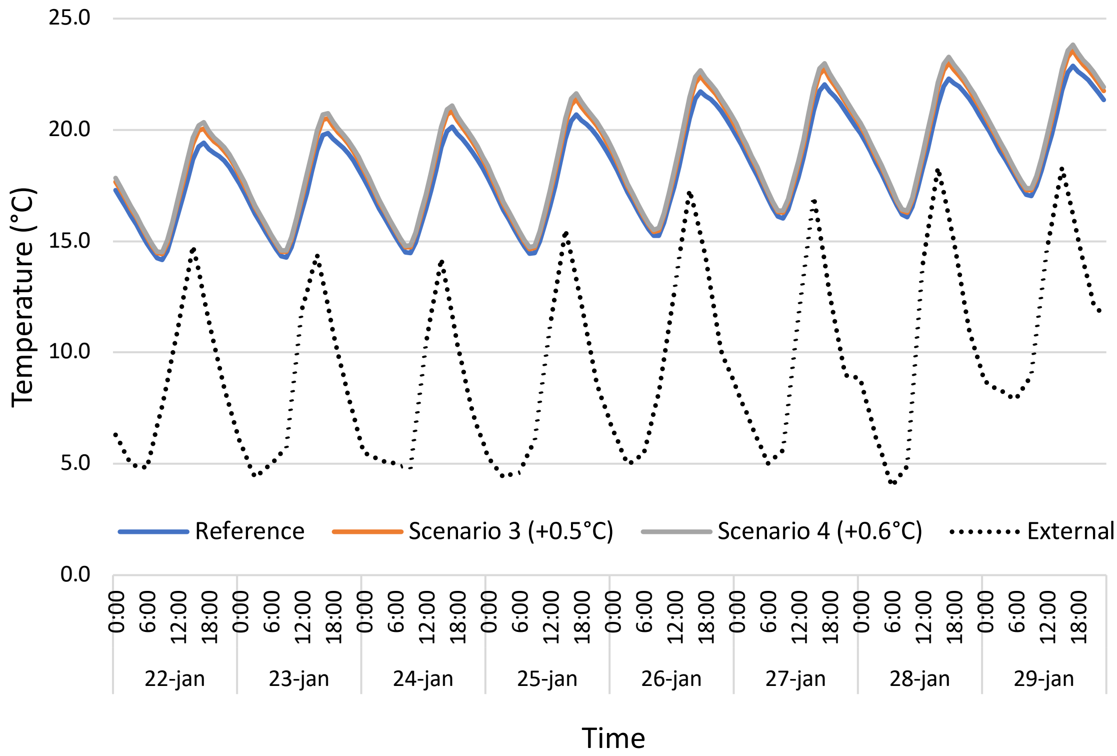


Figure 35 - Impact of changes in the dimension of the vents.

The third parameter analysed was the thickness of the water storage wall of the Trombe wall. The reference model has a 5 cm storage wall composed of black steel, filled with water. For this parameter the alterations proposed were to increase the thickness of the storage wall to 10 cm (scenario 5) and to 15 cm (scenario 6). The Figure 36 presents a graph with the evolution of inside air temperature of module 2 for the reference scenario, scenario 5 and scenario 6.

The results suggest that as the thickness of the storage wall is increased, the maximum peaks of temperature decreases, as does the average temperature inside the module. Scenario 5 has an average temperature of 17.5°C for the period (-0.7°C) in comparison with the reference), and for scenario 6 it is 17.2°C (-1.0°C). The decrease in the temperature peaks could indicate that the larger volumes of water present in scenarios 5 and 6 take longer to heat and are not heated as effectively as in the reference model, where the volume is smaller. Hence, the best option for this configuration is to have a thinner storage wall.

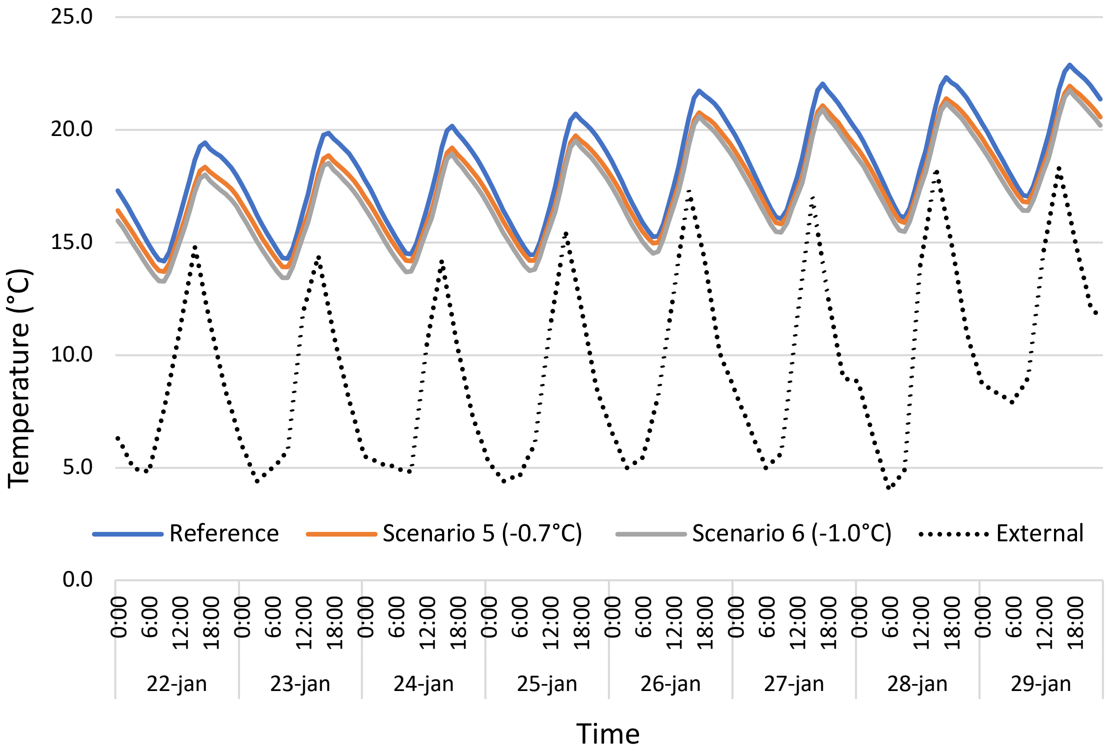


Figure 36 - Impact of changes in the thickness of the storage wall.

The last parameter studied was the material of which the Trombe wall is composed. As stated before the reference Trombe wall is composed of a water storage wall, but most commonly the device uses heavy materials such as concrete or stone to accumulate solar heat. From that, the scenarios proposed are a 10 cm concrete wall painted black (scenario 7) and a 10 cm basalt wall (scenario 8). To consider that the concrete is painted black, the material had its surface properties altered in the DesignBuilder`s database. The parameter "Solar absorptance" was set to 0.9, as the "Visible absorptance" altered to the same value (ASHRAE, 2005). The basalt, however, already has properties that indicates a dark colour. Figure 37 presents a graph with the evolution of inside air temperature of module 2 for the reference scenario, scenario 7 and scenario 8.

From the results it is possible to observe that the curves of temperature are similar in format for the three materials, however, the water storage wall delivers the higher inside temperatures to the inside space. Also, it is important to highlight that the water storage wall is 5 cm thick, while the other scenarios proposed have a 10 cm heavy solution. For the concrete wall the average temperature for the period is 17.2°C (-1.0°C), and for the basalt wall it is 16.8°C (-1.4°C). The better performance of the reference wall may be linked to the fact that the water has a higher specific heat than other construction materials as concrete and stones which enables it to store a higher amount of heat. While the specific heat of the concrete is 840 J/kg.K and 1000 J/kg.K for the basalt, the specific heat of water is 4190 J/kg.K. Another advantage of the usage of water as a storage wall is that, as a fluid, convection occurs inside of the container, which makes the heat to be transferred to the interior space faster in comparison with a classic Trombe wall (Saadatian *et al.*, 2012).

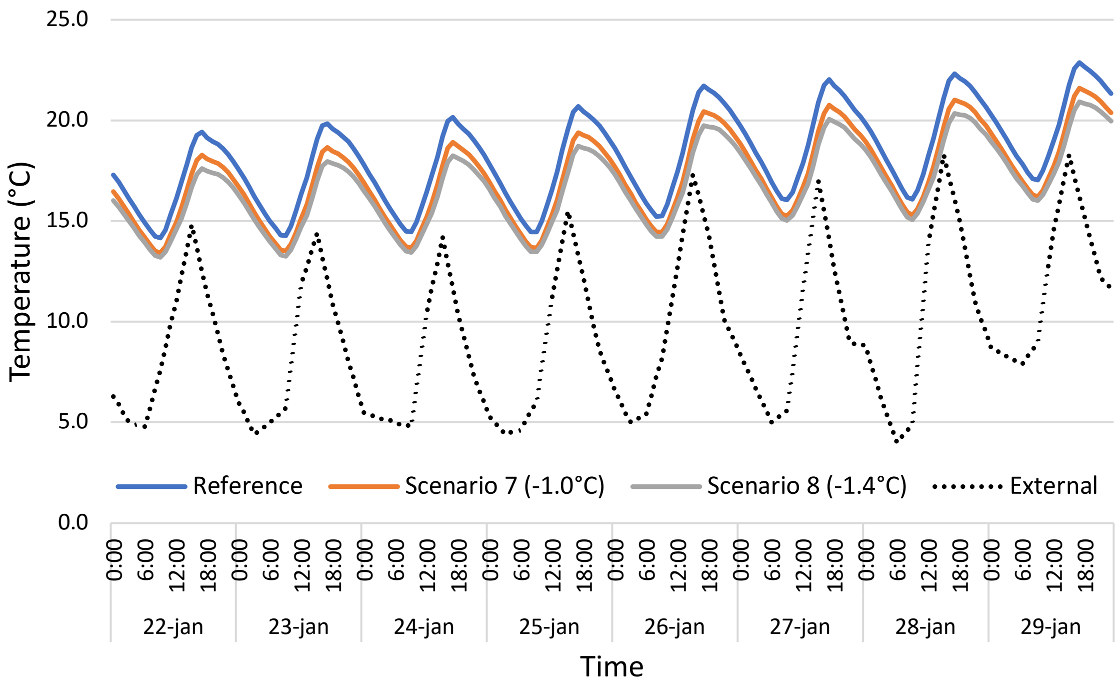


Figure 37 - Impact of changes in the material of the storage wall.

In conclusion, the parametric study showed that the design of a Trombe wall is no simple task, and many parameters have to be considered, as they can impact on the performance of the device. More, the study showed that the design of Trombe wall created during the PhD thesis of Rosa, 2018 was carefully considerate, as the changes in parameters proposed had a small impact in performance, and negative, in majority. The only parameter that could elevate the average inside temperature and maximum temperature peaks was the increase in the dimensions of the vents present in the storage wall.

7. CONCLUSIONS

This dissertation has the main objective to study the impacts of indirectly gains from solar energy in LSF construction through a Trombe wall, aiming to improve its thermal behaviour and reduce energy consumption, keeping the comfort level of occupants. This section presents the conclusion obtained during the development of this work.

The objects of study of this dissertation were two LSF modules constructed in the University of Coimbra campus. Those experimental modules are identical cubic compartments, being the only difference the presence of a water Trombe wall in the south facade of one of them. Measurements of internal temperature were taken in both modules, to evaluate the effects of the Trombe wall, as well as to help calibrate / validate the models of the two modules developed on the software DesignBuilder. Regarding the modelling of module 1, the reference module (without the Trombe wall), it was important to input the material properties of the actual materials used for the construction of the modules, taken from the technical brochures of the fabricants. The ASHRAE zone method was used to calculate the *U*-value taking in consideration the effects of the steel sections inside the construction elements. From that it was concluded that the steel sections in LSF construction have great effects over the thermal transmittance of the construction elements, as the *U*-value without considering its influence was 26% smaller for the walls and 53% smaller for the ceiling.

For the modelling of the module 2 (with the Trombe wall), the main challenges were to consider correctly all the construction aspects of the Trombe wall, including the surface properties of the materials and the geometry of the device, as well as to correctly assess the calculation parameters on DesignBuilder, as it is necessary to model the effects of convection between the outer surface of the thermal storage wall and the glazing area, allowing to a correct assessment of the convection coefficients inside the device. After the development of the model for module 2, a CFD analysis was conducted to verify if the modelled Trombe wall was operating coherently. It was perceptible through the results that the air enters the cavity of the device in a lower temperature from the lower vent and gets heated up as it flows upwards, to re-enter the indoor space through the upper vent, as it was expected. The high congruence in the internal temperature data from the simulations and the data measured inside the module, plus the results from the CFD analysis, shows that the model is reliable.

When analyzing the data of internal temperature recorded simultaneously inside both modules, some conclusions are made in terms of the effects of the Trombe wall on the thermal behavior of the modules. During the summer the air temperature of module 2 was hotter than module 1 both during the sunny and the cloudy week studied, as expected from a heating device. However, it is important to highlight that the effects of the Trombe wall observed during the summer is not beneficial to module 2 in terms of indoor thermal comfort, as it causes overheating. If the device was installed on an occupied building, shading devices would be necessary to avoid this excess of heat, or the external top vent present in the glazing area should be open, and the internal top vent sealed, in order to allow the heated air to scape to the outdoor. The same study was made for the winter season, during a sunny and a cloudy week, in which again the air temperature of module 2 was hotter than module 1 during both weeks, this time being a beneficial effect. From that analysis it was possible to stablish a link between solar radiation and efficiency of the Trombe wall, as during the sunny weeks the difference between average temperatures of the modules were higher than for cloudy weeks on both summer and winter stations.

Next, the benefits of the Trombe wall were quantified in terms of indoor thermal comfort and energy efficiency for the winter season, using simulations from the models developed on DesignBuilder. The analysis of indoor thermal comfort has shown that neither module 1 nor 2 is capable of reach comfort without another kind of heating system, as although the Trombe wall approximated the temperatures from the comfort temperature stipulated by the national regulation, the system alone does not guarantee comfort throughout the winter season. Hence, the next analysis aimed to evaluate how the Trombe wall can help reduce the energy demand for heating, considering a split air conditioning system, with a COP of 2.35, as support.

The analysis of influence of the Trombe wall in terms of energy efficiency were conducted for the scenario of an office space, where the heating would necessary during the day, and for a residential space, where the heating would be necessary during the night. The results indicate that, for the scenario where the heating needs occur during the day, the Trombe wall can help reduce the energy demand in 17.7% when climatizing the space until 20°C, and in 30.6% when climatizing the space until 18°C. Moreover, according to the results it is necessary to use 43% more energy to climatize the module 2 to 20°C instead of 18°C, which confirms that the decrease in the reference temperature to calculate the energy needs for heating on the regulations can help to decrease the energy consumed by buildings in the country. For the scenario in which the heating needs occur during the night, however, the module where the Trombe wall is installed actually required more energy to heat the module 2 to 20°C, 3.7% more, which shows that if not correctly insulated the Trombe wall can lead to higher heat losses during the night.

Lastly, a parametric study was conducted in order to assess the impact of changes in parameters of the Trombe wall on its efficiency. The results have shown that increasing the thickness of the air cavity decreased the performance of the device, as, given the incident solar radiation and vent dimensions, higher volumes of air cannot be heated as effectively as smaller volumes. The increase in the dimensions of the vents, in the other hand, helped increase the performance of the Trombe wall in terms of indoor temperature increment. The increase in thickness of the storage wall also did not increased the device performance, as the larger volume of water takes longer to heat and are not heated as effectively. The change in the material of the storage wall to heavyweight materials as concrete and basalt did not increase the performance of the Trombe wall, which may be linked to the fact that the water has a higher specific heat than other construction materials as concrete and stones which enables it to store a higher amount of heat.

From the analysis made, the final conclusion is that the Trombe wall can, in fact, improve the thermal behaviour of LSF buildings and reduce energy consumption. However, it is necessary to mitigate some challenges intrinsic to the device, being the possibility of overheating during the summer season and the increment in heat loss during the night. As stated before, for the first, shading devices would be necessary to avoid the excess of heat, or the external top vent present in the glazing area should be open, and the internal top vent sealed, in order to allow the heated air to scape to the outdoor. Regarding the nocturnal heat losses, the device should be insulated appropriately, as it is a weaker point on the building's envelope.

Finally, as future work recommendations, it is proposed the analysis of heat fluxes through the construction elements of the LSF experimental modules, in order to analyse the influence of the Trombe wall on them, especially in the south facade, where the device is installed. It would also be interesting to evaluate the change in efficiency of the Trombe wall due to the implementation of mechanical ventilation to increase the air flux inside its air cavity. Moreover, the methodology utilized in this work could be used to assess the influence of a Trombe wall on a full scale residential or office building, to analyse the effects of the Trombe wall on an occupied space. Also, it would be interesting to study the effects of the Trombe wall in different climate zones, such as in northern or tropical countries.

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