NOVA SCHOOL OF SCIENCE & TECHNOLOGY

DEPARTAMENT OF
CIVIL ENGINEERING

THERMAL REHABILITATION OF RESIDENTIAL BUILDINGS USING SOLAR PASSIVE TECHNOLOGIES

CONCEPTUALIZATION AND DEVELOPMENT OF THE SOLAR BRIDGE RETROFIT SYSTEM (SBRS) - AN INNOVATIVE VARIANT OF THE TROMBE WALL

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Thermal Rehabilitatin of Residential Buildings Using Solar Passive Technologies

To my beloved family and friends, whose unwavering support, encouragement, and love have been my greatest source of strength throughout this journey. Thank you for always being there for me.

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“There is no better teacher than adversity. Every defeat, every heartbreak, every loss, contains its own seed, its own lesson on how to improve your performance the next time.”

(Malcolm X).

ABSTRACT

Most of Portugal's residential building stock was constructed before the first thermal code, leading to poor energy efficiency and thermal performance. As a result, many buildings require retrofitting to achieve energy savings and improve thermal comfort, especially during the heating season. Structural components of load-bearing concrete frame buildings, such as concrete beams and columns, often act as thermal bridges, contributing significantly to poor energy performance and inadequate indoor thermal comfort.

To leverage Portugal's solar availability and mitigate the impact of structural thermal bridge areas in non-retrofitted buildings, an innovative solar passive retrofit solution, the Solar Bridge Retrofit System (SBRS), was developed. This concept is a variant of the unvented Trombe wall, incorporating an external transparent skin in front of the structural areas, combined with traditional ETICS for the remaining façade. Unlike traditional Trombe walls, this innovative design allows the heavy structure of the building to absorb solar radiation and slowly conduct the heat inward or to the adjacent structure, helping to offset heat loss

This PhD research aimed to: (1) Identify the advantages and drawbacks of Solar Passive Technologies; (2) Design the SBRS concept; (3) Conduct both experimental and numerical studies to assess the behaviour of a façades equipped with SBRS.

The study´s findings demonstrate that SBRS: 1) can significantly increase indirect-solar gains in structural thermal bridge areas during the heating season; 2) performs better with a double-glazing layout compared to single glazing; 3) requires ventilation strategies to optimize summer performance; and 4) is suitable across all Portuguese climate zones.

Keywords: Thermal rehabilitation; Solar passive technologies; Solar Bridge Retrofit System (SBRS); Trombe wall; Energy efficiency; Mediterranean climate.

RESUMO

Uma parte significativa do parque habitacional português foi construído antes da primeira regulamentação térmica, o que resultou numa fraca eficiência energética e desempenho térmico inadequado. Consequentemente, muitos edifícios necessitam de uma reabilitação térmica, especialmente para garantir as devidas condições durante o inverno. Um dos motivos para que tal aconteça são as áreas estruturais, como as vigas e os pilares de betão, que tendem a funcionar como pontes térmicas - zonas de perda de calor para o ambiente exterior.

Para aproveitar a disponibilidade solar de Portugal e mitigar o impacto das pontes térmicas estruturais em edifícios não reabilitados, foi desenvolvida uma solução inovadora de sistema solar passivo, o *Solar Bridge Retrofit System* (SBRS). Este conceito é uma variante da parede de Trombe sem ventilação, e consiste numa camada exterior transparente na frente das áreas estruturais, combinada com o tradicional ETICS na restante fachada. Contrariamente às tradicionais paredes de Trombe, este sistema permite que a estrutura do edifício absorva a radiação solar e conduza lentamente o calor para o interior ou para a estrutura adjacente.

Os objetivos deste trabalho de doutoramento foram: (1) Identificar as vantagens e desvantagens das Tecnologias Solares Passivas; (2) Desenvolver o conceito SBRS; (3) Elaborar estudos experimentais e numéricos para avaliar o comportamento de fachadas com SBRS.

Os resultados demonstram que o SBRS: 1) pode aumentar significativamente os ganhos solares indiretos em áreas de pontes térmicas estruturais durante o inverno; 2) desempenha melhor com vidro duplo do que com vidros simples; 3) precisa de grelhas de ventilação para otimizar o desempenho no verão; e 4) é adequado para todas as zonas climáticas de Portugal.

Palavas chave: Reabilitação térmica; Tecnologias solares passivas; Solar Bridge Retrofit System (SBRS); Parede Trombe; Eficiência energética; Clima mediterrânico.

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ACRONYMS

2D	Two-dimensional
BW	Black Wall
Csa	Hot and dry summer Mediterranean climate
Csb	Warm and dry summer Mediterranean climate
EPBD	European Performance of Buildings Directive.
ETICS	External Thermal Insulation Composite Systems
EU	European Union
FEM	Finite Element Method
GHI	Global Horizontal Irradiation
GSI	Global Solar Irradiation
HVAC	Heating, Ventilation and Air Conditioning.
IRR	Internal Rate of Return
OSB	Oriented Strand Board
MAS	Membrane Alternative Sunspace
MC	Monitoring Campaign
MC-C	Monitoring Campaign during the Cooling Season (summertime)
MC-H	Monitoring Campaign during the Heating Season (wintertime)

NPV Net Present Value

NOVA FCT School of Science and Technology of NOVA University of Lisbon

PMV Predicted Mean Vote

PP Payback Period

PT1 First prototype of the external transparent layer of the proposed retrofit solution

PT2 Second prototype of the external transparent layer of the proposed retrofit solution

RCCTE Regulamento das Características de Comportamento Térmico dos Edifícios

(EN: Thermal Performance Building Code)

SIR Savings-to-investment Ratio

SBRS Solar Bridge Retrofit System

SCF Solar Control Film

TW Trombe Wall

WW White Wall

SYMBOLS

ρ	Density (kg/m^3)
Ø	Time lag (Hour)
ψ	Linear thermal transmittance (W/(m.K))
c	Specific heat (J/(kg.K))
d	The depth of the air space of the SBRS (m).
df	Decrement factor (-)
e	External opaque skin (-)
f	Fluid (air) in the air space of the SBRS (-)
F_i	Heat flux at point *i* (W/m^2)
g	Glazing (-)
g-value	Solar factor (-)
k	Thermal conductivity (W/m.K or W/m. °C)
L_i	Domain boundary of the structure in the horizontal plane, being *i={x,y}* (m)
m	Massive wall (-)
P_i	Horizontal solar radiation at point i (W/m^2)
RH_{int}	Indoor relative humidity (%)

$\mathbf{RH_{out}}$	Outdoor relative humidity (%)
S	Internal heat source
$\mathbf{T_i}$	Surface temperature at point *i* (°C)
$\mathbf{T_{int}}$	Indoor air temperature (°C)
$\mathbf{T_{out}}$	Outdoor air temperature (°C)
U	Thermal Transmittance ($W/m^2.K$ or $W/m^2.$ °C)
$\boldsymbol{U_{eq}}$	Equivalent Thermal Transmittance ($W/m^2.K$ or $W/m^2.$ °C)

1

INTRODUCTION

This chapter presents the foundation of this PhD work, focusing on the thermal rehabilitation of residential buildings in Mediterranean climate regions using Solar Passive Technologies. The chapter is structured into seven parts:

1. **Context**: Provide an overview of the research context on the thermal retrofitting of existing residential buildings, highlighting the significance and scope of the study.
2. **Research gaps and motivation**: Outline the gaps and areas for further Investigation.
3. **Research problem**: Clearly defines the problem that this PhD work intends to solve, explaining its importance and the need for this study.
4. **Research approach**: Clearly defines the research hypotheses, explaining which methodologies will be used to support them.
5. **Research objectives**: Outline the primary goals of this PhD work and how each goal relates to the research problem and approach.
6. **Research questions**: Derived from the research objectives, but more specific, these questions outline the precise problems that this PhD work will address.
7. **Structure of this PhD thesis**: Provides an outline of the thesis structure, briefly describing the content of each chapter.

1.1 Context

Building sector is one of the greatest energy consumers worldwide. In Europe buildings are accountable for nearly 40% of the energy consumption [1] and in Portugal the need is approximately 30% [2]. These levels of energy consumption are recognized to be unsustainable [3], [4]. Therefore, it is increasingly important to balance the energy demand and supply in buildings to ensure a sustainable development [3].

The balance of energy in buildings can be achieved through the endorsing of green policies and the implementation of architectural design and engineering strategies. These strategies should be implemented to both, new and existing buildings, which are absorbing a large portion of energy consumption [5].

In respect of the Portuguese residential building stock, large part of it was built before the 1st Thermal Performance Building Code (RCCTE), published in 1990 [6]. As a result, much of the Portuguese residential building stock built before RCCTE is obsolete in terms of thermal comfort and energy performance and requires a broader use of Heating, Ventilation and Air Conditioning (HVAC) systems. For example, nearly 25% of the energy consumed in Portuguese buildings is due to Air Conditioning [7]. Additionally, as it will be further discussed at Chapter 2 (Literature Review), the energy profile of Portuguese residential building stock is mostly defined by energy needs for heating. Therefore, to save energy while improving the comfort conditions, one must focus on the thermal retrofitting of the existing buildings.

This is a complex and challenging task given the wide range of solutions and strategies, but it is also aligned with European policies such as the recast of the European Performance of Buildings Directive (EPBD), which emphasizes the urgency of addressing climate change by improving building energy efficiency and reducing carbon emissions. The European Green Deal further supports the need for thermal retrofitting as it aims to transition the European Union (EU) into a climate-neutral economy by 2050, promoting extensive building renovations and energy efficiency improvements. Furthermore, studies suggest that in Mediterranean climate regions, reducing heating energy needs can potentially offset increased cooling demands [8]. In the worst climatic scenario, the researchers projected a decrease in net primary energy consumption from 25.4 kWh/m^2 year (first year of life, 2017) to 19.5 kWh/m^2 year (projection to 2050), with a self-consumption rate of 85% (80% for 2017), underlining the potential benefits of energy-saving measures.

1.2 Research gaps and motivation

Within the available retrofit strategies, Solar Passive Technologies are increasingly presented as a key factor to enhance building energy efficiency. The specific architecture and context of buildings (e.g., orientation and climate), a well-designed project with Solar Passive Technologies can improve thermal comfort while reducing HVAC energy demands. However, as shown in Chapter 2 (Literature Review), the following research gaps were identified:

- **The advantages and disadvantages of Solar Passive Technologies for residential buildings in Southern European countries with Mediterranean climate are largely unknown:** The number of case studies based on the integration of these technologies into the building façade in these locations are scarce, although Southern European countries have a great solar availability.
- **There is lack of studies on the use of Solar Passive Technologies on thermal bridge areas:** Both on the assessment and correction of thermal bridges areas related to the use of Solar Passive Technologies in Portugal.

Consequently, this PhD work is motivated by the apparent lack of data regarding the application of Solar Passive Technologies in thermal retrofitting existing Portuguese residential buildings especially with regard to use of technologies with indirect solar gain on structural thermal bridge areas.

1.3 Research problem

Based on the previous, the following research problem was identified:

- **Portuguese residential buildings need to save energy while improving thermal comfort conditions, especially during the heating season**: The building stock was mostly constructed before the 1st RCCTE [6] regarding the thermal and energy performance and, as a result, it has a great use of (HVAC) systems, which is not aligned with European policies such as the EPBD [9]. Also, heat losses from structural thermal bridge areas might be one of the main reasons to the significant heating energy needs.

1.4 Research approach

To address the identified research problems and leverage the research gaps, a literature review was performed on the topic followed by a proposal of an innovative retrofit solution based on a well-known Solar Passive Technology.

The proposed retrofit solution is based on the Trombe wall (TW) concept. A TW is an indirect solar gain mechanism that consists of the application of an external transparent skin (glazing) to the façade. Unlike the traditional TW, which is associated to masonry areas, the proposed solution rather collects and stores the heat at the level of thermal bridges - known to be responsible for significant heat losses during the heating season. Thereby, this innovative retrofit solution intends to transform a thermal weak area of the façade (heat loss area) into a thermal optimized area (heat gains) during wintertime, by taking advantage of the strengths of the TW and introducing adaptations to maximize its advantages and mitigate its drawbacks. Therefore, this innovative retrofit solution aims to save energy while improving the thermal comfort conditions of residential buildings in Mediterranean climate regions, such as Portugal mainland, during the heating season. To support the research activities, the following research hypotheses were formulated:

1. **Hypothesis 1**: Considering Mediterranean climate, it is possible to enhance thermal comfort and energy performance during heating season, without compromising the cooling season, by adding an external transparent skin to the building envelope (façades).
2. **Hypothesis 2**: It is possible to study the application of external transparent skin (glazing) targeting structural thermal bridge areas only.

To test the research hypotheses, an experimental study was conducted. The study consisted of the construction of a small test cell with the prototype of the proposed retrofit solution. Thermal parameters (e.g., surface temperatures) were analysed during both the heating and cooling seasons.

1.5 Research objectives

As a result of the research approach, the objectives of this PhD work were:

1. **Identify the advantages and drawbacks of Solar Passive Technologies:** Evaluate the benefits and limitations of using these technologies to thermal retrofit residential buildings in Mediterranean climate regions.
2. **Design an innovative retrofit solution aiming structural thermal bridges**: Develop a solution based on Solar Passive Technology aimed at increasing indirect solar gains and mitigating the structural thermal bridges effect during the heating season, without compromising the cooling season.
3. **Develop an experimental study**: Conduct studies to assess the thermal-energy behaviour of the proposed innovative retrofit solution.
4. **Develop a numerical study:** Conduct studies to compare the thermal-energy behaviour of the proposed innovative retrofit solution against a non-retrofitted one and another retrofitted with using ETICS (the most common retrofit solution implemented in Portugal).
5. **Assess performance under different conditions:** Numerically assess the performance of the retrofit solution across different Portuguese climate zones.

1.6 Research questions

To achieve the research objectives, the following research questions should be tackled:

1. Can an external transparent skin (glazing solution) increase indirect-solar gains during the heating season, when structural thermal bridge areas are mainly targeted?
2. Which external transparent skin (glazing solution) performs better in terms of heat gains vs heat losses of the proposed retrofit solution? Are there any other features that also help enhance the solar gains?
3. How the proposed retrofit solution performs during the cooling season? Is there any need to adapt the proposed solution in the cooling season or to work with other cooling strategies?
4. Is the proposed retrofit solution suitable for all climate zones in Portugal? How the SBRS performs under different Portuguese climate zones?

1.7 Structure of this PhD thesis

This document is structured in seven chapters, including the current chapter:

Chapter 1.	Introduction.
Chapter 2.	Background on building retrofit with Solar Passive Technologies.
Chapter 3.	Solar Bridge Retrofit System (SBRS).
Chapter 4.	Experimental Study of a Façade with SBRS.
Chapter 5.	Numerical Study of a Façade with SBRS.
Chapter 6.	Summary of this PhD research project.
Chapter 7.	Conclusions.

Chapter 1 presents an overview of this PhD thesis.

Chapter 2 presents the background on the use of Solar Passive Technologies to retrofit residential buildings in Mediterranean climate regions, such as Portugal mainland.

Chapter 3 presents the proposed retrofit solution, the Solar Bridge Retrofit System (SBRS). Topics such as its design, theoretical heat transfer model of a façade with SBRS and to which residential building SBRS is designed for, are discussed in this chapter.

Chapter 4 presents the designed experimental setup and data gathered during the heating and cooling seasons to study the thermal behaviour of the SBRS.

Chapter 5 presents a numerical study comparing the thermal behaviour of a façade retrofitted with SBRS combined with ETICS, a non-retrofitted façade, and a façade retrofitted with only ETICS. Three simulation tools were used to compute the results: BISCO®, BISTRA®, and DesignBuilder®.

Chapter 6 presents the summary of this PhD research project, namely the research subject, advising team and the resulting science communication and achievements.

Chapter 7 presents the main conclusions of this PhD work.

2

BUILDING RETROFIT WITH SOLAR PASSIVE TECHNOLOGIES

This chapter focuses on the literature review. It helps identify the advantages and drawbacks of using Solar Passive Technologies to thermal retrofit residential buildings in Mediterranean climate regions (1st Research Objective). The chapter is structured into six parts as follows:

1. **Portuguese Climate and Solar Availability**: Characterization of the climate and of the solar availability in mainland Portugal.
2. **Advantages of Solar Energy**: Provide an overview of its advantages to the building stock.
3. **Portuguese Residential building stock**: Outline the energy profile of the Portuguese residential buildings, while underlining why the building stock is obsolete in terms of thermal comfort and energy efficiency.
4. **Solar Passive Technologies**: Provide an overview of the solutions used to retrofit buildings in European in Mediterranean climate regions.
5. **Feasibility of building retrofit with Solar Passive Technologies**: Outline the indicators presented in the literature that are often used to assess the feasibility of retrofit projects with Solar Passive Technologies.
6. **Discussion and brief conclusion**: Defining the main findings on this chapter.

The following paper contributed to the development of this chapter:

- S. Brito-Coimbra, D. Aelenei, M. Gloria Gomes, and A. Moret Rodrigues (2021) "Building Façade Retrofit with Solar Passive Technologies: A Literature Review," Energies, vol. 14, no. 6, p. 1774, https://doi.org/10.3390/en14061774.

2.1 Portugal mainland: climate and solar availability

Portugal mainland is in Southwestern Europe and is mostly defined by Mediterranean climate. The World Map of Köppen-Geiger classification [10] characterizes Mediterranean climate by cool and wet winters and dry summers. This climate occurs in the Mediterranean basin and in similar latitudes in the North and South Hemisphere (25º <φ < 45º), such as the Western of United States of America and Southern Africa (**Figure 2.1**). For this reason, Portugal climatic pattern is very similar to other locations, such as Spain, southwest Italy and Greece [11].

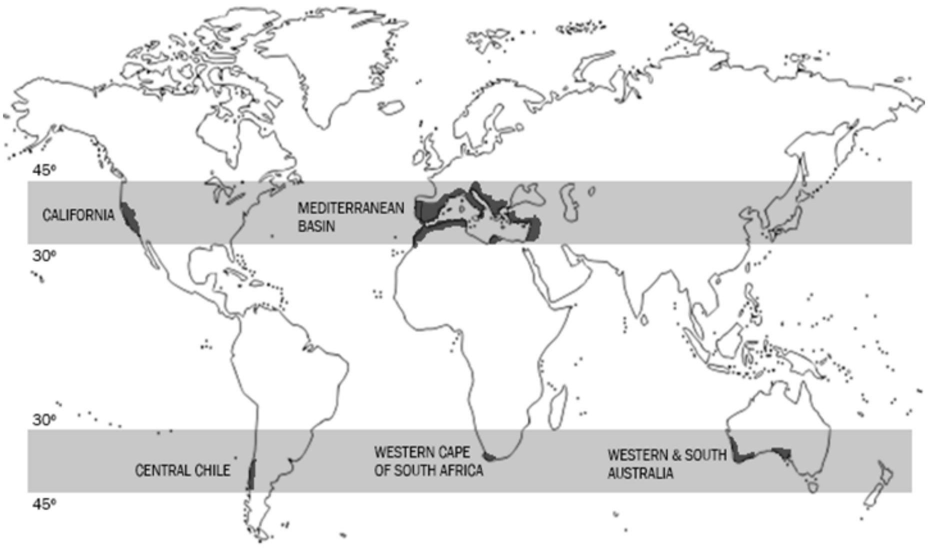


Figure 2.1 Locations with Mediterranean climate.

The Köppen-Geiger climate classification [10] also indicates that Mediterranean climate can be defined, in accordance with its summer characteristics, by two different climatic-types (or climate zones), Csa – hot and dry summer and Csb – warm and dry summer. As shown in **Figure 2.2**, Portugal mainland is divided in two Mediterranean climate zones: South is classified as Csa, whereas the North and Centre are classified as Csb.

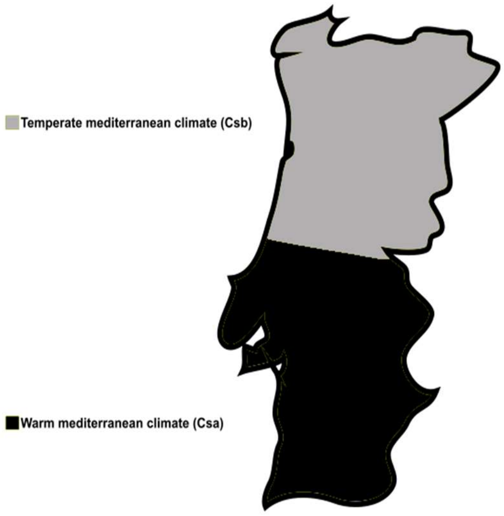


Figure 2.2 Map of Portugal mainland according to the Mediterranean climate zone.

The literature often refers Mediterranean climate to as "temperate climate or "mild climate", as seen in [11], [12], [13], [14]. In the European context, it is also known by its great solar availability. To analyse the solar availability across different European climates, Brito-Coimbra et al. [15] compared the annual Global Solar Irradiation (GSI) of Lisbon to Ancona, Barcelona, London, München, Paris and Stockholm (**Figure 2.3**).

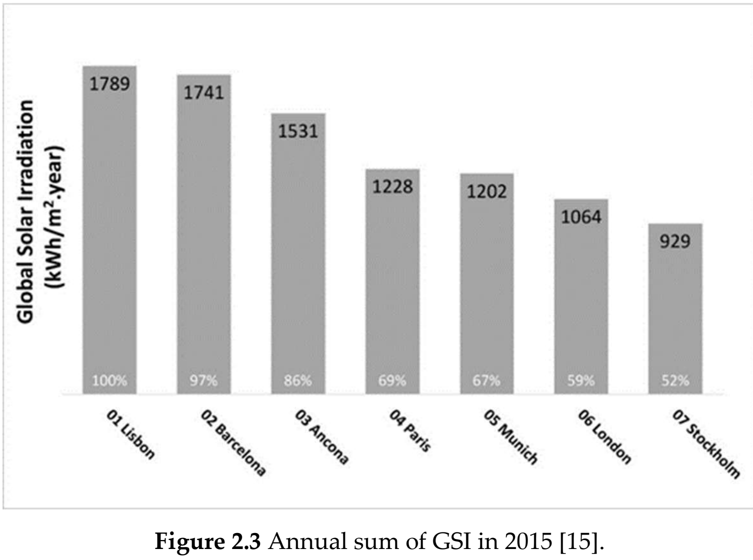


Figure 2.3 Annual sum of GSI in 2015 [15].

Among the locations with Mediterranean climate (Lisbon, Ancona and Barcelona), the highest annual GSI occurred in Lisbon. When Lisbon was compared to other non-Mediterranean climate locations, the annual GSI of Lisbon was more than double of the annual GSI of those cities. The annual GSI of Paris, Munich, London and Stockholm were 31%, 33%, 41% and 48%, respectively, lower than the annual GSI of Lisbon.

The study developed by Gonçalves Silva et al. [16] showed that the annual availability of Global Horizontal Irradiation (GHI) can reach values up to 2028.4 kWh/m^2.year in Sagres (southernmost part of Portugal). The analysis of the solar availability in the context of Portuguese buildings was also presented in the literature by Brito et al. [17], whom studied the solar potential of roofs and façades of two different neighbours in Lisbon. The study showed that the annual solar irradiation of roofs varied between 1000-1800 kWh/m^2.year, while façades varied between 100-1000 kWh/m^2.year, depending on the orientation of the façade. The study also showed that façades facing East and West presented a wide range of irradiation values (100-800 kWh/m^2.year), and that the sum of their potential could surpass the ones facing South.

2.2 Advantages of solar energy

As shown in the previous section, Portugal mainland is characterized by a good solar availability. According to Robertson and Athienitis [18], the use of Solar Energy in buildings over conventional energy presents several advantages, such as:

- In terms of applicability, solar energy is available everywhere and is inexhaustible.
- Economically, following the initial investment, the use of the solar technologies is free, and their payback time can be relatively short.
- Solar energy is clean. Besides, its greater use can reduce the demand for fossil fuels and hydroelectricity, and their environmental drawbacks.
- In energy efficiency terms, the energy distribution needs of a building can be reduced through building-integrated of Solar Technologies.

The use of Solar Energy in buildings can be leveraged through Solar Design, which aims to minimize energy costs while maintaining interior comfort. The potential of Solar Design mainly relies on the availability of solar radiation, which is determined by the climate and latitude of the location and by the placement and position of the Solar Technology [19], [20]. The technology can be based on either an active, passive or a hybrid strategy. Solar active technologies require the use of electrical or mechanical equipment to leverage solar energy in buildings. Passive strategies are characterized by the direct interaction between the building envelope and the environment, and they address the heating, cooling, and lighting needs of a building with the intent to reject, prevent, collect or control heat gains and/or natural lightning, without the use of electrical or mechanical equipment [21], [22]. Hybrid strategies result from the mix of active and passive strategies.

2.3 Portuguese residential building stock

According to the 2011 Census [23], Portuguese residential building stock consisted of 3.544.389 buildings and 5.877.991 house units. In 2019, the report of Construction and Housing statistics [24] estimated that the Portuguese residential building stock was at 3.612.472 buildings and 5.968.354 housing units, which represents a growth of 1.9% and 1.5% respectively.

Figure 2.4 shows the Portuguese residential building stock according to the construction period, according to 2011 Portuguese Census [23].

The first Portuguese legal instrument on thermal and energy performance of the buildings was published in 1990 [6]. From the observation of **Figure 2.4**, it can be said that most of the Portuguese residential building stock (**Figure 2.5**) was built with lack of care concerning the thermal performance and energy efficiency of Portuguese buildings [25].

The 2011 Census [26] also showed that near 29% of the Portuguese residential buildings needs intervention works and that most of the needs of repair occur in elements of the envelope, namely on roofs, external walls and window systems. As the envelope directly affects the indoor thermal comfort, these needs of repair are of particular concern. These envelopes can also be assumed as having poor energy performances because more energy for heating and cooling might be necessary to counter the lack of indoor thermal comfort.

Abreu et al. [27] studied the energy performance of the Portuguese residential building stock. The study showed that energy demands for heating are significantly greater in buildings built prior the first thermal regulation [6]. Buildings built prior to 1990 are responsible for energy demands for heating, ranging from 265 to 334 kWh/m^2.year, while buildings built between 1990 and 2010 require between 112 and 265 kWh/m^2.year.

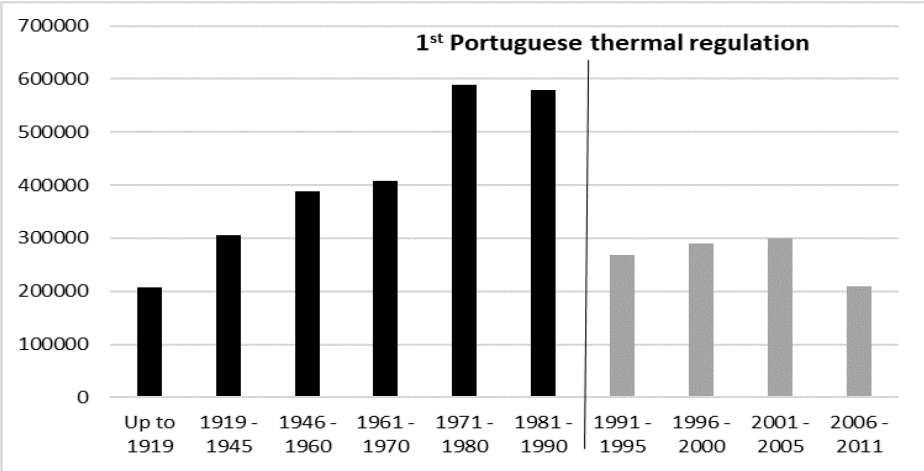


Figure 2.4 Portuguese building stock in 2011: according to construction era [23].

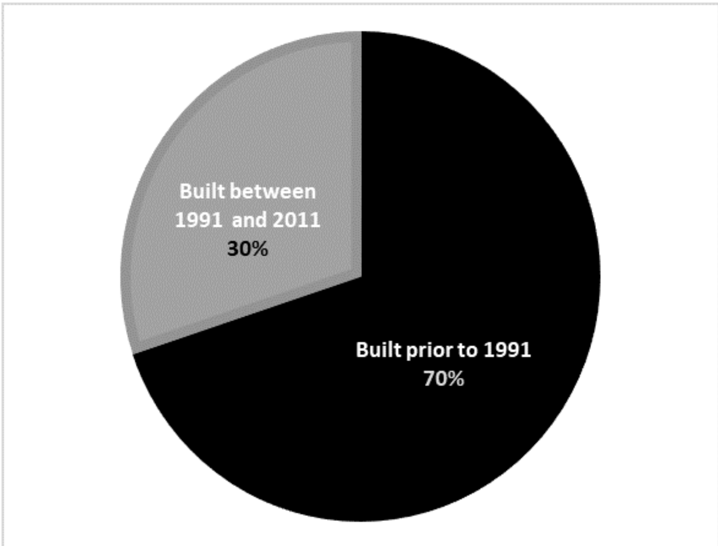


Figure 2.5 Residential Portuguese building stock in 2011 – prior and following the 1st building code [23].

Overall, most of the Portuguese residential building stock (near 80%) presents energy demands for heating higher than 100 kWh/m^2.year, which is somehow concerning when analysed in the context of often referred "mild climate" [28]. Thus, the retrofit of residential buildings built prior to 1990 might be more impactful to the energy consumption of the overall Portuguese residential building stock. When compared to other European locations with Mediterranean climate, the need to building retrofit to keep up with current building standards is very similar, as seen in [3], [29], [30], [31], [32], [33].

When comparing energy needs demands for heating and cooling, Magalhães and Leal [28] showed that Portuguese residential building stock is mostly defined by its energy needs for heating. For example, in 2011, the entire Portuguese mainland was characterized by a total annual nominal energy needs of 119 469 GWh for space heating and 9129 GWh for space cooling – which represents only 7.6% of the needs for space heating. For this reason, building retrofit should mainly focus on upgrade the energy efficiency during the heating season. Besides, two aspects should be emphasized. When compared to other European countries, Portugal has one of the lowest average heating energy consumptions per square meter (17 kWh/m^2), as shown in **Figure 2.6**. And, despite the temperate climate, Portugal has one of the highest excess winter morbidities in Europe, as shown in a study devised by Vasconcelos et. al. [34]. Thus, there is a need to reduce thermal discomfort and the exposure to cold in order to promote better health conditions, housing quality [34].

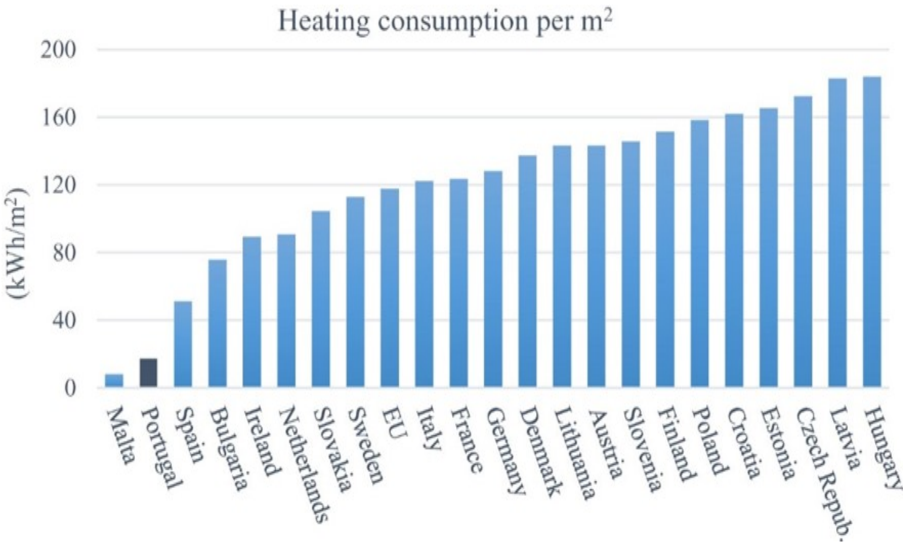


Figure 2.6 Heating consumption per m^2 in European Countries (2015) [23].

The highest Portuguese excess winter morbidity can be perhaps justified to the low budget that citizens have to spend on acclimatization purposes, when compared to other European countries. The literature describes this problem as fuel poverty, a term that is not consensual but that can be described as "anyone who meets, in its housing, particular difficulties to have the necessary energy to meet its basic energy needs because of the inadequacy of its resources or of its housing conditions". For this reason, the thermal retrofit of Portuguese residential buildings should mainly rely on passive solutions.

Most of the retrofit projects of Portuguese residential buildings already rely on a very known passive solution: the adding of External Thermal Insulation Composite Systems (ETICS) to the envelope [35], [36], [37], [38], [39]. Historically, ETICS have been selected to retrofit European buildings since 1970's, because they lead to better indoor thermal comfort (due to the higher interior thermal inertia), as well as to the finished appearance of ETICS that is similar to traditional renderings [40]. ETICS as a retrofit strategy seems to be very suitable, however it does not take advantage of the good solar availability that characterizes Portugal mainland.

The following section presents an overview on the Solar Passive Technologies that can be used to leverage the good solar availability. For the reasons stated in the above paragraphs, this PhD work will exclusively focus on Solar Passive Technologies.

2.4 Solar Passive Technologies used to retrofit buildings in Mediterranean climate

The greatest opportunities for the integration of Solar Passive Technologies occur during design phase, by determining constructive strategies that have critical influence on building performance [22]. These technologies can be defined as Direct or Indirect Solar Gain Technologies [41]. Direct Gain Solar Technologies absorb, store and release solar energy directly into the indoor environment (**Figure 2.7**) [41]. Indirect Solar Gain Technologies capture solar energy through a thermal mass, which subsequently transfers the stored heat into the indoor environment for later use. (**Figure 2.8**) [41].

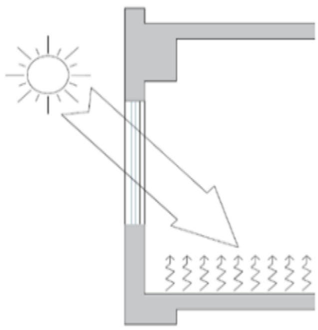


Figure 2.7 Example of a Direct Gain Solar Passive Technology (window) [15].

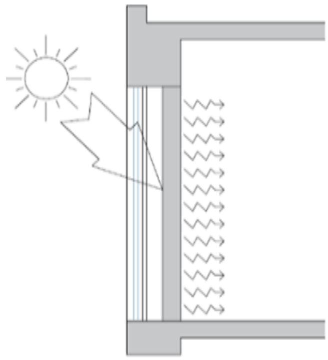


Figure 2.8 Example of an Indirect Gain Solar Passive Technology (Trombe wall) [15].

Table 2.1 presents the Solar Passive Technologies that can be used to thermal retrofit buildings in locations with Mediterranean climate, such as Portuguese mainland. The table distinguish the solar technologies according to the type of solar gain (direct and indirect) and for which season it is designed (heating or cooling season).

The following sections provide a detailed overview of three Solar Passive Technologies listed on **Table 2.1**, namely Glazing, Sunspace and Trombe wall. These technologies are discussed in greater depth due to their primary application during the heating season. Understanding their design principles and performance characteristics is crucial for developing innovative Solar Passive Technologies aimed at mitigating the thermal bridge effect during this period.

Table 2.1 Solar Passive Technologies used in building retrofit: depending on type and season [15].

Type of Solar Gain	Solar Technology	Targets	
		Heating season	Cooling season
Direct	Glazing technologies	✔	✔
	Sun shading technologies		✔
Indirect	Sunspace technologies	✔	
	Trombe wall technologies	✔	

2.4.1 Glazing technologies

Worldwide, window retrofit is the most popular retrofit measure. The reasons behind this are threefold. Firstly, the thermal transmittance values (U-values) of windows are usually higher than the opaque façade [42] and, as a result, most of the heat exchange between the outdoor and indoor environment occurs via glazed spans [43]. Secondly, financial support programs often encourage window retrofit. In the Portuguese context, "Renew Home & Office" programme [44] is an example of this sort of programs. And, thirdly, windows are the simplest Solar Passive Technology and the easiest building element to retrofit [21], [41].

In the Portuguese context, window retrofit is either done by: a) Replacing the entire window system; b) Installing a secondary window in addition to the existing single-glazed window, c) Adding Solar Control Films (SCF) to the existing window.

As a result of the Portuguese residential building stock built prior to the first thermal regulation [6], most building elements were designed with poor performance. For example, these buildings were mainly designed with single-glazed windows, even in the Centre-North and North of Portugal mainland, where the winter is more severe. For this reason, retrofit projects typically consider the replacement of single-glazed with multi-layer glazing. The literature showed that the replacement with triple-glazing were usually chosen for locations in the North and Centre-North of the mainland, as illustrated in [45]. However, the replacement of single- with double-glazing windows is the most common solution nationwide for both, residential and non-residential buildings, as shown in [38], [39], [46], [47], [48], [49], [50], [51] and [52], [53], respectively.

The literature also presented the measurable impact of replacing single- with double-glazing windows In the Portuguese context. Eskander et al. [50] concluded that, following the retrofit, the heat transferred through the windows could be lowered down to near 40%. Eicker et al. [54] studied the impact of replacing glazing systems with ones with lower total solar energy transmittance (g-value), a parameter which is also known as solar factor. The study concluded that the cooling energy needs of a residential building in Almada could be lowered down to 11%, if single-glazed windows with g-value of 0.8 were replaced with double-glazed windows with g-value of 0.51 [54]. Other studies considered the replacement of single-glazed windows with double and low-emissive (e-low) glazing windows [45], [55]. E-low glazing can be a good option for temperate climates (Portugal mainland), as it provides a good thermal insulation during the heating season and reduces the entrance of heat during the cooling season, while allowing the passage of visible light for favouring daylight [43], [56].

The installation of a secondary window is also a common window retrofit measure, especially in historic urban centres. The retrofit strategy is based on the internal addition of a second pane of glass, or plastic, while keeping the original single-glazed window, to improve the thermal performance of the window system during the heating season [57]. This solution allows to maintain the external original aesthetics of the renovated window system, which is useful in the case of rehabilitation of historical buildings [46]. The measurable impact of this type of retrofit measure was not found in the literature for the Portuguese context.

To encourage visual comfort and daylighting for energy savings, non-residential buildings tend to have high window-to-wall ratios [58]. However, this design can lead to a significant increase of cooling loads in warm climates, such as the Mediterranean climate, due to the increased solar heat gain [59]. For this reason, in recent years, many studies have been devised on the glazing retrofit with SCF [60], [61], [62]. In Portugal, Teixeira et al. [62] studied the application of SCF on an office building with large glazed areas in Lisbon and concluded that SCF can be a suitable retrofit measure, as they can reduce solar heat gains, the peak demand load and the annual energy consumption. Besides, Pereira et al. [60] verified that SCF has the potential to promote daylight availability, while limiting the visual discomfort.

2.4.2 Sunspaces

Sunspace is a technology is based on a glass house (**Figure 2.9**) that absorbs solar radiation and partially convert it into energy for heating the indoor environment [63], [64], [65], [66]. It recreates, in a small-scale, the greenhouse effect that happens between the Earth and the atmosphere and it works as a buffer zone against heat losses towards the outdoor environment [63], [64].

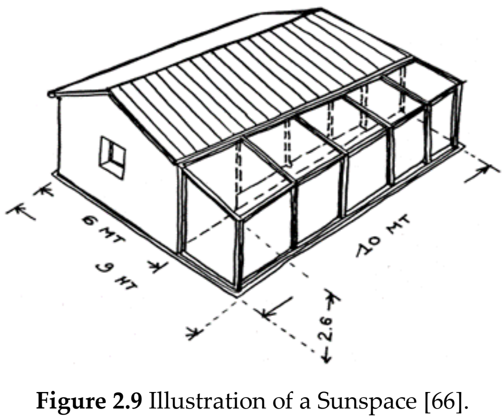


Figure 2.9 Illustration of a Sunspace [66].

Portuguese sunspaces are usually south oriented, with single glazing and a high glazing to floor surface ratio (between 60% and 250%) [67]. However, even though it is common to close existing balconies so that they can act as sunspaces, studies on the impact of retrofit with sunspaces are scarce. Aelenei et al. [7] and Macieira et al. [68] studies are two of the few exceptions in the literature on the application of this sort of retrofit strategy in Portugal.

Aelenei et al. [7] studied the impact of four attached-sunspaces configurations (**Figure 2.10**) and concluded that fully integrated sunspaces led to better perform results, because they have smaller glazing area in contact with the external environment. The study also pointed that sunspace may be very efficient solution in the South of Portugal mainland (e.g. Faro region), as it showed a potential of 100% energy saving during the heating season. In locations with more severe winters (e.g. Bragança region), the potential energy savings lowers down to 48%. Aelenei et al. [7] also stated that sunspaces might be a very attractive solution to retrofit dwellings built prior to 1990, when compared to retrofit approaches based on thermal insulation, because Portugal has a good solar potential and due to the economic benefits of sunspace technologies.

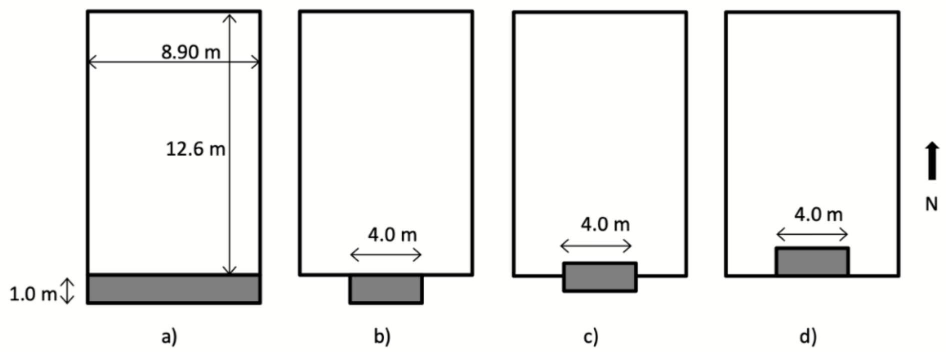


Figure 2.10 Types of sunspaces: a) adjacent; b) adjacent; c) partial integrated; d) totally integrated [7].

Macieira et al. [68] studied the use of transparent membrane screens (of PVC or EFTE) to close Portuguese balconies (**Figure 2.11**).

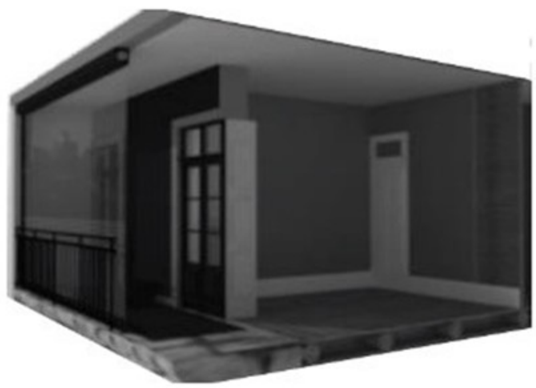


Figure 2.11 MAS during the heating season [68].

As the proposed retrofit solution uses membranes as an alternative to conventional glazing, the retrofit technology was named Membrane Alternative Sunspace (MAS). To optimize the thermal performance, MAS can be completely open during all day or night-time and can integrate an additional opaque/reflective membrane to work as a vertical shade (with adjustable height). Overall, the study concluded that MAS is an efficient retrofit alternative to traditional sunspaces, based on constructive, environmental, and economic aspects.

2.4.3 Trombe wall systems

Also known as storage wall or solar heating wall, Trombe wall is an indirect solar gain technology that consists of an external transparent skin in front of the external wall (known as massive wall), with a small air space between them [15]. It works by absorbing solar energy through the external transparent skin, which results in a buffer effect in the air space, where the heat is stored during the daytime [69], [70], [71]. In the hours following the sunset, the energy is transmitted, as heat, to the indoor environment, resulting in the indoor air temperature enhancement [69], [70], [71]. To absorb more solar energy, the outer surface of the massive wall is typically painted in a deep colour [72].

Trombe wall can be classified as non-ventilated (or unvented), ventilated (or vented) or double ventilated. The ventilation mode relies on the existence of vents (ventilation openings) on the external transparent skin or on the massive all. When the vents are non-existent or are closed, Trombe wall is classified as unvented. If just one of the layers of the technology, either the external transparent skin or massive, has (open) vents, Trombe wall is classified as vented. When two layers, namely the external transparent skin or massive, have (open) vents, Trombe wall is classified as double ventilated. Each one of the described ventilation modes of the Trombe wall is illustrated in **Figure 2.12**.

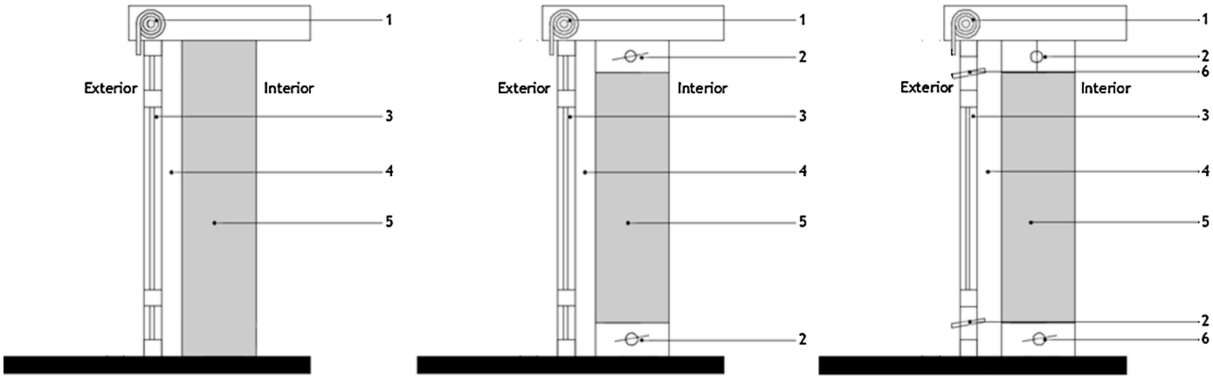


Figure 2.12 Configuration of different Trombe walls (from left to right): Non-ventilated or unvented; Classic or ventilated; and Double ventilated: 1 – Shading device; 2 – Ventilation openings in the massive wall; 3 – Glazing; 4 – Air space layer; 5 – Massive wall; 6 – Ventilation openings in the glazing [73].

Trombe wall is not commonly used in Portugal, perhaps due to the lack of information among designers on its application and efficiency [74]. Even so, it seems to be a suitable retrofit solution due to its simple configuration, zero running costs, among other reasons [75], [76].

As Trombe wall technologies are not commonly used in Portugal, studies on their application and impact are also scarce. One the few exceptions are the studies developed by Briga-Sá et al. [73], [74], [77]. The researchers stated that Portuguese buildings benefit of the integration of Trombe wall, as the energy needs for heating can be reduced up to near 16% [74]. Other key findings have been presented in the literature on the application of Trombe walls in other European locations with Mediterranean climate. For example, the optimized design of Trombe wall is often a double-glazing layer, as seen in [73], [78] and [77], [79], [80], [81], with air layers depths lower than 10 cm, as seen in [77], [79], [82]. During the cooling season is strongly recommended the use of sun shading to counter overheating. This statement was mentioned both in Portuguese studies [73], [80] and in studies developed in other locations with Mediterranean climate [79], [83]. Briga-Sá et al. [73] noted that the outer surface of the Trombe wall can reach temperatures above 60°C when it is not screened but under 30°C when it is shaded.

The literature also presented an innovative approach to Trombe wall technologies. Sacht et al. [80] proposed a modular Trombe wall to retrofit residential buildings under different Portuguese climate zones. The proposed retrofit solution is innovative for two reasons. The technology is based on multiple modules of Trombe wall, instead of a single zone, and because modules are normally used in active technologies (e.g. PV modules). The study concluded that, regardless of the geographical location, buildings with Trombe wall present lower heating energy needs than the maximum limits of the Portuguese building code requirements.

Overall, Trombe wall technologies have exclusively been target areas (massive walls) designed with a single type of material (e.g. concrete, masonry) and there is an apparent lack of studies regarding the application of Trombe wall technologies on thermal bridge areas [84].

2.5 Feasibility of retrofit with Solar Passive Technologies

Each building is unique. It is difficult to define general action guidelines and the optimal retrofit solution should be defined for each case [85]. To simplify the process, the literature presented assessment methodologies on the feasibility of the retrofit works, such as the ones presented in [86], [87]. Those methodologies were designed to assess the feasibility of any kind of retrofit works and can be extended to retrofit works with Solar Passive Technologies.

The literature also mentions that not all retrofit actions lead to lower global costs, even though they often result in lower energy needs [86]. As a result, studies on the feasibility of retrofit works should not be exclusively based on energy efficiency indicators, but also on thermal performance and comfort, indoor air quality and acoustics, environment and economic indicators. **Table 2.2** presents a brief list of these types of assessment indicators.

Besides the indicators presented in **Table 2.2**, retrofit design projects should also consider the following aspects:

- Retrofit conditions. Questions, such as, the disturbance levels to the inhabitants or site and the possibility of working from the inside of the building VS need of scaffoldings in high rise buildings, should be made, as shown in [88].
- Compatibility between the existing constructive solutions and the proposing retrofit technologies, including the possible retrofit consequences (e.g. reduction of air permeability; creation of new thermal bridge areas following the fixation of new constructive systems) and how to mitigate them [89].
- Fire safety [88].
- Impact on cultural heritage [90]. Aspects and constrains like the affection to the envelope's aesthetics, aesthetic quality and effect on cultural heritage should be considered [90]. In the Portuguese context, such example is shown by Santos et al. [46] on the rehabilitation of the UNESCO's Historic Centre of Porto.

Table 2.2 Assessment indicators that can be used to assess the feasibility of retrofit projects with Solar Passive Technologies [15].

Scope	Indicator	Unit
Solar availability	Solar irradiation on the façade surface	$kWh/m^2.year$
	Hours of solar exposure	Hours
Thermal performance and comfort	Discomfort period	Hours; %
	Heat gain	MJ/m^2; kW/m^2
	Heat transmission (Heat flux)	W/m^2
	Predicted Mean Vote (PMV)	--
	Relative humidity	%
	Temperature (surface: glazing and massive wall; cavity)	°C
	Time lag	Hours
Indoor air quality and acoustics	CO_2 concentration	ppm
	Acoustics	-dB; RT60
Energy efficiency	Cooling energy needs (or cooling energy needs savings)	kWh; kWh/year; %
	Energy storage (and release)	Hours
	Heating energy needs (or heating energy needs savings)	kWh; kWh/year; %
Environment	CO_2 emissions (production and operational phase)	kg CO_2 eq.
	Energy demand (production and operational phase)	kWh; kWh/m^2
Economic	Annual savings	€; %
	Internal rate of return (IRR)	--
	Investment costs	€
	Net present value (NPV)	--
	Payback period (PP)	Years
	Savings-to-investment ratio (SIR)	--

2.6 Discussion and brief conclusion

The main findings from this chapter can be summarised as follows:

- Considering the European context, **Portugal mainland has a great solar availability**. This is especially evident when the GSI of Lisbon (Portuguese capital) is compared to other locations with Mediterranean climate, such as Barcelona.
- **Portuguese residential building stock is obsolete in terms of thermal comfort and energy efficiency**. There is a need to retrofit the ones built before 1990 (when the 1st thermal regulation was published), to update them into today's standards.

- **Building retrofit projects should mainly target the heating season performance** (wintertime), **once energy needs for heating are significantly greater than for cooling** (summertime). This might happen mainly due to heat losses caused by structural thermal bridge areas in buildings built between 1960, when construction with reinforced concrete started on a large scale, and 1990, when the first legal instrument on buildings thermal performance was published.
- The **retrofit strategies should focus on passive solutions** due to fuel poverty.
- **ETICS is the primary solution to thermal retrofit the envelope of Portuguese residential buildings**.

Furthermost, to enhance the effectiveness of Solar Passive Technologies, the literature suggests that:

- **External transparent skin, usually glazing, help promote and/or maximize solar heat gains during the heating season**,
- **Double-glazing (over single glazing) glazing seams to lead to better annual performances** (heating and cooling combined)

3

SOLAR BRIDGE RETROFIT SYSTEM (SBRS)

This chapter introduces an innovative retrofit solution aimed to enhance indirect solar gains at structural thermal bridges during the heating season, without compromising the cooling season (2nd Research Objective). It is structured into five parts:

1. **Buildings targeted by the application of the innovative retrofit solution:** This section defines the specific buildings to which the proposed retrofit solution was designed for, while presenting the main design features of those buildings.
2. **SBRS constructive concept**: The design of the proposed innovative retrofit solution is presented, while clearly underlining the design features for both heating and cooling season.
3. **The theoretical heat transfer model of the SBRS:** This part provides the mathematical formulation for heat transfer through a façade equipped with SBRS during the heating season.
4. **SBRS as a modular solution**: Present the solution as a module, while underlining its advantages and defining its design and technical installation.
5. **Discussion and brief conclusion**: The chapter concludes by summarizing the main findings on this chapter and revisiting the research questions of this PhD work.

The following paper contributed to the development of this chapter:

- D. Aelenei, S. Brito-Coimbra, M. Glória Gomes, and A. Moret Rodrigues (2021) "Solar Bridge Retrofit System: An innovative solution to renovate structural

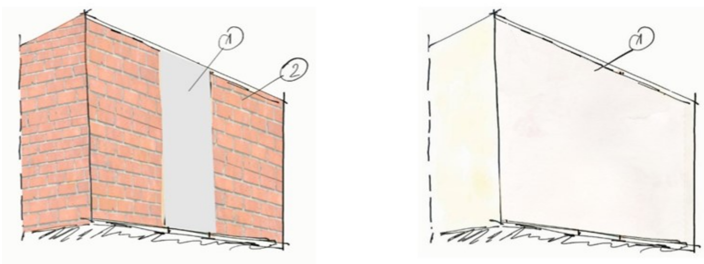
thermal bridge areas," Energy Building, vol. 236, p. 110784, 2021, doi: https://doi.org/10.1016/j.enbuild.2021.110784.

3.1 Buildings targeted by the application of the proposed retrofit solution

The buildings targeted by the proposed retrofit solution are those constructed between 1971 and 1990. This period precedes the introduction of the first legal framework for thermal and energy performance of the buildings known as the 1st RCCTE [6]. According to the 2011 Portuguese Census [23], buildings from this era constitute approximately 33% of the residential building stock.

The construction methods used in Portuguese residential buildings from 1971 to 1990 were predominantly characterized by reinforced concrete structures filled with non-bearing masonry walls, as shown in **Figure 3.1**. **Figure 3.2** further illustrates a conceptual drawing of a typical façade from this period, prior and following the painting.

Figure 3.1 Example of typical constructive design of the residential buildings built after 1970's based on reinforced concrete structures with non-bearing masonry walls [91].



(a) (b)

Figure 3.2 Conceptual drawing of a non-retrofitted façade of a 1971-1990 Portuguese residential building: (a) prior to the painting and (b) following the painting: 1 – Concrete column; 2 – Masonry wall; 3 - Wall finish.

The façades of Portuguese residential buildings constructed between 1971 and 1990 typically consist of cavity walls without thermal insulation. These walls are rendered with factory-made mortars (sand and cement or sand, cement and lime, and plaster mortars) and are interrupted by structural components of load-bearing concrete (beams and columns) [84]. The cavity walls in these buildings usually consists of two masonry layers made of clay hollow bricks, each with a thickness of 11 cm and 15 cm, separated by atypically 5 cm air gap.

3.1.1 Structural thermal bridges

The façades of Portuguese residential buildings constructed between 1971 and 1990 are usually characterized by the presence of structural thermal bridges.

Thermal bridges are areas where there is a significant reduction in the thermal resistance (R-value) compared to that of the surrounding areas. This phenomenon is caused due to changes in the geometry of opaque elements, to the discontinuities or gaps in the insulation material and significant differences in the thermal conductivity of materials, such as the case when structural components (e.g. concrete beams and columns) encounters other building elements with significant lower thermal conductivities (e.g. cavity walls) [25], [92], [93]. As a result, in these areas are generated locally multidimensional heat flow and there is an increase of heat flow transmitted through the envelope [92], [94]. Thus, thermal bridge areas can significantly increase heat losses and increase energy demand for heating [94], [95], [96].

Figure 3.3 shows thermography images of structural thermal bridges areas at the level of a façade that lacks thermal insulation during winter. As it can be seen, the structural components exhibit lower surface temperature than the adjacent areas indicating that the heat losses through thermal bridges are substantially higher than the heat losses through the surrounding area.

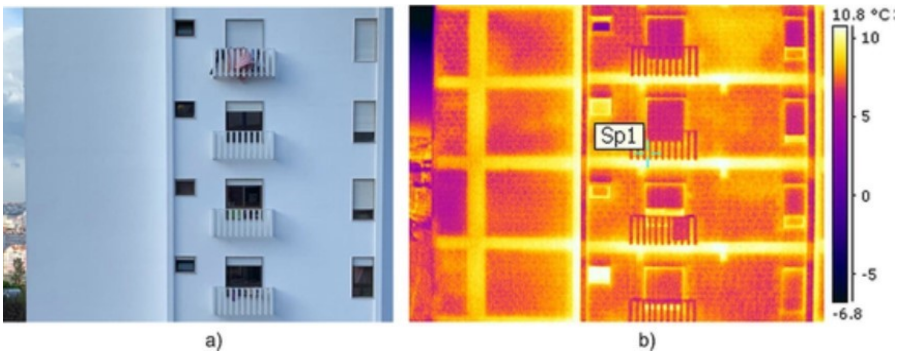


Figure 3.3 Photography of the façade of a typical Portuguese multi-family building (a) and the respective IR image (b) [84].

The horizontal cross-section of a Portuguese residential building constructed between 1971 and 1990 is shown in **Figure 3.4a**. The corresponding 2D numerical analysis carried out using BISCO [97], with the aim to provide a qualitative assessment of the thermal bridge effect, is shown in **Figure 3.4b**. The figure depicts the temperature field of the wall and the corresponding isothermal profile, obtained through steady-state thermal simulation in accordance with EN ISO 10077-2:2017 [98]. The R-value of the frame structure (concrete column) in buildings of this category is more than three times lower than that of the adjacent area (cavity wall), leading to a pronounced thermal bridge effect [84]. The figure also shows that the concentration of the heat flow lines is higher in the frame structure area and that the heat flow entering and leaving the façade has large lateral component (heat flow is no longer one-dimensional - 1D), which in turn causes the heat flow lines to diverge, increasing the portion of the wall that is thermally affected by the frame structure [84].

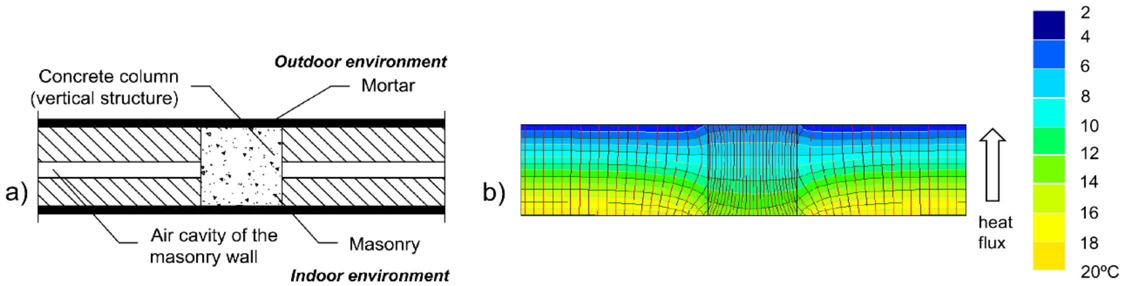


Figure 3.4 View of a horizontal cross section through a typical external envelope consisting of a cavity masonry wall interrupted by a reinforced concrete frame structure (a) and the graphical output of the 2D heat flow simulation (b) [84].

As pointed by the Aelenei et al. [84], this constructive design can lead to significant heat losses during wintertime and, thus, thermal bridges can justify the renovation of these buildings. This conclusion is further supported by other studies conducted in other Southern European locations.

Evola et al. [94] study concluded that primary energy needs for heating and cooling of a terraced house could be reduced up to 25% and 3%, respectively, if the thermal bridge effect was corrected. The researchers justify the discrepancy of results between the seasons by pointing out that in Mediterranean climate the cooling loads are mostly impacted by solar gains and internal loads, and not as much by heat transfer across the envelope.

Rosselló-Batle et al. [99] study showed similar results. The correction of thermal bridges at the wall-to-floor slab junctions of a detached house resulted in the reduction of nearly 25%

of heating energy needs, but only contribute to the reduction of nearly 6% of cooling energy needs.

Kotti et al. [100] study estimated that thermal bridges impact 13% of the overall annual heating load of a single-family building.

Aside from the negative impact on the energy needs, thermal bridges can also lead to other challenges. The definition itself of the thermal bridge puts in evidence that it represents an area consisting of elements with different thermal resistances [101]. As a result, the temperature of the inner surface on the areas influenced by thermal bridges can vary, which may result in surface condensation and biological growth (mould) [94], [101]. These not only can affect the quality of the building elements, but also the living quality of the building inhabitants. Mould growth can cause the formation of diseases, such as allergies and allergic reactions, and the occurrence of a specific smell [102].

3.1.2 Retrofit approach

As discussed in Chapter 2, Portuguese residential buildings, including those built between 1971 and 1990, are typically thermal retrofitted with ETICS (**Figure 3.5**). It was also highlighted that the impact of thermal bridges is proportional to the increase of insulation in the building envelope, and, for this reason, thermal bridges can significantly contribute to the winter heat losses, particularly in high insulated buildings [103].

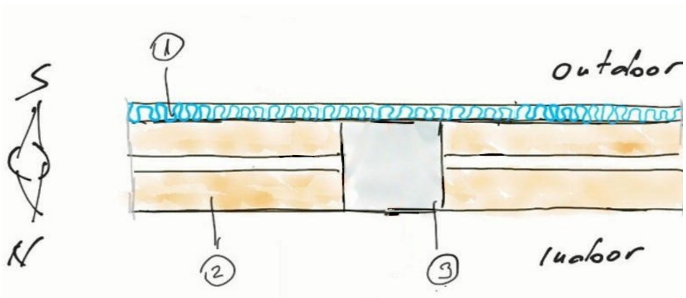


Figure 3.5 Conceptual drawing of a typical constructive design of opaque façades of 1971-1990's Portuguese residential buildings retrofitted with ETICS: 1 – ETICS; 2 – Masonry wall; 3 – Concrete column.

To address the specific challenge of structural thermal bridge areas of the façade, a complementary retrofit solution to ETICS would be highly beneficial. Such a retrofit solution would specifically target structural thermal bridge areas, aiming to reduce winter heat losses caused by the multi-dimensional heat flow, while allowing to implement ETICS in areas where one-dimensional heat flow is predominant.

3.2 SBRS constructive concept

As outlined in literature review, Southern European locations have favourable solar conditions, making Solar Passive Technologies, such as Trombe wall (**Figure 3.6**), suitable for thermal retrofitting residential buildings.

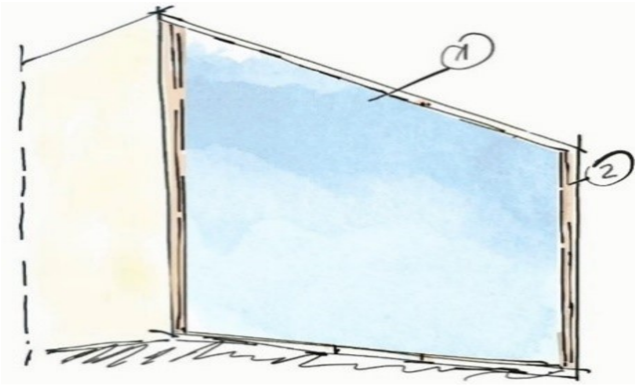


Figure 3.6 Conceptual drawing of a Trombe wall: 1 – External transparent skin (glazing); 2 – Frame of the glazing.

Despite this high solar availability, there are no references to any published studies addressing the use of Solar Passive Technologies specifically for correcting thermal bridge areas in Portuguese façades. Moreover, there is an apparent lack of research on the application of Trombe walls to thermal bridge areas. In response to these identified research gaps, an innovative retrofit solution was designed to improve the thermal performance of the structural thermal areas in load-bearing concrete frame buildings.

3.2.1 Constructive design for the Heating season

The concept design of the proposed retrofit system is inspired by the principles of Trombe wall, but rather than targeting large areas of the South facing wall of the façade, the external transparent layer is only applied to the frame structure (concrete column) area of the envelope, where the structural thermal bridges are located [84], as shown in **Figure 3.7**. By combining Solar Passive Technologies with the retrofitting of thermal bridge areas, this new constructive solution has been named Solar Bridge Retrofit System – SBRS [84].

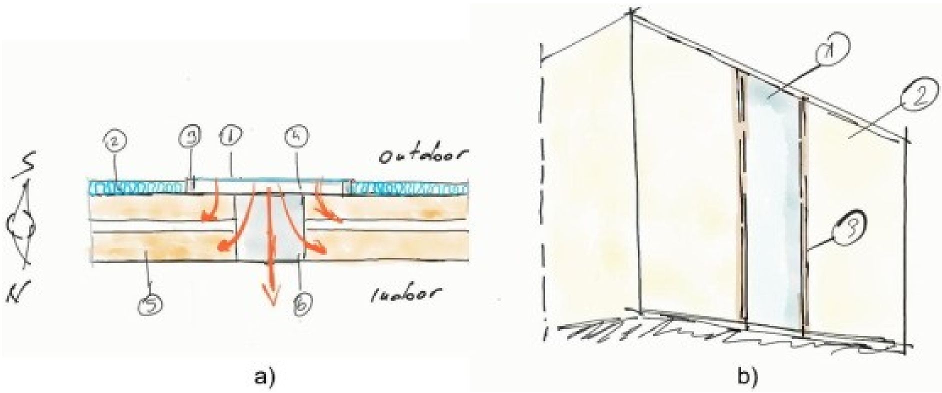


Figure 3.7 Conceptual drawing of the SBRS designed to correct the thermal bridges introduced by concrete columns (a) Horizontal cross section and (b) 3D View: 1 – External transparent skin (glazing); 2 – ETICS; 3 – Frame of the glazing; 4 – Air space of the SBRS; 5 – Masonry wall; 6 – Concrete column [84].

The constructive design of the façades with SBRS allows the adjacent areas (cavity wall) to be retrofitted with ETICS [84] creating a complementary system where both solutions enhance the building´s thermal performance. As pointed by Aelenei et. al [84], this feature may prove to be effective as a retrofit strategy in Southern European countries with a Mediterranean climate, while also addressing one of the main drawbacks of traditional Trombe walls: their aesthetic impact. The literature frequently points the low aesthetic value of Trombe walls compared to other building elements [75], [104], [105].

3.2.2 Constructive design for the Cooling season

To optimize the SBRS for cooling season performance, literature recommendations [79], [106] suggest, the air space of the SBRS should be ventilated. For this reason, vents (openings) at the external transparent skin layer can be considered, as shown in **Figure 3.8**. When these vents are open, no greenhouse effect is created in the air space of the SBRS and, as a result, less heat is transferred into the indoor environment during the summer.

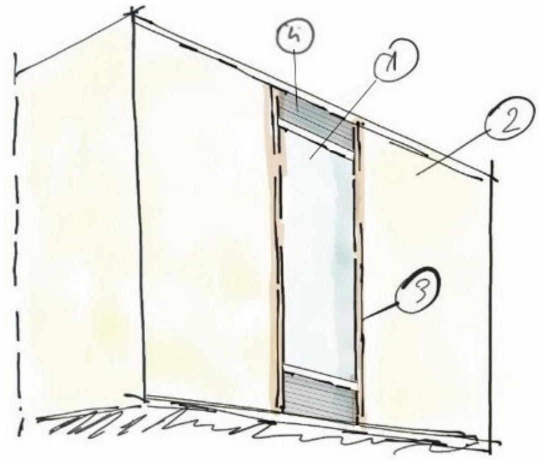


Figure 3.8 Conceptual 3D view of a SBRS without vents (a) and with vents (b): 1 – External transparent skin (glazing); 2 – ETICS; 3 – Frame of the glazing; 4 – Vent.

3.3 SBRS theoretical heat transfer concept

This section presents the theoretical heat transfer model of a façade retrofitted with the Solar Bridge Retrofit System (SBRS) during the heating season, the primary focus of this PhD research.

In the presence of structural thermal bridges within a multi-layered wall, heat transfer occurs through a multidimensional flux. For this scenario, the model assumes a two-dimensional (2D) heat flux governed by the Fourier´s law to represent the dynamic heat conduction throughout the wall structure Therefore, the mathematical model of 2D transient (dynamic) heat conduction within the multilayer wall (façade) structure, considering a heat source (S), is written as follows:

$$\rho_l \cdot c_l \frac{\partial T_l}{\partial t} = \frac{\partial}{\partial x}\left(k_l \frac{\partial T_l}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_l \frac{\partial T_l}{\partial y}\right) + S \qquad in\,\{0 \leq x \leq L_x\ 0 \leq y \leq L_y \qquad (1)$$

Where:

- ρ_l, c_l and k_l are the density, specific heat capacity and thermal conductivity of layer l, respectively.
- $T_l(x, y, t)$ is the temperature field of layer l, as a function of the spatial coordinates x and y and time t.
- S represents the internal heat sources (assumed to be zero).
- L_x and L_y define the domain boundaries of the structure in the horizontal plane (x and y directions).

Dynamic Thermal Regime

To take into the account the inertia of the wall structure, a transient regime should be considered meaning that the temperature field of the wall varies with both time (t) and space (x, y).The spatial coordinates exhibit elliptic behaviour as heat flows bidirectionally across the wall, while the time coordinate follows parabolic behaviour, meaning that the temperature at a given time depends only on prior states, not future values.

Heat Transfer Processes

In this study, to fully describe the heat transfer within the façade with SBRS, the following heat transfer should be considered:

- **Radiation**: The absorption of solar radiation by the outer layers of the wall structure and the exchange of long wave radiation between layers.
- **Convection**: Heat transfer between the outdoor and indoor environment and the wall structure, as well the convective heat transfer between the air space of the SBRS and the layers of the wall structure.
- **Conduction**: Heat flow through the opaque elements of the wall structure.

The façade model consists of several layers, each contributing to the heat exchange:

- g: External transparent skin, or glazing.
- e: External opaque skin.
- f: Air space of the SBRS, representing a fluid layer.
- m: Massive wall, comprised by the concrete column and masonry.

3.3.1 Energy balance across layers

The energy balances describing the heat exchange for each layer is given as follows.

External transparent skin (glazing)

Since the glazing layer (g) is considered to be very thin, the horizontal heat transfer is considered to be negligible, i.e. the temperature of the external transparent skin is assumed to be uniform across the glazing layer [107].

The glazing receives thermal energy in the form of solar radiation and radiation from the massive wall, whereas it loses heat to both fluid in the air space of the SBRS and to the outdoor environment. Therefore, the energy transfer over the glazing can be written as:

$$\emptyset_g = \emptyset_{s,g} + h_{r,f}\left(T_{m,o} - T_g\right) + h_{c,f}\left(T_f - T_g\right) + h_{c,out}\left(T_{out} - T_g\right) + h_{r,g}\left(T_{sky} - T_g\right) \qquad (2)$$

where:

- $\emptyset_{s,g}$ is the solar radiation absorbed by the glazing layer.
- $h_{r,f}$ and $h_{c,f}$ are the radiation and convection coefficients between the air space and the glazing´s inner surface.
- $h_{c,out}$ and $h_{r,g}$ represent radiation and convection coefficient on the outside surface of the glazing.
- $T_{m,o}$, T_g, T_f, T_{out} and T_{sky} represent the temperatures of the outer surface of the massive wall, glazing, air space, outdoor environment and sky, respectively.

External opaque skin (ETICS)

The external opaque skin (ETICS) receives thermal energy in the form of solar radiation and loses heat to the outdoor environment. Therefore, the energy transfer for the opaque skin can be written as:

$$\emptyset_e = \emptyset_{s,e} + h_{c,out}(T_{out} - T_e) + h_{r,g}\left(T_{sky} - T_e\right) \qquad (3)$$

where:

- $\emptyset_{s,e}$ represents the solar radiation absorbed by the external opaque skin.
- T_e, T_{out} and T_{sky} represent the temperature of the external opaque skin, outdoor environment and sky, respectively.

Massive wall

The energy balance for the outer surface of the massive wall is given by:

$$\emptyset_{w,o} = \emptyset_{s,w} + h_{r,f}\left(T_{w,o} - T_g\right) + h_{c,f}\left(T_f - T_{w,o}\right) \qquad (4)$$

where:

- $\emptyset_{s,w}$ represents the solar radiation absorbed by the outer surface of the massive wall.
- $h_{r,f}$ and $h_{c,f}$ represent the radiation and convection within the air space of the SBRS.

3.3.2 Simulation and Solution Approach

While the mathematical formulation for the heat transfer model in the Solar Bridge Retrofit System (SBRS) was developed, solving these equations analytically or numerically was not pursued. Instead, to ensure a comprehensive analysis, simulations were conducted using three different simulation tools - BISCO®, BISTRA®, and DesignBuilder® - as described in **Chapter 5**. BISTRA, in particular, not only solves Equation 1 for appropriate boundary conditions, but also offers additional visualization capabilities such as animations, which essential for assessing the thermal behaviour of the SBRS. Additionally, DesignBuilder® was employed to model whole building simulations. The ability of these simulation tools to model interactions between building elements and environmental conditions provided a robust framework for evaluating the performance of the proposed retrofit solution during both heating and cooling seasons.

3.4 SBRS as a modular solution

The constructive design of the Solar Bridge Retrofit System considers the original external wall of the envelope as the massive wall of the SBRS. The remaining components (external transparent skin, frame and vents) form a singular unit – a modular constructive system referred to as SBRS module.

Retrofitting a façade with a pre-fabricate modular system, offers several advantages, including a shortened overall construction schedule (both assembly and disassembly on-site) and enhanced production accuracy and quality. This leads to improved overall quality of the building and in the reduction of resource wastage [108], [109], [110], [111], [112]. However, to ensure a proper assemble of the modules, design tolerances for the modular solution must be carefully considered. Connections (e.g. inter-module connection in multi-storey residential buildings) are also key to the installation and performance of modular solution [108], [109], [110]. Despite these challenges, as noted by Lacey et al. [108], the benefits of modular solutions outweigh the potential drawbacks, especially for residential development applications.

Figure 3.9 illustrates a conceptual 3D view of a SBRS module. On the left side of the figure is shown the non-retrofitted (unpainted) masonry wall, while on the right side is shown the façade already retrofitted with ETICS, aligned with the SBRS module.

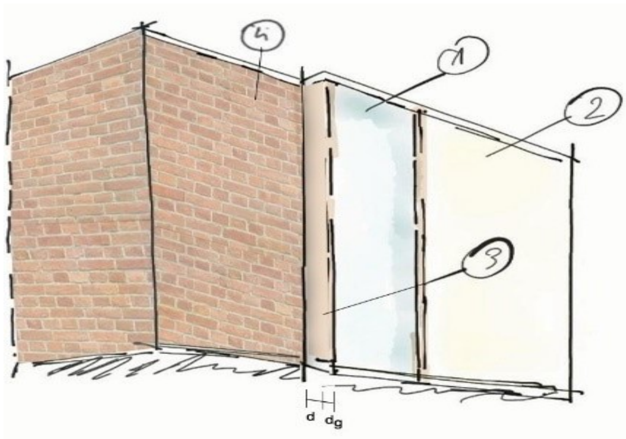


Figure 3.9 Conceptual 3D view of the SBRS: 1 – External transparent skin (glazing); 2 – ETICS; 3 – Frame of the glazing; 4 – Masonry wall (non-painted); d – depth of the air space of the SBRS; dg – thickness of external transparent skin layer.

The depth (d-value) of the air space within the SBRS module is ensured by the frame supporting the external transparent skin, as shown in **Figure 3.9**. The frame of the SBRS also represents the structural system, providing the appropriate stiffness to the façade module.

The following sections will be discussed the SBRS module in greater detail, focusing on:

- Design parameters (configuration).
- Placement of modules
- Type of integration
- Technical characteristics of the installation

3.4.1 Design parameters

Table 3.1 presents the main design configurations of a standard SBRS. These configurations are based on the literature concerning the application of Trombe walls in locations with Mediterranean climate.

Table 3.1 Design parameters of each component of the SBRS.

Components of the SBRS	Standard configuration	Optional configurations to optimize the annual thermal performance
External transparent skin	Double-glazing	Single-glazing Triple-glazing
Frame of the glazing	Aluminium	PVC Wood
Air space	d ≤ 0.10 m	0.10 m < d ≤ 0.15 m
Vents	Upper and lower vents at the external transparent skin layer	--
Colour of the outer surface of the massive wall	Original colour of the façade	Alternative colour

With regard to the massive wall, since the SBRS considers the original external wall of the envelope as the massive wall, the colour of its outer surface is the only modifiable configuration.

3.4.2 Placement of the modules

In the Northern Hemisphere, SBRS modules are primarily designed to be applied on structural thermal bridge areas of South-, East- and West-facing of residential buildings. These orientations are considered for two reasons. First, both East and West are part of the solar path and, receiving significant solar radiation. Second, a study conducted in Lisbon by Brito et al. [17] found that the sum of the potential solar irradiation levels on East- and West facing façades can sometimes surpass those of South facing façades. In contrast, North-facing façades are excluded from the application of SBRS modules due to minimal exposure. For this reason, these façades will only be retrofitted as they usually are in Portugal, with only ETICS.

3.4.3 Type of Integration

From the architectural integration point of view, three aspects are considered:

- Materials used
- System's integration
- Universal design

The SBRS modules are made from typical materials used by the window industry in Portugal. This ensures that there is a coherence between the SBRS system and the architectural resources typically used in Portuguese building industry.

Regarding system integration, two aspects are considered in the design phase for the SBRS module to be seamless integrated:

1. **It is preferable for the outer surface of the massive wall to retain the original colour of the façade to maintain design consistency**, as shown in **Figure 3.10**. Studies indicate that architects and homeowners often perceive dark colours nf the outer surface of the massive wall as having lower aesthetic value, [105], [113], [114], [115], [116]. By keeping the outer surface painted in the original colour of the façade, SBRS can potentially mitigate this aesthetic concern. Additionally, since Portuguese buildings are typically painted in light colours, this choice may improve summer performance by reducing heat absorption.
2. **The thickness of both SBRS and ETICS should be the same to maintain a uniform building envelope**. By considering this aspect, SBRS is designed as a constructive element of the building envelope and the façade is maintained as a linear structure.

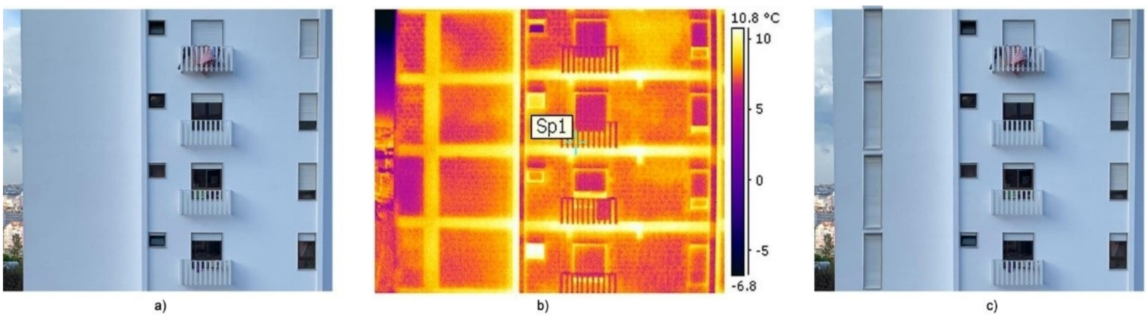


Figure 3.10 Photography of a typically Portuguese façade (a), its respective thermography (b) and an edit photography of the same façade retrofitted with SBRS (c).

The SBRS concept is based on a simple configuration with zero running costs and is designed for use in regions with cool winters, such as areas with a Mediterranean climate. Although originally conceived for retrofit projects, SBRS can also be integrated into new building projects, making it versatile for multiple applications worldwide. Therefore, the SBRS module can be considered a universal design, adaptable to various climates and locations.

The overall building integration of the SBRS is positive, as it serves both energy efficiency and constructive functions.

3.4.4 Technical characteristics of the installation

The SBRS modules are intended to be installed vertically on building façades, more precisely, targeting the structural thermal bridge areas– typically at the junction of masonry walls and concrete columns. Each module should be horizontally centred with the concrete column. The frame of the SBRS is assembled mechanically to the external façade, more precisely on the masonry wall component, where pre-drill holes should be previously done to attach the module to the wall.

3.5 Summary and Research directions

The proposed retrofit solution, named Solar Bridge Retrofit System (SBRS), is based on the principles of the Trombe wall. However, rather than targeting large areas, the SBRS focuses specifically on structural components (beams and columns) of non-retrofitted buildings, where the thermal bridge effect is pronounced due to the lack of thermal insulation [84].

The design of the SBRS enables the heavy concrete structure of the façade to effectively absorb, store and transfer solar energy to the indoor environment of the building in a more effective way, while allowing the application of the traditional ETICS in the adjacent opaque area of the envelope [84]. Additionally, to optimize the annual thermal performance, the inclusion of vents allows the SBRS to be adjusted for both the heating and cooling seasons.

The SBRS appears to be promising solution for retrofitting the façade of 1970–1990′s Portuguese residential buildings. However, as previously highlighted in Chapter 1 and reiterated here for contextual clarity, several key research questions should be tackled:

1. Can an external transparent skin (glazing solution) increase indirect-solar gains during the heating season, when structural thermal bridge areas are mainly targeted?
2. Which external transparent skin (glazing solution) performs better in terms of heat gains vs heat losses of the proposed retrofit solution? Are there any other features that also help enhance the solar gains?

3. How the proposed retrofit solution performs during the cooling season? Is there any need to adapt the proposed solution in the cooling season or to work with other cooling strategies?
4. Is the proposed retrofit solution suitable for all climate zones in Portugal? How the SBRS performs under different Portuguese climate zones?

These research questions are explored in the following chapters.

4

EXPERIMENTAL STUDY OF A FAÇADE WITH SBRS

This chapter presents the experimental study conducted to assess the thermal performance of the innovative retrofit solution, the Solar Bridge Retrofit System (SBRS). It addresses the 3rd Research Objective of this PhD thesis: to assess the system´s efficiency under real conditions. The experimental analysis is fundamental for determining the practical viability of SBRS in retrofitting Portuguese residential buildings.

The experiments were conducted in a Mediterranean climate, with Lisbon, Portugal, as the test location. This climate represents a useful setting for evaluating the system´s performance in both heating and cooling seasons.

The experimental study specifically addresses the 1st, 2nd and 3rd Research Questions, namely:

1. Can an external transparent skin (glazing solution) increase indirect solar gains during the heating season when applied to structural thermal bridge areas? If so, to what extent can it reverse the thermal bridge effect?
2. What type of external glazing solution (single- or double-glazing) offers the best balance between heat gains and heat losses in the SBRS? Are there additional features that could further optimize the system's solar gains?
3. How does the proposed SBRS retrofit solution perform during the cooling season? Is there a need for adaptation or additional cooling strategies to mitigate heat gains?

The chapter is structured into five parts:

1. **Location and climate:** Overall description

2. **Experiment design and procedure:** Explanation of the study design, including limitations and measurement procedures, as well as a characterization of the test cell (e.g., materials and thermal properties) and prototypes of the SBRS
3. **Heating monitoring campaigns:** Presentation and discussion of the results
4. **Cooling monitoring campaigns:** Presentation and discussion of the results
5. **Discussion and brief conclusion:** Summary of the main findings and conclusions from the chapter

The following papers contributed to the development of this chapter:

D. Aelenei, S. Brito-Coimbra, M. Gloria Gomes, and A. Moret Rodrigues (2021) "Solar Bridge Retrofit System: An innovative solution to renovate structural thermal bridge areas," Energy and Buildings, vol. 236, p. 110784, 10.1016/j.enbuild.2021.110784.

S. Brito-Coimbra, D. Aelenei, M. Gloria Gomes, and A. Moret Rodrigues (2023) "Experimental Design for Building Retrofit Studies: The Assessment of the Thermal Behaviour of a Solar Passive Retrofit Solution," Testing and Experimentation in Civil Engineering, RILEM Bookseries, vol 41, p. 291 - 301, https://doi.org/10.1007/978-3-031-29191-3_25.

4.1 Experimental Setup

The experimental setup was devised at the campus of the NOVA School of Science and Technology (NOVA FCT), Portugal. Specifically, the experimental study was conducted on the rooftop of the Civil Engineering Department (latitude: 38º39′36′′ N; longitude: 9º12′25′′ W; altitude 110 m) (**Figure 4.1**).

Figure 4.1 Location of the experimental setup.

This location is characterized by a Mediterranean climate (Csa) with cool and wet winters, hot and dry summers, and high solar radiation.

A specially designed thermal test cell was constructed to replicate the façade of a typical Portuguese residential building built between 1971 and 1990.

4.1.1 Design and characterization of the Test Cell

To ensure the safety of the experimental campaigns (limited assess) and to guarantee full exposure (no shade) on the South-facing wall, the experimental campaigns were conducted on the rooftop of the Civil Engineering Department, as mentioned at 4.1.

Giving the rooftop setting, the design of the test cell should ensure a safe structural load of the rooftop. Consequently, a reduced-scale thermal box was chosen as the test cell to represent a thermal room instead of a full-scale model. According to Wang et al. [105], this type of experimental method saves space and money saving but has drawbacks related to the similarity law. Moreover, only one configuration could be tested at a time. Therefore, multiple monitoring campaigns were conducted in the same season to evaluate different configurations.

To study the thermal behaviour of the SBRS, a reduced-scale thermal box (test cell) was designed and built with external dimensions 1.1 × 3.0 × 1.20 m (width x depth x height).

To reduce thermal exchanges between the rooftop of the Civil Engineering Department and the cell test, the floor of the test cell was constructed with (from the inside to the outside) a concrete layer (4.5 cm) and XPS Insulation layer (5 cm), as shown in **Figure 4.2**. The U-value of the floor is 0.59 W/m²K.

(a) (b) (c)

Figure 4.2 Building of the floor of the test cell.

To replicate the constructive design of Portuguese residential buildings from 1971–1990's, the South-facing wall, which was the focus of this study, was built as a cavity wall made of clay hollow bricks and mortar on both surfaces (**Figure 4.3a** and **Figure 4.4**). The outer and the inner brick layers are 11 cm and 9 cm, respectively, separated by a 5 cm air space (**Figure 4.3b**). To recreate the structural thermal bridge effect, a concrete column (25 × 25 cm) was built in the middle of the South-facing wall (**Figure 4.3c**). The remaining walls of the test cell were built constructed with a lightweight structure made of OSB (Oriented Strand Board) layer (1.8 cm) and an external layer of EPS insulation (4 cm), as shown in **Figure 4.5**. The calculated thermal transmittance (U-value) of the cavity wall, the concrete column, and lightweight solution are 1.1, 2.9 W/m^{2}K and 0.71 W/m^{2}K, respectively.

The roof was also constructed using a lightweight solution using oriented strand board OSB panels (1.8 cm) and an external layer of EPS insulation (6 cm), as illustrated in **Figure 4.6**. The U-value of the roof is 0.52 W/m^{2}K.

The test features a removable door on the North-facing wall to allow access inside the cell (**Figure 4.7**).

(a) **(b)** **(c)**

Figure 4.3 Construction of the test cell: (a) South-facing wall based on a cavity wall made of clay hollow bricks; (b) Side section of the South-facing wall, (c) South- (cavity wall with a concrete column in the middle) and East-facing (OSB) walls [78].

(a) **(b)**

Figure 4.4 Mortar at the South-facing wall: (a) application of the outer layer; (b) Inner layer.

(a) **(b)** **(c)**

Figure 4.5 East-facing wall: (a) OSB layer; (b) application of the EPS layer; (c) finishing the application of the EPS layer.

Figure 4.6 Construction of the roof of the test cell.

Figure 4.7 North-facing wall of the test cell.

4.1.2 Characterization of the SBRS prototypes and configuration

To investigate the thermal performance of the SBRS, two prototypes were designed and tested to evaluate their performance under both heating and cooling conditions. These configurations included variations in glazing and venting to assess their thermal performance and adaptability.

1. First prototype

The first prototype (PT1) consisted of a single-glazing with a thickness of 5 mm, made from low-iron glass (λ = 1.05 W/m·K), chosen for its high solar transmittance (**Figure 4.8a**). This layer formed the external transparent skin of the SBRS and was separated from the underlying masonry by an air space of 50 mm. The single-glazing system was selected to maximize solar gains during the heating season while keeping material costs low. No thermal insulation was applied on either side of the SBRS. Therefore, the cavity wall described in 4.2.2 remains the same.

(a) **(b)**

Figure 4.8 The SBRS prototypes applied to the test cell: (a) Single-glazing configuration; (b) Double-glazing configuration with external vents (covered).

2. The second prototype

The second prototype (PT2) consisted of a transparent external layer consisting of a double-glazing (4 mm +16 + 4 mm) mounted on a plastic (PVC) frame, with external (upper and lower) vents (**Figure 4.8b**). The air space between the glazing and the concrete column was also set at 50 mm in this configuration. This air cavity played a critical role in the thermal behaviour of the SBRS, acting as a buffer zone for heat transfer. The vents were strategically placed at the top and bottom of the external glazing layer, allowing for natural ventilation during the cooling season. These vents could be manually opened or closed to control airflow, thereby reducing the risk of overheating in the summer months. When closed during the heating season, the vents created a greenhouse effect, trapping heat within the air cavity to warm the interior space. In this configuration, a layer of ETICS (4 cm) was installed on both sides of the SBRS to insulate the masonry cavity wall. Additionally, the exterior surface of the concrete column in one of the tests was coated with a black, solar-absorbing paint (absorptivity = 0.9), designed to maximize heat absorption during the heating season (**Figure 4.9**). In contrast, a second test was performed with the wall painted white (absorptivity = 0.2), to assess the influence of surface colour on the system's performance during both heating and cooling seasons.

Figure 4.9 The SBRS prototypes applied to the test cell with the double-glazing configuration, external vents (covered) and outer surface of the wall painted in black.

4.1.3 Experimental measuring procedure

The experimental campaign aimed to monitor the thermal performance of the Solar Bridge Retrofit System (SBRS) under real conditions across both the heating and cooling seasons. To achieve this, a set of calibrated sensors and measuring instruments were employed to track temperatures, heat flux, air velocity, and solar irradiation at various points within the test cell and on the SBRS prototypes.

1. Temperature measurements

Thermocouples (Type T) were installed at critical locations to capture temperature variations across the SBRS and test cell (**Figure 4.10**). A total of 25 thermocouples were placed in the following locations:

- Inside the air cavity of the SBRS, between the glazing and masonry wall, to measure the temperature gradient across the air space.
- On the internal and external surfaces of the masonry wall and concrete column to assess the heat transfer through these elements.
- Inside the test cell to monitor indoor air temperature.

Each thermocouple was calibrated to an accuracy of ±0.5°C, ensuring high precision in temperature measurements. Data from the thermocouples were recorded at 10-minute intervals using two dataloggers, a Delta-T DL2e and a Delta-T GP2, with measurements taken continuously over the monitoring period. To avoid value alterations due to direct solar radiation exposure, the thermocouples located on the exterior surface of the wall and glazing were screened.

Additionally, a Delta-T™ RHT2nl probe was used to measure indoor temperature and relative humidity (RH) in the interior of the test cell.

2. Heat Flux measurements

Heat flux sensors (Hukseflux™ HFP01) were positioned on the interior and exterior surfaces of the concrete column and masonry wall to quantify heat transmission through the façade **(Figure 4.11)**. These sensors were installed at both the upper and lower portions of the SBRS to capture potential variations in heat flux across the height of the column. The heat flux sensors had a sensitivity of 61 $\mu V/W.m^{-2}$ and an accuracy of ± 3%, ensuring reliable data collection.

Heat flux data was recorded simultaneously with temperature measurements, allowing for a direct comparison between thermal gradients and heat transfer rates. This combination of measurements provided insights into the overall thermal performance of the SBRS in both vented and unvented configurations.

3. Solar Radiation and Environmental Conditions

Pyranometer (Kipp & Zonen™ CMP11) was used to measure both horizontal global solar radiation (**Figure 4.12)**. A horizontal pyranometer was positioned on top of the test cell to capture global horizontal irradiation (GHI), while a vertical pyranometer was mounted on the South-facing wall to measure solar radiation directly impacting the SBRS.

Additionally, a TinyTag™ TGP-4500 was deployed to measure the outdoor ambient temperature and relative humidity in close proximity to the test cell.

4. Thermographic Survey

A thermographic camera (FLIR™ C3) was used to conduct thermal imaging surveys of the SBRS prototypes. The survey targeted the interior surface area of the SBRS, consisting of the concrete column and the adjacent masonry wall. The thermograms were obtained at 60-min intervals, from 6 pm until 12 midnight, at a distance of 2.0 meters.

(a) **(b)**

Figure 4.10 Temperature sensors (thermocouples type T) being installed within the cavity of the masonry wall: (a) front view of the sensor in the air space of the cavity wall; (b) top view.

(a) **(b)**

Figure 4.11 Heat flux sensors Hukseflux™ HFP01 on the interior surface of the: (a) masonry wall; (b) concrete column**.**

Figure 4.12 Pyranometers Kipp & Zonen™ CMP11 (horizontal global solar radiation).

Table 4.1 lists the equipment deployed used during the monitoring campaigns and their accuracy. **Figure 4.13** and **Figure 4.14** map the sensor locations in the test cell and the SBRS, respectively.

Table 4.1 List of equipment used during the monitoring campaigns.

Equipment	Symbol (Units)	Measurement	Accuracy
Thermocouple Type-T	T1 up to T23 (°C)	Inner/outer surface temperature of the wall/glazing Temperature of the air cavity of the masonry wall Temperature of the air space of the SBRS	±0,5 °C
	Tout (°C)	Outdoor air temperature	
Probe	Tint (°C)	Indoor air temperature	± 0,1 °C
	RHint (%)	Indoor relative humidity	±2%
Tinytag	Tint and Tout (°C)	Indoor and outdoor air temperature	±0,5 °C
	RHint and RHout (%)	Indoor and outdoor relative humidity	±2%
Heat flux sensor	F1 up to F3 (W/m²)	Heat flux at the inner/outer surface of the wall	±3%
Pyranometer	P1 (W/m²)	Horizontal solar radiation	<7 W/m²

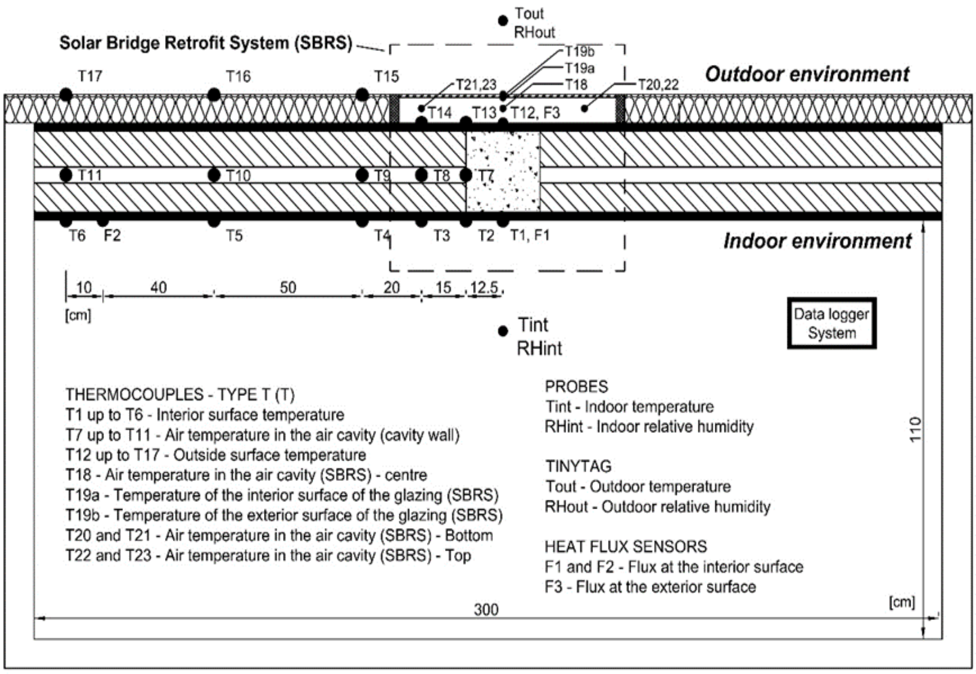
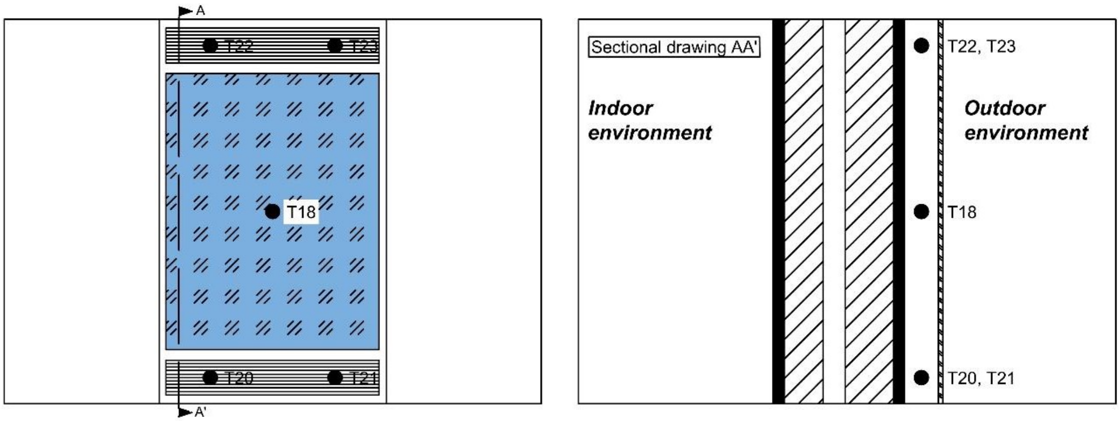


Figure 4.13 Horizontal cross-section of the test cell, singling the location of the sensors and SBRS.



(a) **(b)**

Figure 4.14 The map with the location of the sensors in the air space of the SBRS (vertical section): (a) front view; (b) side view.

The experimental study involved a series of monitoring campaigns (MC) conducted during both the heating and cooling seasons. These campaigns are labelled as MC-H for the heating season (wintertime) and MC-C for cooling season (summertime), followed by a numeral suffix indicating the sequence of the campaign. Although several campaigns were conducted in 2020 and 2021, this section focuses on seven key campaigns (three heating and four cooling) that best represent the thermal behaviour of the test cell and directly address the Research Questions, particularly the 3rd and 4th.

Heating season campaigns:

- MC-H1: 13th - 14thFebruary of 2020
- MC-H2: 15th - 17thMarch of 2020
- MC-H3: 14th - 20th March of 2021

Cooling season campaigns:

- MC-C1: 01st and 05th August of 2020
- MC-C2: 10th and 14th August of 2020
- MC-C3: 08th September 2021
- MC-C4: 18th September of 2021

Tables 4.2 and **4.3** detail the equipment used and the SBRS configurations implemented during each of the MC-H and MC-C campaigns, respectively.

Table 4.2 Configuration of each campaign devised during the heating season (MC-H).

		MC-H1	MC-H2	MC-H3
Equipment	T1 toT19a	✔	✔	✔
	T19b to 23			✔
	Tint	✔	✔	✔
	Tout	✔	✔	✔
	RHint	✔	✔	✔
	RHout			✔
	F1 a F3	✔	✔	✔
	P1	✔	✔	✔
SBRS Configuration	PT1	✔		
	PT2 with open vents			
	PT2 with close vents		✔	✔
	Wall painted in white	✔	✔	
	Wall painted in black			✔
Wall Configuration	Cavity wall without ETICS	✔		
	Cavity wall with ETICS		✔	✔

Table 4.3 Configuration of each campaign devised during the heating season (MC-C).

		MC-C1	MC-C2	MC-C3	MC-C4
Equipment	T1 toT19a	✔	✔	✔	✔
	T19b to 23	✔	✔	✔	✔
	Tint	✔	✔	✔	✔
	Tout	✔	✔	✔	✔
	RHint	✔	✔	✔	✔
	RHout	✔	✔	✔	✔
	F1 a F3	✔	✔	✔	✔
	P1	✔	✔	✔	✔
SBRS Configuration	PT1				
	PT2 with open vents	✔		✔	
	PT2 with close vents		✔		✔
	Wall painted in white	✔	✔		
	Wall painted in black			✔	✔
Wall Configuration	Cavity wall without ETICS				
	Cavity wall with ETICS	✔	✔	✔	✔

4.2 Results of Heating Monitoring Campaigns

This section presents the experimental findings from the three monitoring campaigns (MC-H1, MC-H2, MC-H3). It begins with an overview of the climatic conditions during each monitoring campaign, followed by an analysis focusing on the measured temperatures, heat fluxes and overall heat transfer characteristics of the SBRS and the test cell.

4.2.1 Climatic conditions

The climatic data, including outdoor air temperature (Tout) and global solar radiation, for each monitoring campaign, is illustrated in **Figure 4.15, Figure 4.16** and **Figure 4.17.**

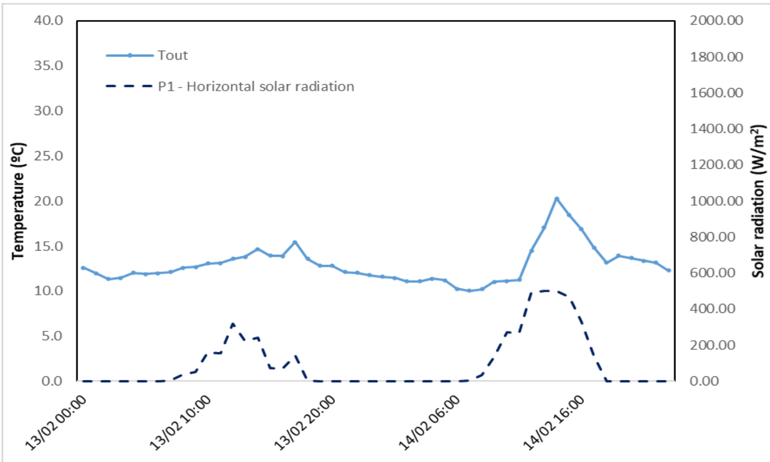


Figure 4.15 Climatic conditions during MC-H1 (13th and 14th February 2020).

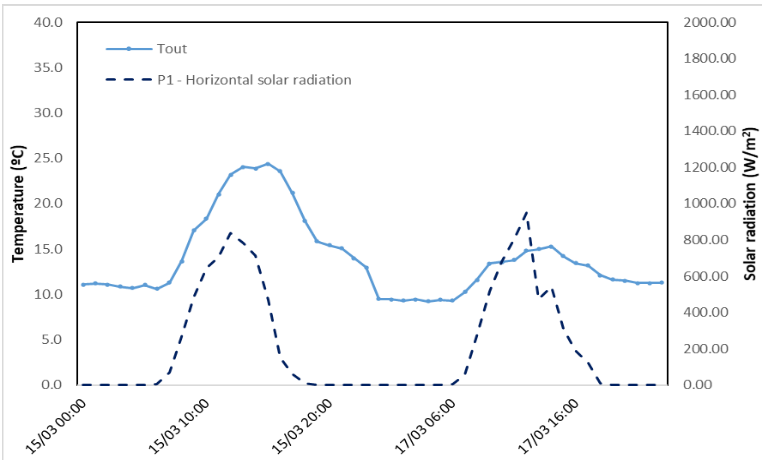


Figure 4.16 Climatic conditions during MC-H2 (15th and 17th March 2020).

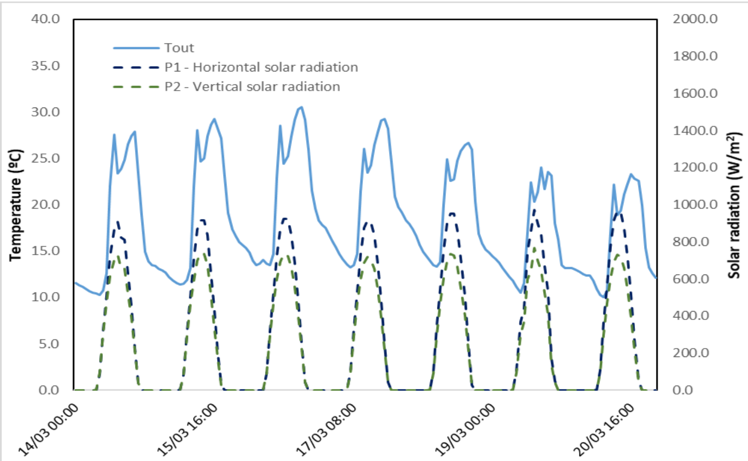


Figure 4.17 Climatic conditions during MC-H3 (between14th and 20th of March of 2021).

4.2.2 Temperature in the Air Space of the SBRS and in Ambient Air

Figure 4.18 and **Figure 4.19** illustrate indoor (Tint), outdoor (Tout) and SBRS air space (T18) temperatures during MC-H1 on both a cloudy and a sunny day, respectively.

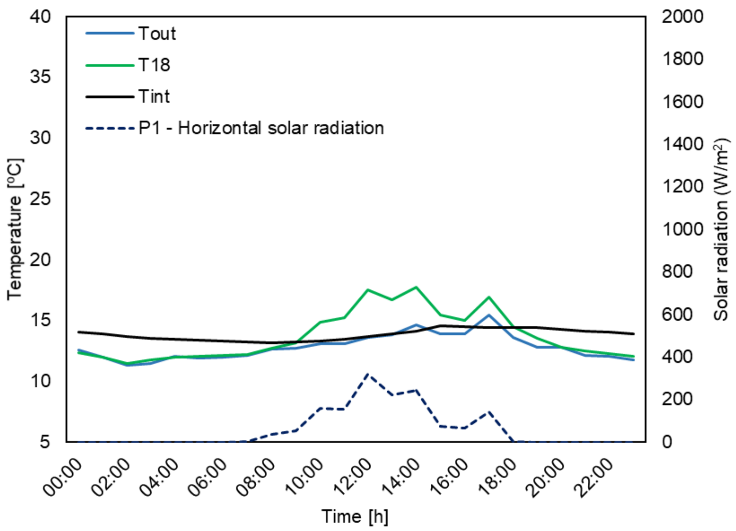


Figure 4.18 The measured indoor (Tint), outdoor (Tout) and SBRS air space (T18) temperatures during MC-H1, with single-glazing configuration, during a cloudy day [78].

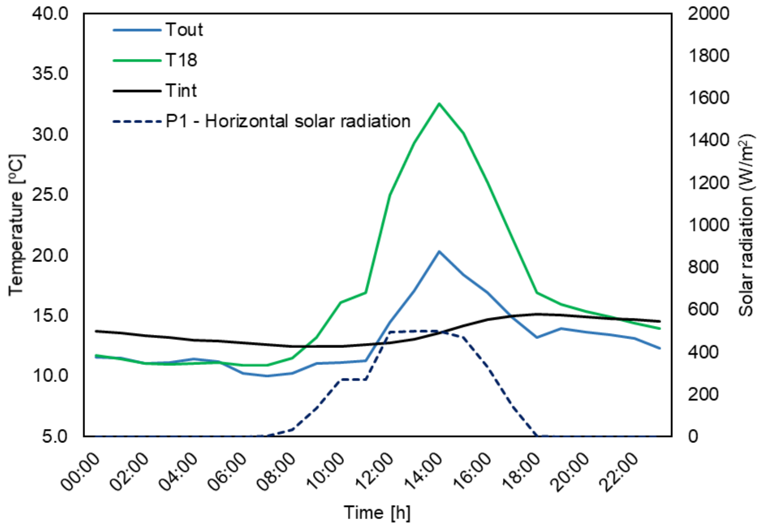


Figure 4.19 The measured indoor (Tint), outdoor (Tout) and SBRS air space (T18) temperatures during MC-H1, with single-glazing configuration, during a sunny day [78].

During the cloudy day of MC-H1, Tout varied between 11.2 °C and 16.2 °C (average 12.8 °C), whereas on the sunny day, temperatures ranged from 10.0 °C to 22.6 °C (average 13.1 °C). T18 reached a peak of 33.3 °C during maximum solar radiation hours. Overnight, Tint typically remained 2 °C above Tout, fluctuating between 13 °C and 15 °C on both days.

Figure 4.20 and **Figure 4.21** illustrate measured indoor (Tint), outdoor (Tout) and SBRS air space (T18) temperatures during MC-H2 on a partially cloudy and a sunny day, respectively.

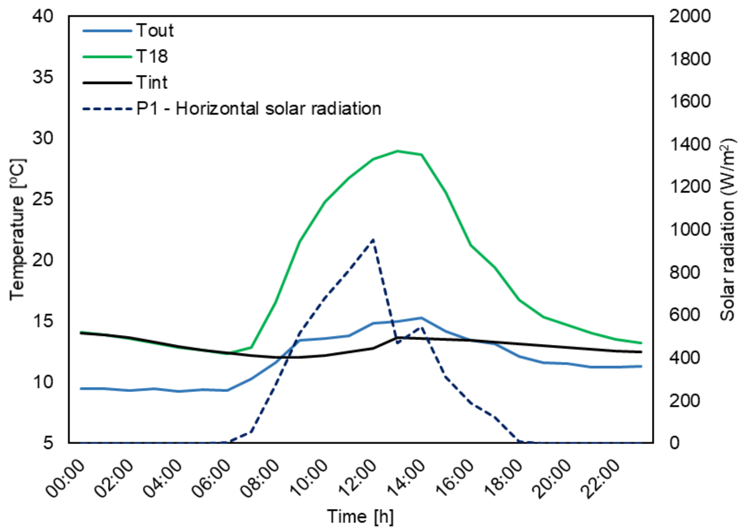


Figure 4.20 The measured indoor (Tint), outdoor (Tout) and SBRS air space (T18) temperatures during MC-H2 with double-glazing configuration, during a cloudy day [78].

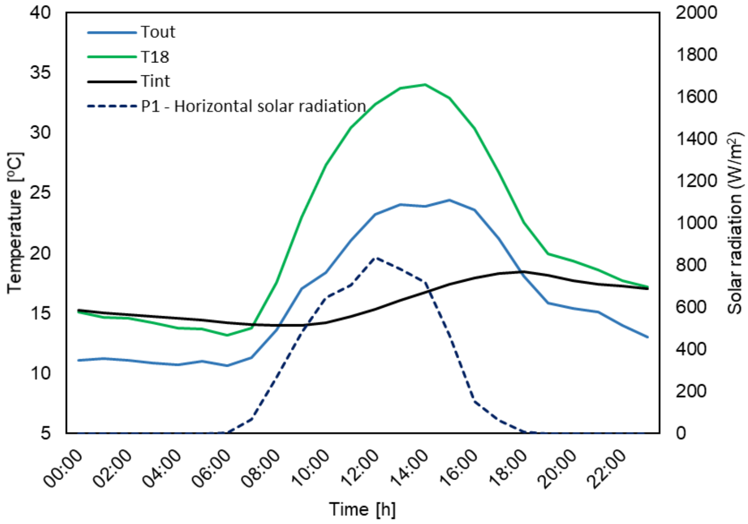


Figure 4.21 The measured indoor (Tint), outdoor (Tout) and SBRS air space (T18) temperatures during MC-H2, with double-glazing, configuration, during aa sunny day [78].

On the cloudy day of MC-H2, Tout varied between 8.7 °C and 16.0 °C (average 11.8 °C), whereas on the sunny day, temperatures ranged from 10.0 °C to 26.4 °C (average 16.2 °C). T18 reached 35.4 °C during maximum solar radiation hours of the sunny day. Overnight, the temperature difference between Tint and Tout was most pronounced on the sunny say, with Tint being 4.5 °C higher than Tout.

The comparison between of MC-H1 and MC-H2 demonstrates that the SBRS with the double-glazing configuration and ETICS (PT2) provided greater benefits to the indoor environment than the single-glazing without ETICS (PT1), as evidenced by the higher Tint-Tout differential. This result is consistent with findings in the literature on Trombe wall systems, particularly in Mediterranean climates, where double-glazing configurations are shown to significantly improve façade performance by enhancing thermal insulation and reducing heat loss (**2.4.3**).

4.2.3 Temperature distribution across the SBRS

To better understand the thermal behaviour of the proposed innovative system, an analysis was conducted based on the evolution of the temperatures recorded across the cross-section of the SBRS at the concrete column. This analysis included monitoring Tint, T1, T12, T18, T19a and Tout, during sunny days of MC-H1 and MC-H2. The graphical representation of these temperature profiles is shown in **Figure 4.22** and **Figure 4.23**, respectively.

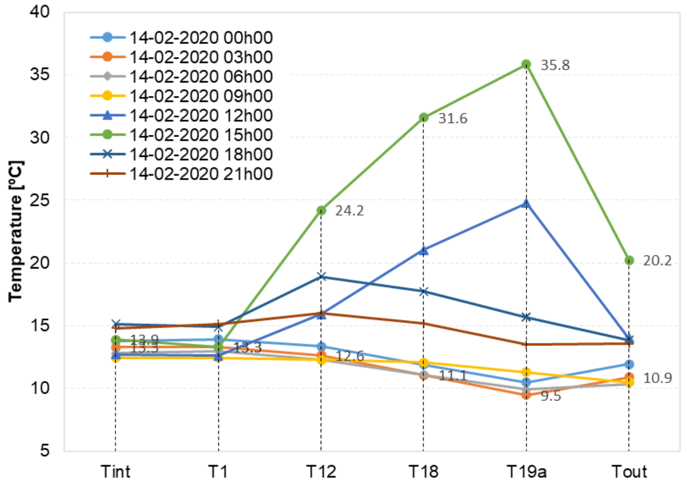


Figure 4.22 Evolution of the temperatures recorded at different time steps across the SBRS in sunny days during, MC-H1 (single-glazing configuration) [78].

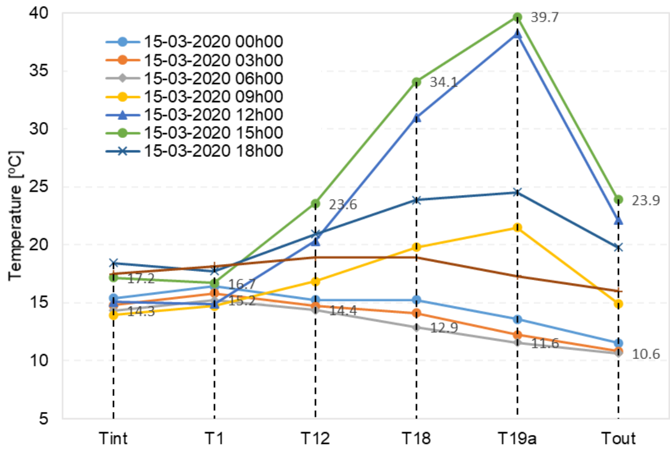


Figure 4.23 Evolution of the temperatures recorded at different time steps across the SBRS in sunny days during MC-H2 (double-glazing configuration) [78].

The measured temperature profile in the SBRS air space (T18) shows the expected evolution, with a sharp increase driven by incident solar radiation. This behaviour is observed in both single-glazing (**Figure 4.22**) and double-glazing configurations (**Figure 4.23**). The temperature at the exterior surface of the concrete column (T12) follows a similar trend but at a lower magnitude due to the thermal inertia of the concrete and the gradual conduction of heat into the building´s interior. T12 continues to rise until 15h00, when the SBRS receives the highest amount of solar radiation. By 18h00, as solar intensity decreases, the temperatures begin to fall. By 21h00, the temperatures values at the exterior and interior surfaces of the concrete column (T12 and T1, respectively) start to level up due to thermal equilibrium. Even at this time, all recorded temperatures remain higher than those recorded at 06h00, indicating that the thermal mass of the concrete column was activated by absorbing heat from the SBRS air space throughout the day.

In MC-H1, the temperature gradient from the exterior surface (T12) to the interior surface (T1) of the concrete column is more pronounced, reflecting greater heat loss through the single-glazing configuration. The lower thermal resistance of the single-glazing system allowed more heat to escape, resulting in a wider differential between the air space (T18) and the interior surface temperature (T1).

In contrast, MC-H2, which employed the double-glazing configuration, shows a more balanced temperature distribution across the SBRS. The additional glazing layer reduced the heat loss, leading to a smaller temperature differential between T12 and T1. This more gradual temperature change across the SBRS indicates that the double-glazing system better retained the heat gained during the day, allowing it to be more evenly distributed through the concrete column.

Moreover, the interior surface temperature (T1) in MC-H2 remained consistently higher throughout the day compared to MC-H1, demonstrating improved thermal performance in maintaining thermal comfort. The reduced gradient across the SBRS in MC-H2 also indicates that the system was more effective at mitigating the thermal bridge effect, with less heat escaping through the concrete column.

4.2.4 Interior surface temperatures: thermocouples

To a better understanding of the thermal behaviour of the South-facing wall, an additional analysis was conducted based on the evolution of the temperatures recorded along the interior surface of the test cell. Specifically, temperature at locations T1, T2, T3, T4, T5 and T6 were monitored during sunny days in both MC-H1 and MC-H2. The graphical representation of these temperature profiles is shown in **Figure 4.24** and **Figure 4.25**.

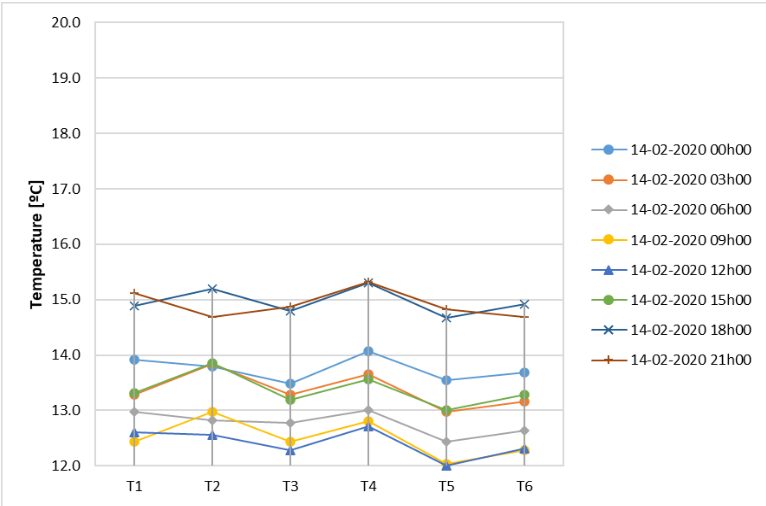


Figure 4.24 Evolution of the temperatures recorded along interior surface of the test cell at different time steps across the SBRS during a sunny day of MC-H1 (single-glazing configuration) [78].

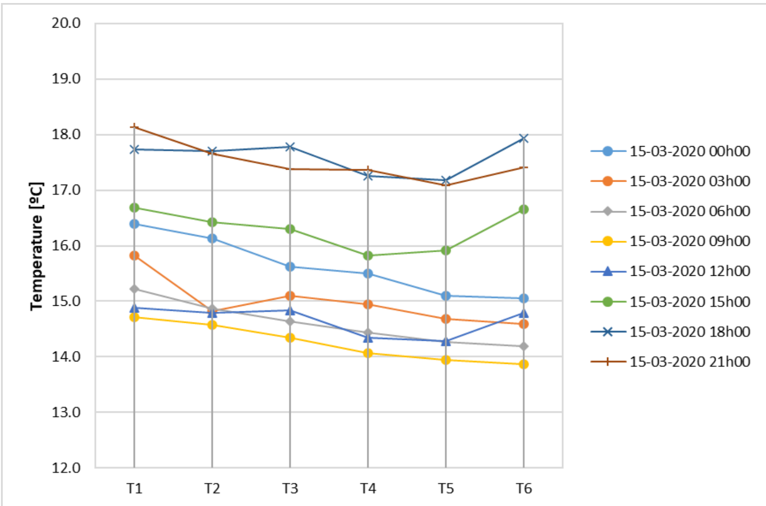


Figure 4.25 Evolution of the temperatures recorded along interior surface of the test cell at different time steps across the SBRS during a sunny day during of MC-H2 (double-glazing configuration) [78].

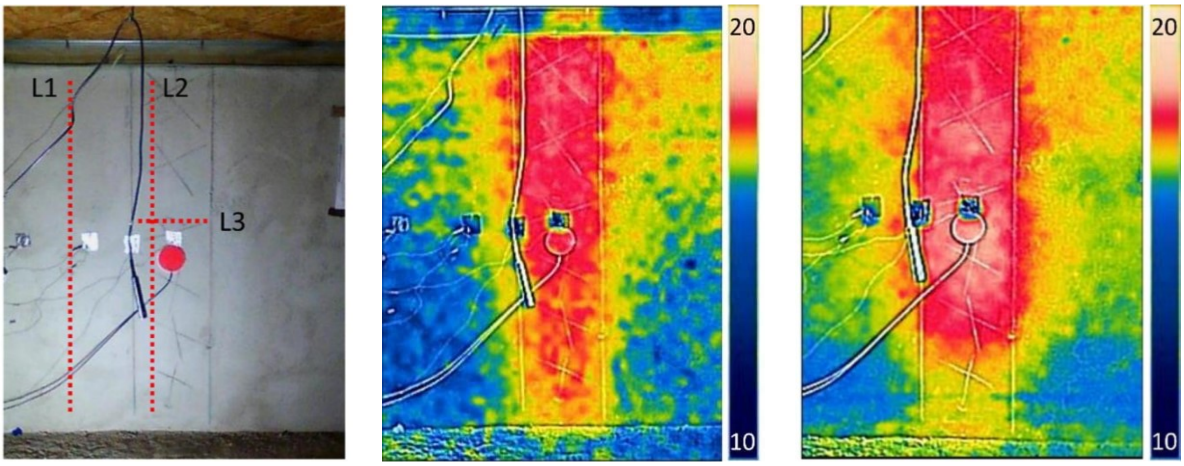
Both figures show that all surface temperatures increase until 18h00 and remain relatively stable until 21h00 due to thermal inertia. This thermal inertia helps retain the heat gained during the day, delaying the cooling process even as solar radiation declines.

When MC-H1 (single-glazing configuration) and MC-H2 (double-glazing configuration), remarkable differences in the way the heat flow is transferred through the massive wall are noticed. In the double-glazing configuration (MC-H2), which benefits from higher efficiency in solar radiation absorption and the presence of ETICS, the heat flow transferred through the concrete column to the interior has la more pronounced lateral component. This results in a broader area of the wall being thermally influenced by the concrete structure, with the thermal effect extending up to 85 cm on either side of the concrete column. In contrast, the single-glazing configuration (MC-H1) shows a more localized heat transfer, with less lateral heat diffusion into the surrounding wall.

4.2.5 Interior surface temperatures: thermographic survey

To assess the impact of SBRS heat gains on interior surface temperatures during sunny days, thermographic surveys were conducted for both configurations of SBRS, following the procedure outlined in Section 4.2.4. These surveys provided a visual representation of temperature distribution across the interior surfaces of the test cell.

Figure 4.26 shows the thermograms captured at 21h00 for each configuration during sunny days, along with corresponding photographs. This specific time was chosen to illustrate the temperature distribution a few hours after the sunset and, aligning with one of the time steps discussed in Section 4.3.4 (21h00). The uniformity of the temperature distributions is further analysed and summarized in **Table 4.4**.



(a) **(b)** **(c)**

Figure 4.26 Thermographic study: (a) photography of the interior area under investigation; (b) Thermogram of the interior surface of the SBRS during MC-H1 (single-glazing configuration); (c) Thermogram of the interior surface of the SBRS during MC-H2 (double-glazing configuration); L1 – vertical direction of the masonry wall, L2 – vertical direction of the concrete column, F3 – horizontal direction of the concrete column [78].

A visual comparison between the thermograms in **Figure 4.28** shows that the surface temperature of the concrete column is higher than the masonry surface in both configurations MC-H1 (single-glazing configuration) and MC-H2 (double-glazing configuration). This observation aligns with the findings discussed in Section 4.3.4, where the heat flow transferred through the concrete column into the interior exhibited a greater lateral component in the double-glazing configuration. This is evidenced by a greater thermal influence on the wall's portion adjacent to the concrete frame, depicted in red and yellow colours.

Additionally, the thermograms also show that the surface temperature of both the concrete column and the adjacent masonry wall is higher in the upper part of the wall compared to the lower part. This variation is likely due to the upward movement of heat, a result of the natural convection within the SBRS air cavity.

Table 4.4 summarizes the results of the thermographic survey for MC-H1 and MC-H2. The temperature distribution along **Line 3 (L3)**, which represents the horizontal direction of the concrete column, was the most uniform in both configurations, with temperature variations below 1.0°C. When comparing the temperature profiles along all three lines, the double-glazing configuration (MC-H2) exhibited smaller temperature differences, resulting in a more uniform distribution of heat across the wall surfaces compared to the single-glazing configuration (MC-H1).

Table 4.4 Results of thermographic survey developed during MC-H1 and MC-H2 [78].

Type of configuration	**Line 1 (L1)**		**Line 2 (L2)**		**Line 3 (L3)**	
	MC-H1	MC-H2	MC-H1	MC-H2	MC-H1	MC-H2
Avg temp (°C)	15.7	17.7	14.3	16.9	15.7	17.9
Min temp (°C)	13.2	15.7	13.7	15.8	15.2	17.6
Max temp (°C)	16.5	18.2	15.1	16.5	16.1	17.9
Difference temp (°C) (Max - Min temp)	3.3	2.5	1.4	0.7	0.9	0.3

4.2.6 Transmission heat fluxes

The internal and external heat flux densities (F1 and F3) of the concrete column were measured for both sunny and cloudy days during MC-H1 (single-glazing configuration) and MC-H2 (double-glazing configuration). **Figure 4.27** and **Figure 4.28** illustrate the heat fluxes for MC-H1 on sunny and cloudy days, while **Figure 4.29** and **Figure 4.30** show the corresponding data for MC-H2

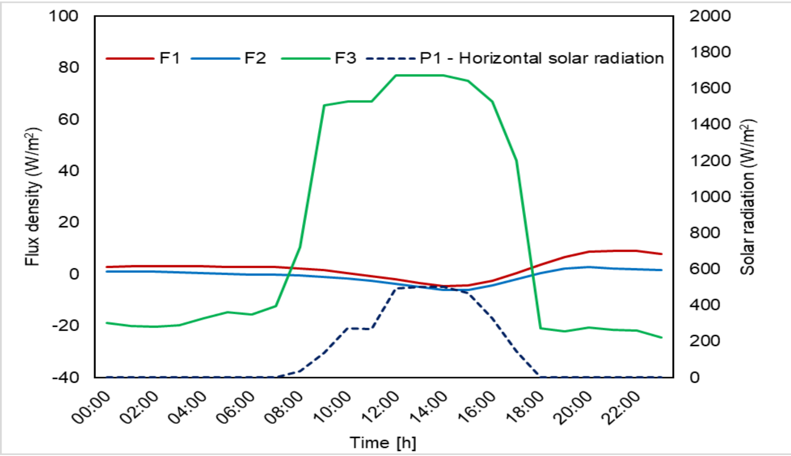


Figure 4.27 Internal and exterior heat flux densities of the concrete column during MC-H1, with single-glazing configuration, on a sunny day [78].

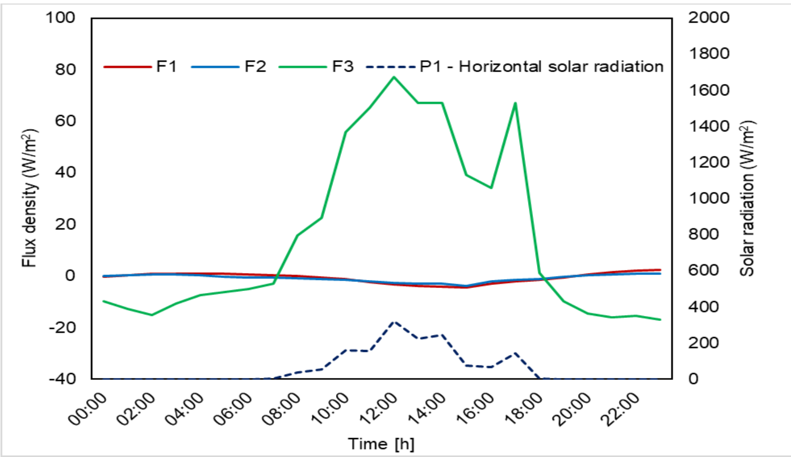


Figure 4.28 Internal and exterior heat flux densities of the concrete column during MC-H1 with single-glazing configuration, on a cloudy day [78].

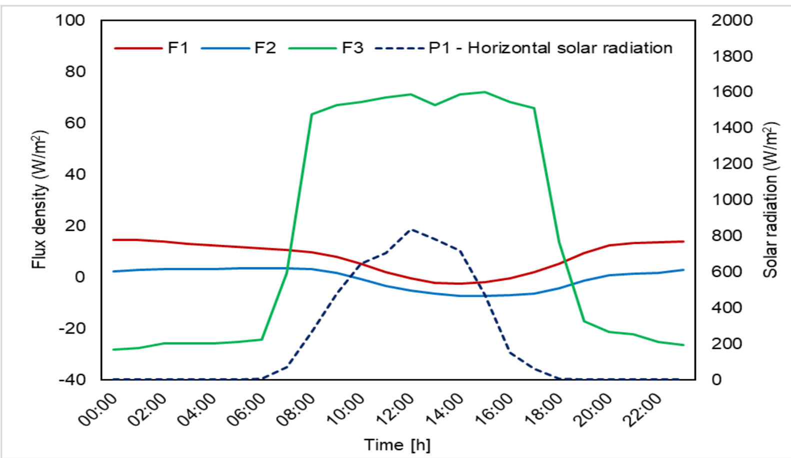


Figure 4.29 Internal and exterior heat flux densities of the concrete column during MC-H2, with double-glazing configuration, on a sunny day [78].

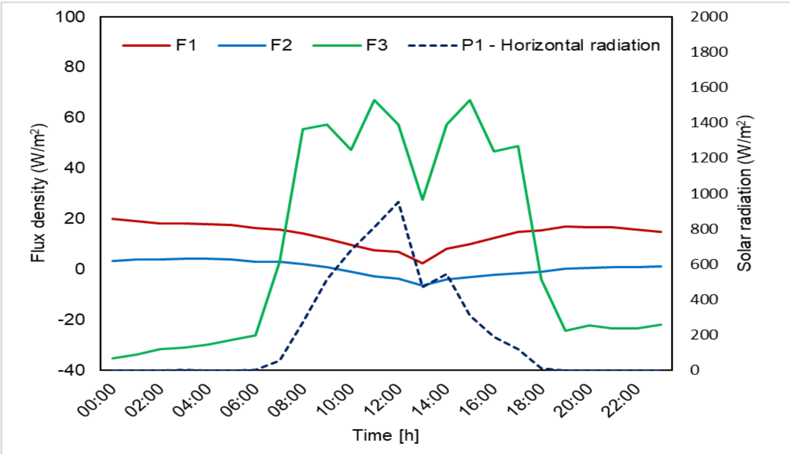


Figure 4.30 Internal and exterior heat flux densities of the concrete column during MC-H2, with double-glazing configuration, on a cloudy day [78].

A comparison of the internal (F1) and external (F3) heat flux densities reveals significant differences in both their evolution and magnitude across the different configurations and weather conditions. The external flux density (F3) exhibits a pattern similar to solar radiation, reflecting the impact of incident solar radiation on the exterior surface plate and the greenhouse effect within the SBRS air space. The absorbed heat at the exterior surface activates the thermal mass of the concrete column and the adjacent masonry wall, allowing the heat to be transferred slowly through conduction to the building indoor environment and the adjacent area.

As a result, the magnitude of the external heat flux density surpasses that of the internal flux, with a time delay of 8 to 11 hours, depending on prevailing weather conditions. This delayed heat transfer is a key feature of the system's thermal inertia, which allows the SBRS to extend its heating benefits beyond periods of direct solar exposure.

Regarding the internal heat flux densities of the concrete column (F1), positive values indicate heat flowing from the column to the indoors (heat gains), while negative values indicate heat losses from indoors to the column. Across all F1, the double-glazing configuration (MC-H2) consistently exhibits positive heat flux values, indicating sustained heat gains, whereas the single-glazing configuration (MC-H1) shows both positive and negative values, indicating periods of both heat gain and loss. This confirms the finding in the previous sections that the double-glazing configuration, combined with the ETICS, provides higher efficiency in absorbing and retaining solar radiation. In fact, even during periods of limited solar exposure, the double-glazing system preserves the building´s internal contributing to heat gains throughout the day.

An analysis of F1 values in MC-H2 on a sunny day (**Figure 4.29**) shows that, with the exception of the period between 12:00 and 16:00, when the flux is negative, the SBRS consistently shows heat gains, which are beneficial during the heating season. Moreover, these heat gains predominantly occur during the evening and night, which is the period when residential buildings are typically occupied. Therefore, the proposed innovative retrofit solution, the SBRS, effectively enhances indoor thermal comfort during the heating season.

When comparing internal heat flux densities, the heat gains of the concrete column (F1) are consistently higher than those at the masonry (F2), regardless of the SBRS configuration (single- or double-glazing) and weather conditions (sunny or cloudy). This trend is particularly pronounced in the double-glazing configuration with ETICS, which, once again, confirms the findings in the previous section.

Figure 4.31 illustrates the daily heat gains and losses at the level of the concrete column (F1). During MC-H1, the SBRS showed daily heat losses of 2.43 MJ/m^2 on 13th February 2020 and 1.51 MJ/m^2 on 13th February 2020. In contrast, during MC-H2, the SBRS exhibited only minimal heat loss of 0.67 MJ/m^2 on 15th March, a sunny day.

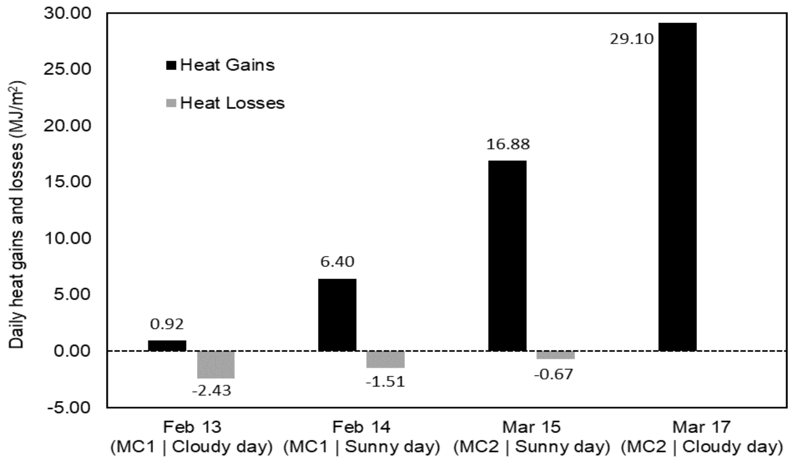


Figure 4.31 Daily heat gains and losses at the level of the interior surface the concrete column (F1) under different configurations (MC1 and MC2) and weather conditions [78].

The thermal behaviour of the system depends on the overall global heat budget, determined by the difference between daily heat gains and losses. Except for 13th February (MC-H1), when there is a daily heat loss of 1.51 MJ/m^2, the global heat budget on 14th February (MC-H1), 15th March (MC-H2) and 17th March (MC-H2) remained positive with heat gains of 4.89 MJ/m2, 16.21 MJ/m^2 and of 29.10 MJ/m^2, respectively.

A comparison of MC-H1 and MC-H2 reveals that the daily heat gains in the double-glazing configuration were at least 3.3 times higher than those in the single-glazing configuration, highlighting the significant improvement in energy performance offered by the double-glazing system combined with ETICS.

4.2.7 Influence of the colour of the SBRS exterior surface wall

To better understand the impact of the exterior surface colour of the SBRS wall, an analysis was conducted on the daily heat gains and losses at the interior surface of the concrete column (F1). This analysis compared configurations: a white exterior wall (WW) during MC-H2 and black (BW) exterior walls during MC-H3. **Figure 4.32** illustrates the daily heat gains at the concrete column level (F1) during MC-H3.

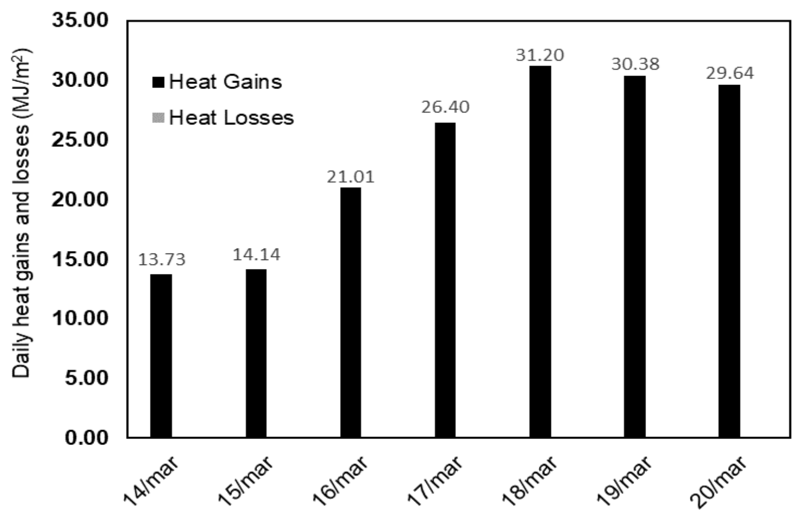


Figure 4.32 Daily heat gains and losses at the level of the interior surface the concrete column (F1) during MC-H3.

Compared to **Figure 4.31**, which presented data from the WW configuration during MC-H2, **Figure 4.32** shows that the BW configuration did not result in any heat losses, even on days with lower total heat gains, such as 14th and 15th of March of 2021. Although the daily heat gains for the BW configuration on these days were lower than those for the WW (and double-window) configuration on 15th of March of 2020, the BW configuration proved more effective at enhancing heat gains and minimizing heat losses. This is due to the higher absorptivity of the black surface, which allows for greater solar energy absorption, thereby facilitating more efficient heat transfer through the concrete column and into the interior space.

To further assess the impact of the surface colour on the SBRS´s thermal behaviour, an additional analysis was conducted based on the temperature differences between the outdoor air temperature (Tout) and key temperature points: indoor air temperature (Tint), SBRS air space temperature (T18), interior surface temperature of the concrete column (T1), and interior surface temperature of the masonry within the SBRS (T3). Two days with comparable daily heat gains were selected for this comparison: 17th March of 2020 (29.10 MJ/m²) for the WW configuration and the 20th March of 2021 (29.64 MJ/m²) for the BW configuration. The results of this comparison are summarized in **Table 4.5**.

Table 4.5 Summary of comparative results in terms of temperatures (Tout, Tint, T18, T3 and T1) based on data from MC-H2 and MC-H3.

	Tint - Tout (°C)			**T18 - Tout (°C)**			**T3 - Tout (°C)**			**T1 - Tout (°C)**		
	WW	BW	BW-WW	WW	BW	BW-WW	WW	BW	BW-WW	WW	BW	BW-WW
Max	4.6	8.6	4.1	14.0	18.3	4.3	5.0	7.4	2.4	5.6	9.5	3.9
Avg	1.2	3.9	2.7	6.3	8.4	2.1	1.7	2.6	1.0	2.0	4.6	2.7

As expected, the WW configuration exhibits lower temperature differentials compared to the BW configuration. As already mentioned, the BW configuration's enhanced ability to absorb heat more effectively leads to higher surface temperatures. Consequently, the temperature of the SBRS air space (T18) also increases, as observed in the higher T18-values associated to the BW configuration. This also activates the thermal mass of the wall of the SBRS (concrete column and adjacent masonry wall), leading to more heat being transferred through conduction to the indoor environment. As a result, the interior surface temperatures of the concrete column (T1) and the masonry wall (T3) are higher, ultimately raising the indoor air temperature (Tint).

On average, the temperature difference between Tint and Tout is nearly 3 °C higher with the BW configuration. Therefore, during the heating season, the SBRS with a black exterior surface enhances indoor thermal comfort by absorbing more solar energy and transferring more heat to the interior space.

4.3 Results of Cooling Monitoring Campaigns

While the SBRS was primarily designed to mitigate heat losses during winter and enhance indoor temperature during the heating season, its behaviour during warmer months and the optimal management of the vents - whether they should remain closed or open - also needed to be evaluated. This section aims to address these considerations.

4.3.1 White wall configuration: the influence of the vents

Figure 4.33 and **Figure 4.34** illustrate the measured outdoor (Tout), SBRS air space temperature (T18) and indoor air temperature (Tint) during MC-C1 with open vents, and MC-C2 with closed vents, respectively

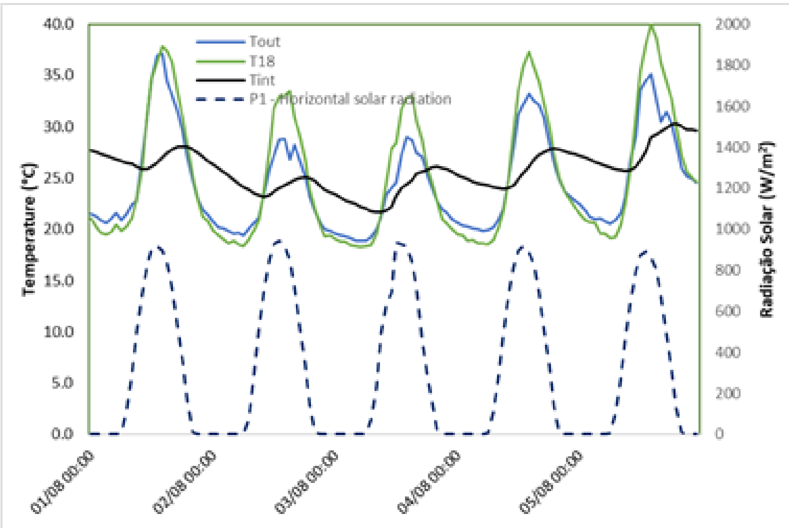


Figure 4.33 The measured indoor (Tint), outdoor (Tout) and SBRS air space (T18) temperatures during MC-C1 (between 01st and 05th August of 2020).

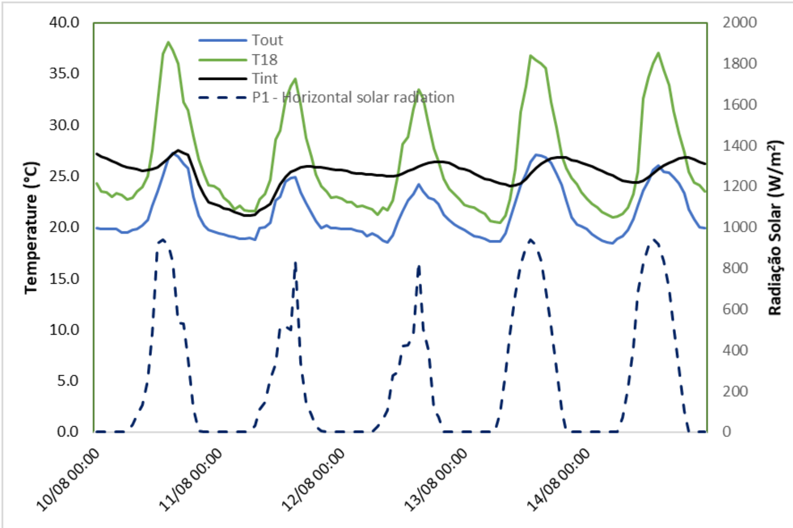


Figure 4.34 The measured indoor (Tint), outdoor (Tout) and SBRS air space (T18) temperatures during: (a) MC-C2 (between 10th and 14th August of 2020).

During MC-C1, when the vents of the SBRS air space were open, the outdoor air temperature (Tout) varied between 21.5 °C and 24.6 °C (average 23.2 °C), while the SBRS air space temperature (T18) varied between 18.3 °C and 40.1 °C (average 25.1 °C). The indoor air temperature (Tint) varied between 21.7 °C and 30.3 °C (average 25.8 °C). Notably, Tint exceeded- 25 °C for 62.5 % of the time. On the hottest day, 1st of August, Tout ranged from 23.8 °C to 24.6 °C (average 24.2 °C), T18 varied between 19.5 °C and 37.8 °C (average 26.1 °C) and Tint varied between 25.8 °C and 28.1 °C (average 27.0 °C).

During MC-C2, with the vents closed, outdoor air temperatures (Tout) were slightly lower, ranging between 18.4 °C and 27.3 °C (average 21.5 °C). The SBRS air space temperature (T18) was higher than in MC-C1, varying between 20.4 °C and 38.1 °C (average 26.3 °C) while the indoor air temperature (Tint) varied between 21.1 °C and 27.6 °C (average 25.2 °C). Tint exceeded 25°C for 70.8% of the time, a higher percentage than MC-C1. On the hottest day, 10th of August, Tout varied between 19.5 °C and 27.3 °C (average 21.9 °C), T18 varied between 22.7 °C and 38.1 °C (average 267.5 °C) and Tint varied between 22.2 °C and 27.6 °C (average 25.8 °C).

When comparing MC-C1 and MC-C2, although the outdoor temperature was 1.7°C higher during MC-C1, the closed vents in MC-C2 created a buffer effect within the SBRS air space, resulting in an average T18 that was 1.1°C higher during MC-C2. However, with vents were closed during MC-C2, a buffer effect was created in the SBRS air space, resulting in an average temperature of the SBRS air space (T18) that was higher by +1.1 °C during MC-C2.

Regarding indoor temperatures, Tint fluctuated more during MC-C1, ranging from 21.7°C to 30.3°C (8.6°C range), compared to a narrower range of 21.1°C to 27.6°C (6.4°C range) during MC-C2.

This variability may be explained by the fact that heat stored in the SBRS air space continued to be transferred indoors through conduction, even after sunset, contributing to prolonged heat retention when the vents were closed. Consequently, this could also explain why the periods with Tint values exceeded 25°C more frequently in MC-C2 (nearly 71%) than in MC-C1 (approximately 63%).

4.3.2 Black wall configuration: the influence of the vents during the cooling season

As in the case of the WW configuration, two SBRS configurations with a black exterior wall (BW) were tested to assess the influence of the vents during the cooling season. Monitoring campaigns were conducted with the vents both open (MC-C3) and closed (MC-C4). **Table 4.6** summarises the main features of the measurements taken for MC-C3 on 8th of September 2021 (open vents) and MC-C4 on 18th of September 2021 (closed vents). The table includes outdoor environment temperature (Tout), indoor environment temperature (Tint), SBRS air space temperature (T18), inner surface temperature of the concrete column (T1), and horizontal global solar radiation (P1).

Table 4.6 Summary of the results in terms of temperatures (Tout, Tint, T18 and T1) and horizontal global solar radiation (P1), adapted from [117].

MC-C3 ǀ 8th September (Vents opened)	**P1 (W/m²)**	**Tout (°C)**	**Tint (°C)**	**T18 (°C)**	**T1 (°C)**	**T18 - Tout (°C)**	**T1 - Tint (°C)**
Min	-	19.0	26.8	20.7	24.9	-	-
Max	993.9	25.3	28.5	32.7	26.6	7.5	-2.0
Avg	542.5	20.8	27.5	23.8	25.7	3.1	-1.8
MC-C4 ǀ 18th September (Vents closed)	**P1 (W/m²)**	**Tout (°C)**	**Tint (°C)**	**T18 (°C)**	**T1 (°C)**	**T18 - Tout (°C)**	**T1 - Tint (°C)**
Min	-	15.9	24.7	21.9	24.5	-	-
Max	940.5	25.8	27.0	43.8	27.3	18.0	0.3
Avg	515.8	19.7	25.8	29.4	25.8	9.7	0.0

As shown in **Table 4.6,** the average temperature difference between the SBRS air space (T18) and outdoor (Tout) was3.1°C with open vents and 9.7°C with closed vents, demonstrating that natural ventilation within the SBRS air space effectively reduces unwanted heat gains during the cooling season. Therefore, the ventilation of the SBRS air space significantly influences the thermal behaviour of the proposed retrofit solution.

Figure 4.35 and **Figure 4.36** illustrated the heat flux density at the inner surface of the concrete column (measured by the F1 sensor) over 24-hour periods on 8th of September of 2021 (MC-C3, open vents) and on 18th of September of 2021 (MC-C4, closed vents), respectively. Positive values indicate heat flux from the column to the indoors (heat gains), while negative values indicate heat loss from indoors to the column (heat losses). Both figures also show the outdoor air temperature (Tout), indoor air temperature (Tint), inner surface temperature of concrete column (T1), and horizontal global solar radiation (P1).

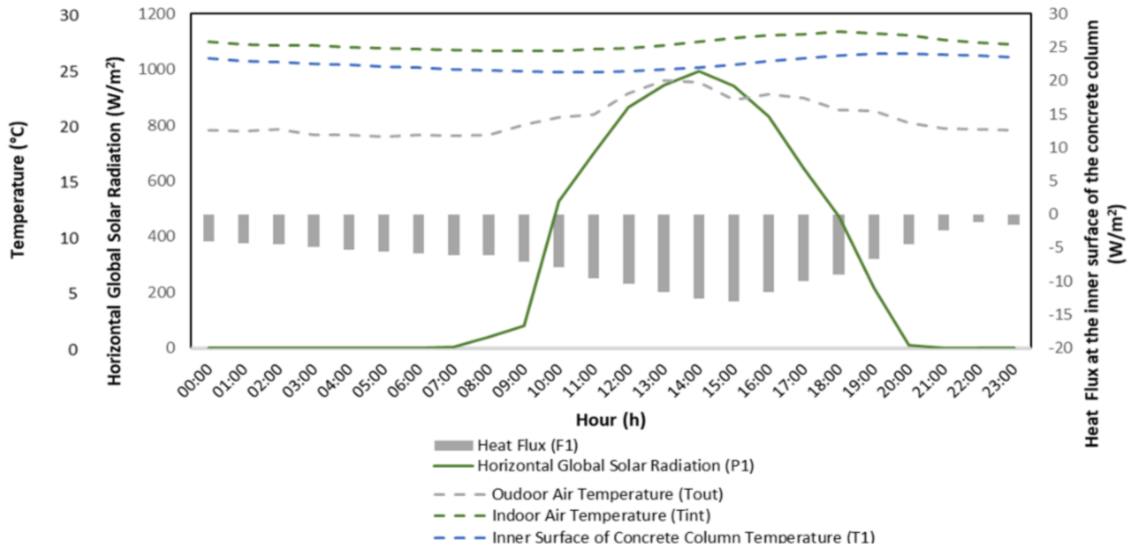


Figure 4.35 Temperatures, heat flux and solar radiation evolution during MC-C3 – opened vents [117].

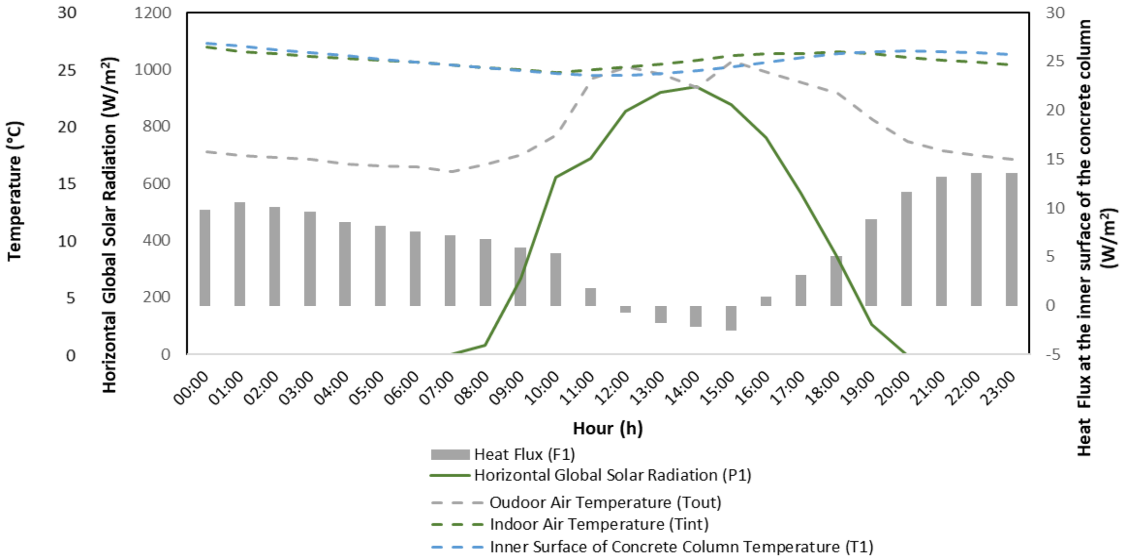


Figure 4.36 Temperatures, heat flux and solar radiation evolution during MC-C4 – closed vents [117].

As observed in **Figure 4.35**, when the SBRS vents were open, the heat flux was negative, indicating heat loss from indoors to the concrete column, which is desirable during the cooling season. Conversely, in **Figure 4.36**, when the SBRS vents were closed, the heat flux was predominantly positive, indicating heat gains from the concrete column to the interior, an undesirable effect during the cooling season.

4.4 Discussion and brief conclusion

The experimental study of the Solar Bridge Retrofit System (SBRS) revealed significant insights into its performance during both heating and cooling seasons.

During the heating season:

- **The SBRS functions effectively as a heat gain technology**, surpassing its primary role of mitigating winter heat losses due to structural thermal bridges.
- **The double-glazing configuration demonstrates superior effectiveness over the single-glazing option**, enhancing more heat gains at the concrete column level. This observation aligns with findings from the literature discussed in Chapter 2 and answers Research Question 2.
- **Painting the exterior wall surface of the SBRS black, compared to white, proves more effective in improving indoor environmental conditions**, with nearly a 3 °C higher difference between indoor and outdoor temperatures. This

aspect also contributes to answering Research Question 2, focusing on features that enhance solar gains during the heating season.

During the cooling season:

- **Opening the SBRS vents reduces the occurrence of periods with indoor temperatures (Tint)** above 25°C compared to configurations with closed vents. With open vents, Tint exceeded 25°C for approximately 63% of the recorded period, whereas this percentage rose to nearly 71% with closed vents. This finding underscores the necessity to adjust vent management during summertime, addressing Research Question 3.
- **Adopting a white wall configuration helps mitigate heat gains effectively** during the summer.

Overall, through a **rigorous experimental design, the SBRS demonstrated**:

- **Ease of application on façades** with good integration potential.
- **Fulfilment of both energetic and constructive functions**.
- **Enhancement of winter thermal performance while offering adaptability for summertime conditions**.

5

NUMERICAL STUDY OF A FAÇADE WITH SBRS

This chapter presents the numerical study conducted to assess the thermal performance of the innovative retrofit solution, the Solar Bridge Retrofit System (SBRS). It addresses the 4th and 5th Research Objective of this PhD thesis, namely: to develop a numerical study comparing the SBRS to other constructive solutions; to assess their performance under different Portuguese climate zones. The constructive solutions- three types of walls - here studied and compared were:

3. **Wall Model 01**: **Pre-retrofit wall**, resembling the façade of 1970-1990's Portuguese Residential building.
4. **Wall Model 02: Retrofit wall with ETICS, one of** the most common thermal solution for retrofitting residential buildings in Portugal.
5. **Wall Model 03: Retrofit wall with ETICS combined with SBRS**, which is the proposed innovative construction solution.

To better understand the thermal impact of the Wall Model 03 (retrofitted with ETICS combined with SBRS), which was the subject of experimental study in **Chapter 4**, its numerical performance was assessed using three different simulation tools: BISCO® [118]; BISTRA® [119]; and DesignBuilder® [120]. Each tool offered complementary capabilities. BISCO provided a steady-state analysis, while both BISTRA and DesignBuilder enabled transient analysis. BISTRA allowed for the generation of dynamic isoflux diagrams of the three types of walls, while DesignBuilder enabled the evaluation of room performance with each wall model, including Wall Model 03 with both closed and open vents during the cooling season.

Furthermore, the numerical study specifically addresses the 3rd and 4th Research Questions, namely:

3. How the proposed retrofit solution performs during the cooling season? Is there any need to adapt the proposed solution in the cooling season or to work with other cooling strategies?
4. Is the proposed retrofit solution suitable for all climate zones in Portugal? How the SBRS performs under different Portuguese climate zones?

The chapter is structured into five parts:

1. **Characterization of the three studied Wall Model:** A horizontal cross-section view is presented for each wall model, along with the thermophysical properties of the materials used.
2. **Steady-state analysis with BISCO (preliminary analysis):** A steady-state simulation was performed to analyse the thermal bridge effect in the three types of walls mentioned above.
3. **Transient analysis with BISTRA:** This section examined the thermal performance of the walls by incorporating transient thermal effects due to solar radiation and thermal inertia. For Wall Model 03 (retrofit wall with ETICS combined with SBRS), only the configuration with closed vents was considered. Thermal parameters such as time lag and decrement factors were analysed.
4. **Transient analysis with DesignBuilder:** A comparative study of the three wall models was conducted across different Portuguese climate zones, with Bragança, Évora, Lisbon, and Porto as representative locations. This study includes data from both the heating and cooling seasons. For the cooling season, Wall Model 03 (retrofit wall with ETICS combined with SBRS) was analysed with both open and closed vent configurations.
5. **Discussion and brief conclusion:** A summary of the main findings and conclusions from the chapter.

5.1 Characterization of the three wall models

As introduced earlier, the three wall models were studied to better understand the thermal impact of the SBRS. They are visually represented in **Figure 5.1**. The thermophysical properties of the external wall materials are shown in **Table 5.1**. The outer surface of the massive wall of the SBRS was painted in white.

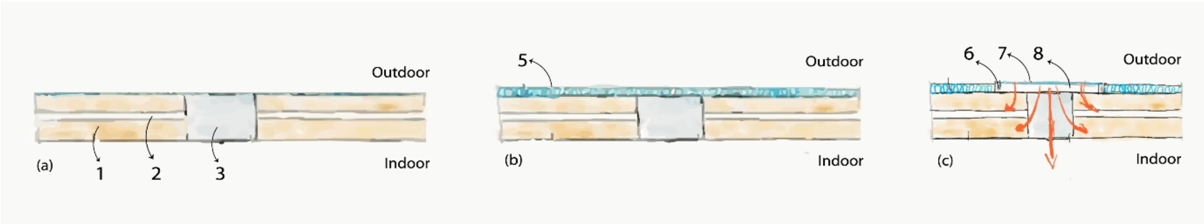


Figure 5.1 Horizontal cross-section view of the three types of walls studied in this PhD work: (a) Wall Model 01 – Pre-retrofit wall, (b) Wall Model 02 – Retrofit with ETICS and (c) Wall Model 03 – Retrofit with SBRS: 1 – Masonry; 2 – Air space of the cavity wall; 3 – Concrete column; 5 – ETICS; 6 – Frame of the glazing; 7– External transparent skin (glazing); 8 – Air space of the SBRS. Adapted from [84].

Table 5.1 The thermophysical properties of the materials presented in external wall models studied.

Construction layer	**Thickness [m]**	**Thermal Resistance [(m².K/W)]**	**Thermal conductivity [W/(m.K)]**	**Emissivity [−]**	**Density [kg/m³]**	**Specific heat [J/(kg.K)]**
1.1 Masonry (9 cm brick)	0.09	0,23	--	0.9	810	800
1.2 Masonry (11 cm brick)	0.11	0,27	--	0.9	740	800
2 Air cavity of the masonry wall	0.05	--	0.28	0.9	1.23	1 000
3 Concrete column	0.25	--	2.00	0.9	1 750	850
4 Mortar	0.015	--	0.82	0.9	1 750	840
5 ETICS	0.05	--	0.36	0.9	15	1 400
6 Frame of the glazing	0.06	--	0.17	0.9	1390	--
7 External transparent skin (glazing)	0.008	--	3.10	0.84	2 210	800
8 Air space of the SBRS	0.05	--	0.26	0.9	--	--

The wall models represented in **Figure 5.1**, along with the characteristics presented in the table above, were consistently used in all simulations carried out with different simulation tools: BISCO® [118]; BISTRA® [119]; and DesignBuilder® [120].

5.2 Steady-state analysis with BISCO

This section lays the groundwork for the numerical study. It begins by defining the three wall models under investigation. The simulation method is then described, including the simulation tool and assumptions used in the analysis. Finally, preliminary results are presented to provide an initial understanding of how the design of the three types of walls affects the linear thermal transmittance (*ψ)* and the equivalent thermal transmittance (U_{eq}), which together offer a comprehensive understanding of heat transfer through the façade.

- **Linear Thermal Transmittance (*ψ*)**: This parameter quantifies the additional heat flow caused by thermal bridges, typically measured in W/m·K. A lower *ψ* -value indicates better thermal performance with minimized heat loss through the thermal bridge.
- **Equivalent Thermal Transmittance (U_{eq})**: The U_{eq} represents the overall heat transfer through the façade, including the impact of thermal bridges. It is a holistic measure of the wall's thermal performance, combining both uniform and localized effects of heat flow.

5.2.1 Simulation method: definition and characterization

To determine the linear thermal transmittance (*ψ*), numerical simulations were conducted using BISCO software version 12.2 by Physibel. This simulation tool calculates the linear thermal transmittance coefficient (*ψ-value*) in accordance with the EN 10077-2:2017 [121]. BISCO allows for steady-state heat transfer simulations in 2D free-form geometries using Finite Element Method (FEM). The simulations involved the three wall models, and the boundary conditions were set as 0 °C and 20 °C for the outdoor and indoor environment, respectively.

Regarding the simulation process in BISCO, the simulation tool requires a 2D drawing of the wall models, which is then converted into a 256-color bitmap image (**Figure 5.2**). Each colour in the image corresponds to a different constructive layer, represented by specific thermal properties (as shown in **Table 5.1**). The simulation is set up with two boundary conditions: the upper surface represents the outdoor environment, and the lower surface represents the indoor environment. The lateral boundaries are considered adiabatic, meaning no heat transfer occurs through them.

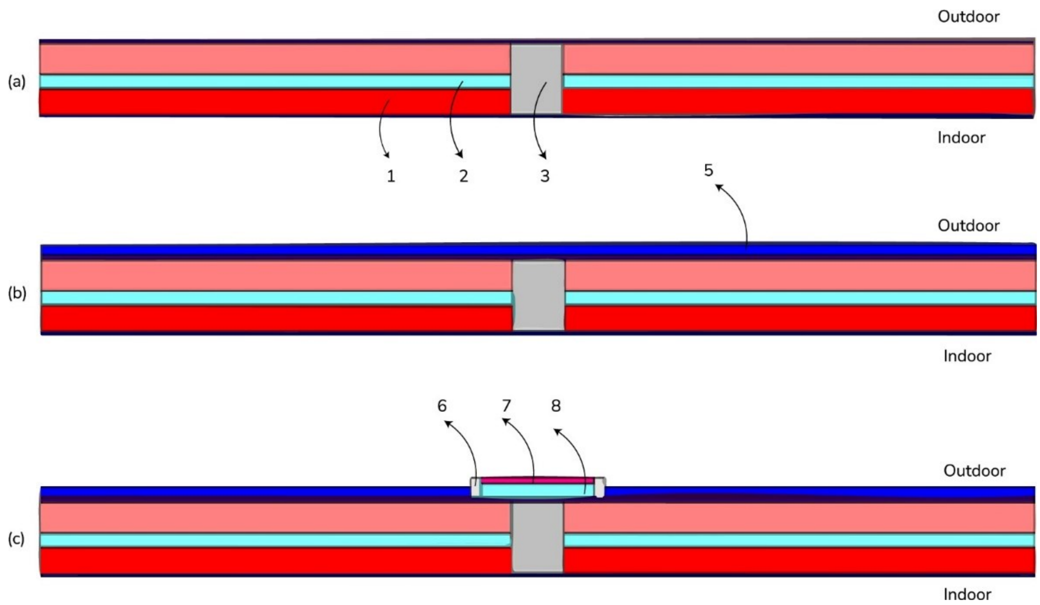


Figure 5.2 The BITMAP image view of a horizontal cross section of the three types of walls studied in this PhD work: (a) Wall Model 01 – Pre-retrofit wall, (b) Wall Model 02 – Retrofit with ETICS and (c) Wall Model 03 – Retrofit with ETICS combined with SBRS: 1 – Masonry; 2 – Air space of the cavity wall; 3 – Concrete column; 5 – ETICS; 6 – Frame of the glazing; 7– External transparent skin (glazing); 8 – Air space of the SBRS.

It is noteworthy to make a few points regarding the use of steady-state data for preliminary analysis with BISCO instead of transient (dynamic) data. The following cautions should be considered:

1. **Simplified assumptions:** Steady-state analysis assumes that conditions do not change over time. While this simplifies calculations, it may overlook significant time-dependent factors such as thermal mass effects, daily temperature fluctuations, and varying solar gains.
2. **Overlooking thermal mass effects**: In transient analysis, thermal mass can buffer temperature changes, delaying the interior response of the building to external temperature variations. A steady-state analysis cannot capture this effect, potentially leading to inaccurate estimations of energy needs and occupant comfort levels.
3. **Limited scope:** Steady-state analysis typically provides a snapshot of performance under a single set of conditions. This approach does not account for performance over an entire year or across different seasons, which is vital for a comprehensive evaluation of a building's energy efficiency.

In summary, while steady-state analysis can provide valuable initial insights, it is essential to recognize its limitations. Therefore, later in this chapter, a comprehensive evaluation incorporating transient simulations is conducted to capture the full complexity of thermal performance over time.

5.2.2 Results

Below, thermograms are presented in **Figure 5.3** to visually capture the temperature distribution across the wall models, providing a clear representation of how the thermal bridge impacts each configuration. Minimum and maximum temperatures of the main constructive layers are summarized in **Table 5.2**. Additionally, linear thermal transmittance values obtained through BISCO are summarized in **Table 5.3**, enabling a comparison of the thermal efficiency of each wall type.

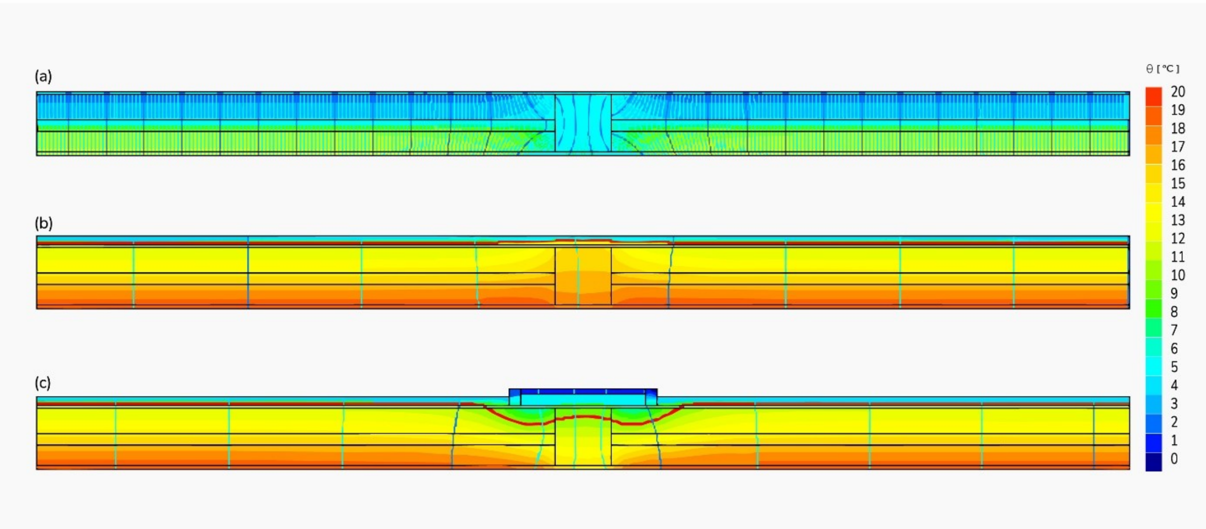


Figure 5.3 BISCO 2D heat flow simulation: (a) Wall Model 01 – Pre-retrofit wall, (b) Wall Model 02 – Retrofit with ETICS and (c) Wall Model 03 – Retrofit with ETICS combined with SBRS.

Table 5.2 Temperatures of the main constructive layers.

Wall	Concrete column		Mortar		Masonry	
	Minimum (°C)	Maximum (°C)	Minimum (°C)	Maximum (°C)	Minimum (°C)	Maximum (°C)
Wall Model 01	3.0	12.9	0.9	17.1	1.3	16.7
Wall Model 02	14.7	17.8	11.5	18.8	11.7	18.7
Wall Model 03	8.5	15.3	6.4	18.7	6.8	18.5

Table 5.3 Linear thermal transmittance and equivalent thermal transmittance of each wall model.

Wall	Linear thermal transmittance (W/m.K)	Equivalent Thermal Transmittance ($W/m^2.K$)
Wall Model 01	0.54	1.23
Wall Model 02	0.07	0.51
Wall Model 03	0.57	0.63

Since the steady-state study do not account for solar radiation, the results reflect night-time conditions. A visual comparison between the temperature profile across the three wall models (**Figure 5.3**) and the analytical comparison (**Table 5.2**) show that the overall temperature of the concrete column is consistently lower than the remaining wall areas, regardless of the wall configuration. In the retrofitted walls (Wall Models 02 and 03), both the minimum and maximum surface temperatures of the concrete column are significantly higher compared to the non-retrofitted wall (Wall Model 01). This highlighting the benefit of retrofitting.

However, while this steady-state analysis offers initial insights, it does not fully capture the thermal behaviour of the wall retrofitted with SBRS combined with ETICS. As discussed in the previous chapter, experimental results (**Figure 4.26**) showed that in the hours following sunset, the inner surface temperature at the concrete column remained higher than in the masonry (both in the SBRS module and the ETICS area). This occurs due to two factors:

1. **Heat stored in the air space of the SBRS:** The heat stored in the SBRS air space during the day is absorbed by the exterior surfaces of the concrete column and masonry within the SBRS module. The stored heat is then slowly transferred through conduction to the indoor environment, resulting in higher interior surface temperatures.
2. **Thermal Conductivity of Concrete:** The concrete column, with its significantly higher thermal conductivity compared to masonry, transfers more heat from the exterior to the interior than the masonry wall.

As shown in **Table 5.3**, as expected, the linear thermal transmittance improved significantly, as expected, from Wall Model 01 (pre-retrofit) to Wall Model 02 (retrofitted with ETICS), decreasing by nearly 87% from 0.54 to 0.07 W/(m.K). This indicates that Wall Model 02 is better at maintaining comfortable indoor temperatures despite fluctuations in outdoor temperatures. However, the ψ-value slightly worsened from Wall Model 01 to Wall Model 03 (retrofitted with ETICS combined with SBRS), increasing by nearly 6% from 0.54 to 0.57 W/(m.K). This could suggest a diminished capacity to maintain comfortable indoor temperatures amid outdoor temperature variations. Consequently, **Figure 5.3** shows that the temperature profile at concrete column is very similar between Wall Models 01 and 03, and significantly lower than that of Wall Model 02.

The ψ-value of Wall Model 03 should be interpreted with caution, as steady-state simulations do not account for the heat gains accumulated in the air space of the SBRS observed in the experimental study (**Chapter 4**). If the linear thermal transmittance is considered as a modulus value, the ψ -value of Wall Model 03 appears advantageous. SBRS incorporates an air cavity where heat is accumulated during the day, allowing the accumulated heat to be more easily transferred to the indoor environment due to the higher linear thermal transmittance. In fact, in **Chapter 4** observed heat gains during the hours following sunset (night-time hours), suggesting that the ψ -value should not merely decrease; it should shift from a positive to a negative value, reflecting heat gain instead of heat loss. This reinforces the notion that the linear thermal transmittance of Wall Model 03 in **Table 5.3** should be viewed as a modulus value.

These preliminary results highlight the importance of considering:

- **Solar radiation effects** (sun exposure),
- **Thermal inertia** (captured through dynamic simulation).

For this reason, the following section will focus on dynamic simulations using BISTRA simulation tool to provide a more accurate depiction of the wall's thermal behaviour.

5.3 Transient analysis with BISTRA

This section presents the dynamic simulation to assess the thermal performance of three wall models during a year in Lisbon, considering an unvented SBRS. Specifically, this section focuses on:

1. The balance of heat gains and losses.
2. Inner surface temperatures.
3. Time lag and decrement factor.
4. Isoflux diagrams (temperature profiles across the wall).

The section first describes the studied wall and then the simulation method used to obtain the results. Finally, the results are presented and discussed.

5.3.1 Simulation method: definition and characterization

The first numerical simulations were conducted using BISTRA software version 5.0.03 by Physibel. BISTRA allows for transient heat transfer analysis of thermal bridges and construction elements in 2D free-form geometries using FEM. As in the preliminary analysis with BISCO, the simulations involved the three wall models. However, with this simulation tool the boundary conditions are defined as time dependent functions: constant, steps, periodic, reference climate, fire curve or defined by the user. In this work, the outdoor environment was a reference climate file (see **Section 5.3.1.1**), while the temperature of the indoor environment (Tint) was set-point as 25 °C from May to October and 20 °C for the remaining months.

Regarding the simulation process, same as in BISCO, BISTRA requires a 2D drawing of the wall models, which is then converted into a 256-color bitmap image. The same 2D drawings used in BISCO were also used in BISTRA.

In this study, an hourly method for assessing the heat flow was adopted [122]. This method considers the thermal capacity, indoor air temperature (Tint), area of the building element and its thermal properties, internal convective surface, internal surface temperature, outdoor air temperature (Tout) and solar radiation.

5.3.1.1 Location and climatic conditions

Regarding the outdoor environment, a representative climate data (EPW weather file provided by DesignBuilder) of Lisbon was used.

To analyse a typical winter scenario, a **Typical Design Winter Week** was chosen. A **Typical Design Winter Week** refers to a set of climate data used for simulating the building's performance under cold weather conditions. This data is typically a representative week drawn from long-term weather records, chosen to reflect typical winter conditions (but not extreme ones). The week between 12th and 18th of March was chosen for the following reasons:

- It is the design week for Lisbon mentioned by DesignBuilder - a simulation tool that will be used in the following section.
- It includes days analysed in the experimental study, such as 15th March (see **Chapter 4**).

5.3.1.2 Assessment indicators

Table 5.4 presents the assessment indicators used in this numerical study to evaluate the performance of the façade with different wall models. These indicators were chosen based on their common usage in studies of Trombe walls and thermal bridges.

Table 5.4 Assessment indicators be used to assess thermal performance: BISTRA simulations.

Scope	Indicator	Unit	References
Thermal performance	Heat gains (and losses)	kWh/m^2	[123]
	Heat transmission (Heat flux)	W/m^2	[124], [125]
	Temperature of the ambience (e.g. indoor)	°C	[82], [123], [124]
	Temperature range	°C	[124]
	Temperature surface/zone (e.g.; air cavity)	°C	
	Time lag	Hours	[123], [125]

5.3.2 Results

5.3.2.1 Heat gains and losses during the year

As mentioned before, the hourly energy balance was calculated assuming a constant indoor temperature (25 °C from May to October and 20 °C for the remainder months) and outdoor conditions according to the representative climate data of Lisbon. **Figure 5.4** shows the calculated monthly average energy balance (difference between gains and losses) for the three wall models (01 Pre-retrofit, 02 Retrofit with ETICS and 03 Retrofit with ETICS combined with SBRS).

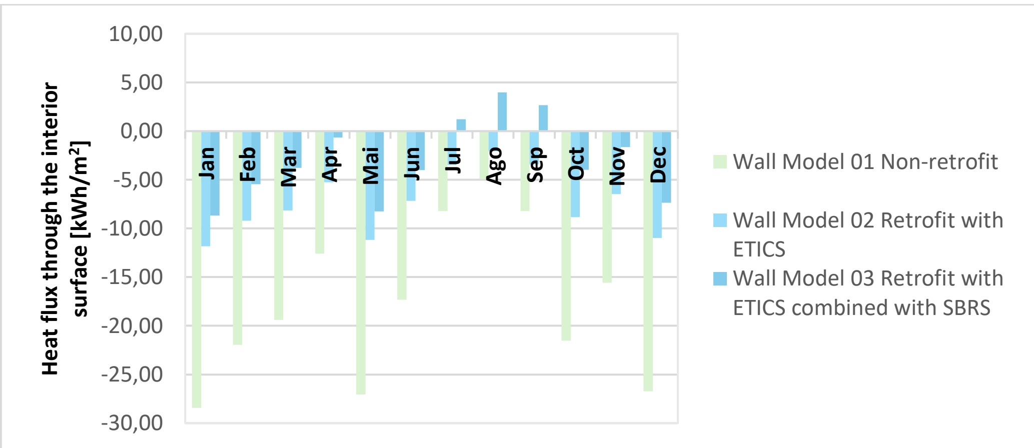


Figure 5.4 Average difference between losses and gains through the interior boundary of each wall model, expressed in kWh per square meter of façade.

As expected, the non-retrofitted wall (Wall Model 01) shows a more significant heat loss. When comparing the retrofit constructive solutions (Wall Model 02 and 03), the façade seems to benefit from having ETICS combined with SBRS (Wall Model 03) because, during the heating season, the heat balance between losses and gains are lower (i.e., fewer overall losses) than when the wall is retrofitted with only ETICS (Wall Model 02). During the cooling season, in months such as August, Wall Model 03 is the only constructive solution that shows heat gains, which is not favourable during that season. However, as mentioned, the numerical study with BISTRA only considers SBRS with closed vents. These results are confirming the experimental study which showed that SBRS with closed vents is not the optimal configuration for SBRS during the cooling season (see **Chapter 4**). For this reason, in **section 5.4**, where DesignBuilder is considered, the cooling (summer) performance will be discussed, taking into account open vents. The main conclusions regarding the comparison of the three wall models during the cooling season will also be discussed there.

Furthermore, to a better understand the thermal performance of the retrofit constructive solutions, **Figure 5.5** presents the monthly heat loses and gains separately for the Wall Model 02 (retrofitted with ETICS) and Wall Model 03 (retrofitted with ETICS combined with SBRS).

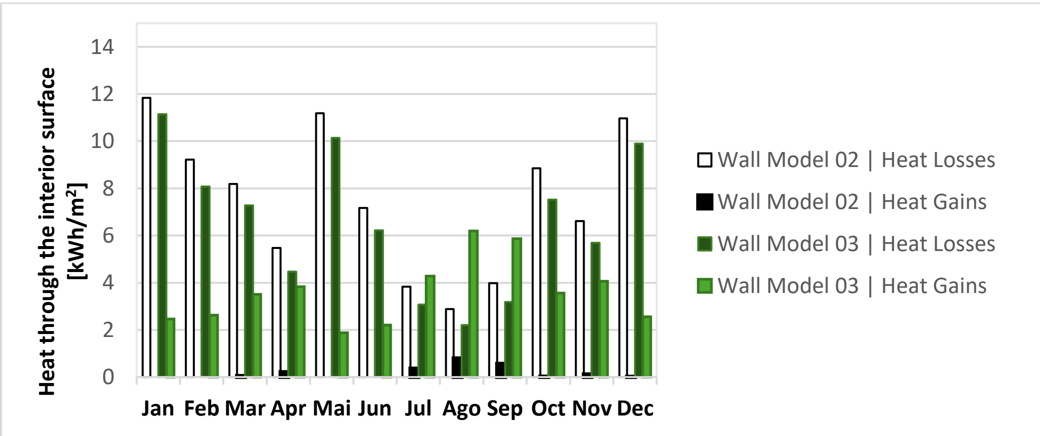


Figure 5.5 Heat flow (losses and gains) through Wall Model 02 (retrofitted with ETICS) and Wall Model 03 (retrofitted with ETICS combined with SBRS), expressed in kWh per square meter of façade.

Comparing both retrofit constructive solutions, **Figure 5.5** shows that while Wall Model 03 (retrofitted with ETICS combined with SBRS) experiences heat gains in every month of the heating season - which is favourable during that season -, Wall Model 02 (retrofitted with ETICS) does not register heat gains during some months of the heating season, such as January and February. In these months, only heat losses are shown. Furthermore, the magnitude of monthly heat gains is more significant with Wall Model 03 (overall above 2 kWh/m²) compared to Wall Model 02.

5.3.2.2 Interior surface temperatures during a sunny day of the Typical Design Winter Week

To better understand the thermal performance of the South-facing wall with the three studied wall models, a comparative analysis was conducted based on the evolution of the numerical temperatures along the internal surface. Three locations were compared: T1 (centre of concrete column), T3 (masonry within the SBRS area), and T6 (masonry distanced 1.20 from the concrete column). March 12 was selected for the analysis because it was the sunniest day of the Typical Design Winter Week in Lisbon, with a maximum global solar radiation of 750 W/m². The graphical representations of these temperature profiles are shown in

Figure 5.6 - Figure 5.8.

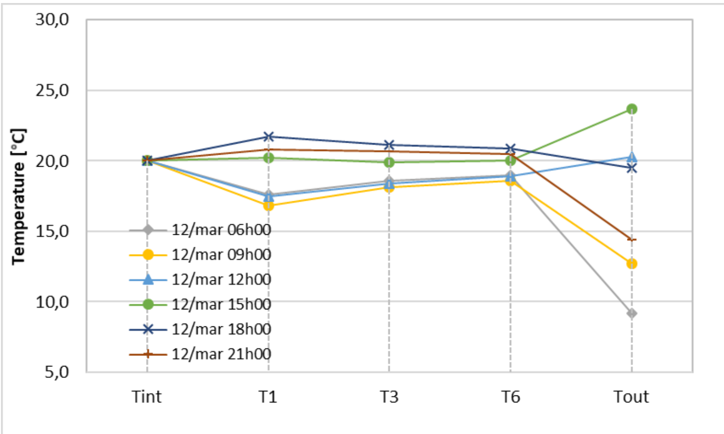


Figure 5.6 Evolution of the interior surface temperature at different time steps: Wall Model 01 (Pre-retrofit).

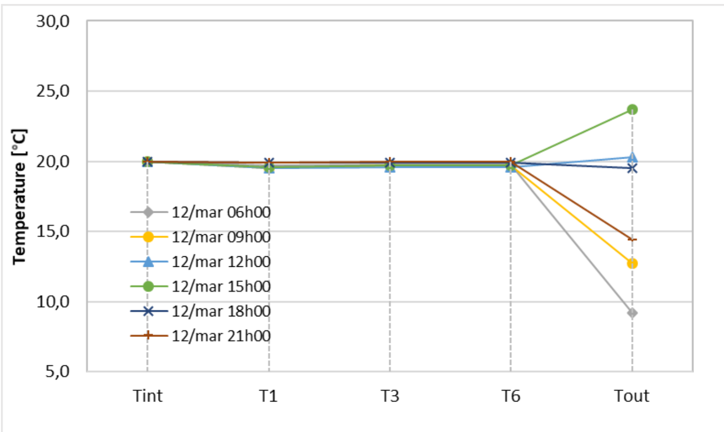


Figure 5.7 Evolution of the interior surface temperature at different time steps: Wall Model 02 (Retrofit with ETICS).

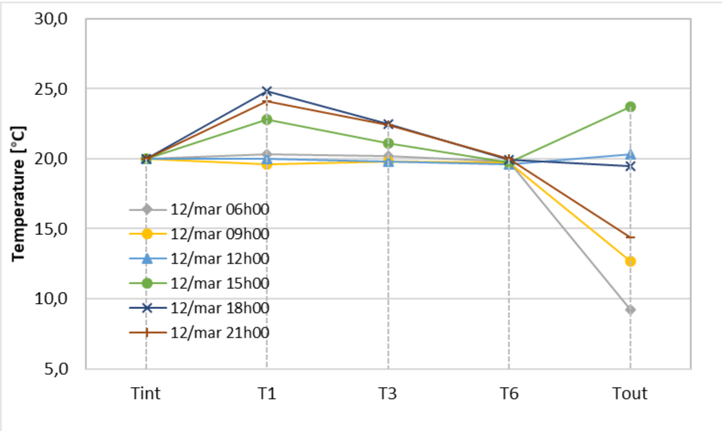


Figure 5.8 Evolution of the interior surface temperature at different time steps: Wall Model 03 (Retrofit with ETICS combined with SBRS).

The graphical representations consider temperature profiles at different time steps of 12th March. As expected, these graphical representations allow drawing several conclusions. First, in all wall models, the interior surface temperatures increase until 18h00 and remain almost identical until 21h00 due to thermal inertia. Second, when the wall is retrofitted with only ETICS (Wall Model 02), the temperature profiles are nearly homogenous throughout the day and across different points of the interior surface. In other words, the interior surface temperature at T1 (concrete column) and T2/T3 (masonry) remains almost the same during the day. Third, while the temperature of the concrete column (T1) is generally lower than the masonry components in Wall Model 01 (pre-retrofit), T1 is overall significantly higher than the masonry components in Wall Model 3 (retrofit with ETICS combined with SBRS). This happens because the heat is accumulated at SBRS air space and then it is mainly transferred to the building internal space through the concrete column, which raises the surface temperature at T1. More heat is transferred through the concrete column (T1) than through the masonry within the SBRS (T3) because the concrete column has a lower thermal resistance.

These results confirm the experimental findings which shown similar behaviour. For example, during the monitoring campaigns the measured interior surface temperatures also increased from 09h00 until 18h00 and remain almost identical until 21h00 due to thermal inertia (see **Figure 4.25**).

5.3.2.3 Time lag and decrement factor during a sunny day of the Typical Design Winter Week

To further the understanding of the thermal performance of the South-facing wall with the three studied wall models, along the analysis of the evolution of the simulated temperatures along the interior surface of the concrete column, the time lag (Ø) and decrement factor (*df*) for each one of these wall models were computed and analysed.

The time lag refers to the duration it takes for the heat wave to propagate from the outer surface to the inner surface of the wall, while the decrement factor represents the decreasing ratio of its amplitude. These thermal parameters are calculated as follows:

$$\text{Ø} = t_{1,max} - t_{12,max} \tag{5}$$

$$df = \frac{T_{1,max} - T_{1,min}}{T_{12,max} - T_{12,min}} \tag{6}$$

where $t_{1,max}$ and $t_{12,max}$ represent the time in hours when the inner and outer surface temperatures of the concrete column are at their maximums, respectively. $T_{1,max}$, $T_{1,min}$, $T_{12,max}$ and $T_{12,min}$ are the maximum and minimum inner wall surface temperatures of the concrete column and maximum and minimum outer wall surface temperatures of the concrete column, respectively.

The decrement factor helps evaluate a building's ability to buffer external temperature changes. A lower decrement factor indicates that a building can better maintain comfortable indoor temperatures despite fluctuations in outdoor temperatures. In turns, thermal bridge areas shown to appreciably increase the decrement factor causing higher inner surface temperature and transmission load fluctuations [126].

Table 5.5 presents the time lag and decrement factor for each studied wall model, along the minimum, maximum, and temperature differences of the inner surface of the concrete column.

Table 5.5 Time lag and decrement factor, along the minimum, maximum and temperature difference of the inner surface of the concrete column, for each wall model.

	Time lag (h)	Decrement factor (-)	$T_{1,min}$ (°C)	$T_{1,max}$ (°C)	$T_{1,max}$ - $T_{1,min}$ (°C)
Wall model 01	3	0,26	16,8	21,7	4,9
Wall model 02	3	0,25	19,5	19,9	0,4
Wall model 03	3	0,27	19,5	24,8	5,3

The decrement factor slightly decreases from Wall Model 01 (pre-retrofit) to Wall Model 02 (retrofitted with ETICS), indicating that the latter constructive solution is better at maintaining comfortable indoor temperatures despite fluctuations in outdoor temperatures. In fact, the literature showed that thermal mass can reduce transmission load and that thermal insulation can be utilized to reduce decrement factor [95], [126]. With the proposed retrofit solution, Wall Model 03 (retrofitted with ETICS combined with SBRS), the decrement factor slightly increases, compared to the Wall Model 01. This could suggest a diminished capacity to maintain comfortable indoor temperatures amid outdoor temperature variations. Nevertheless, in this case, the SBRS incorporates an air cavity where heat is accumulated during the day, and this increase in the decrement factor may be beneficial during the heating season, as the accumulated heat can be more easily transferred to the indoor environment. For this reason, although the time lag between the retrofit solutions (Wall Models 02 and 03) is the same, the inner surface temperature of the concrete column in Wall Model 03 (24,8 °C) is significantly higher than that of Wall Model 02 (19,9 °C), resulting in a temperature difference of 4.9 °C between these two retrofit solutions.

5.3.2.4 Isoflux diagrams during a sunny day of the Typical Design Winter Week

To assess the impact of SBRS heat gains on interior surface temperatures during March 12, temperature diagrams were computed by BISTRA. **Figure 5.9** graphics portrays the temperature profile diagram at 21h00 - a few hours after the sunset - for each wall model.

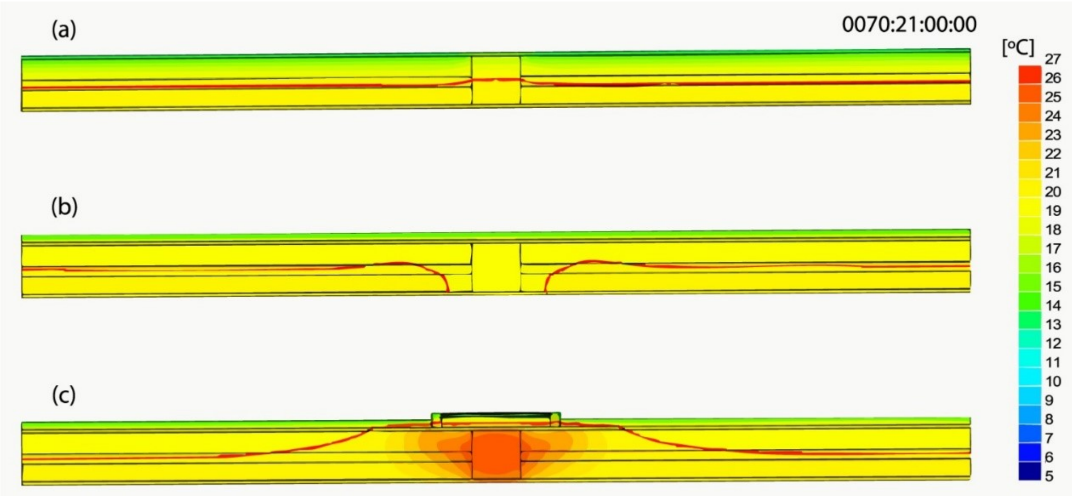


Figure 5.9 BISTRA 2D numerical temperature diagram: (a) Wall Model 01 – Pre-retrofit wall, (b) Wall Model 02 – Retrofit with ETICS and (c) Wall Model 03 – Retrofit with ETICS combined with SBRS.

A visual comparison of the three isoflux diagrams demonstrates the benefits of retrofitting with SBRS. In Wall Model 03 (Retrofitted with ETICS combined with SBRS), the isoflux diagram clearly showed that the inner surface temperatures of both the concrete column and the adjacent masonry wall are higher than the masonry area of the ETICS. This observation reinforces the analysis presented in **section 5.3.2.3**. When retrofitting, the increase in the decrement factor, coupled with a reduction in time lag, may be beneficial during the heating season leading to heat gains in the thermal bridge area.

5.4 Transient analysis with DesignBuilder

This section addresses the Fourth Research Question: How does the proposed retrofit solution (SBRS) perform under different Portuguese climate conditions, and is it suitable for all of them? To answer, the thermal performance of the three wall models was analysed during both the heating and cooling seasons, across various Portuguese locations representing different winter and summer climate zones. Additionally, to account for thermal behaviour during the cooling season, two configurations were considered for the Wall Model 03 (retrofitted with ETICS combined with SBRS): vented and unvented.

The section is organized as follows: first, the simulation method used to obtain the results is described. Then, the results are presented and discussed.

5.4.1 Simulation method: definition and characterization

The performance of the wall models was simulated by using DesignBuilder V6.1.8.021. This building simulation tool integrates with EnergyPlus and provides a user-friendly interface for creating 3D building models, enabling the analysis of energy consumption and thermal performance, among others.

To better explain the simulation method, this section is structured into three parts:

1. **Case study building:** Defines and characterizes the building model used to simulate the annual performance of the wall models, including the proposed innovative retrofit solution, the SBRS.
2. **Target locations and climate data:** Explains the rationale behind selecting each location and the climate data used.
3. **Assessment indicators:** Lists the parameters used to assess the performance of the wall models.

5.4.1.1 Case study building

The case study consists of a single zone area of 48 m^2, with dimensions of (L x W x H) 6.0 × 8.0 × 2.7 m and with two South-facing, non-shaded, windows (**Figure 5.10**). The case study dimensions are based on the 900 FF case of the Building Energy Simulation Test (BESTEST), which involves a heavyweight structure and undergoes a free-floating (FF). However, in the present study, to reflect common Portuguese window dimensions and proportions, the windows were resized (L x H: 1.5 × 1.1 m) [124]. As in the previous sections, the configuration of the South-facing wall was configured with three types of walls, which constructive details were shown in **Figure 5.1**, analysed individually:

1. **Wall Model 01**: **Pre-retrofit wall**, resembling the façade of 1970-1990's Portuguese Residential building.
2. **Wall Model 02: Retrofit wall with ETICS,** the most common thermal solution for retrofitting residential buildings in Portugal.
3. **Wall Model 03: Retrofit wall with ETICS combined with SBRS**, the proposed innovative construction solution.

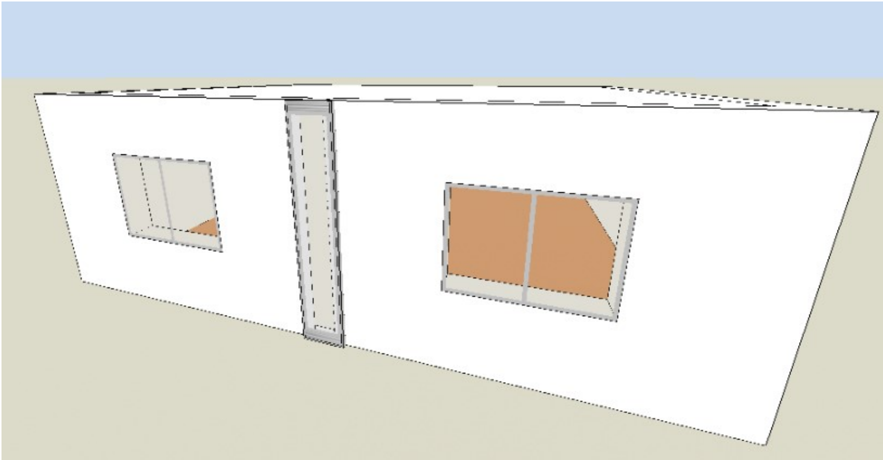


Figure 5.10 The façade of the studied room with Wall Model 03 (façade retrofitted with ETICS combined with SBRS).

To better understand the effect of each wall model, the internal surfaces (remain walls, ceiling and floor) in contact with other internal rooms were considered adiabatic, following procedures used in references such as [124].

To represent the SBRS, a transparent external layer consisting of a double-glazing (4 mm +16 + 4 mm) mounted on a plastic (PVC) frame, with external (upper and lower) vents. The air space between the transparent external layer and the concrete column was set at 50 mm. This constructive solution is the same as the second prototype (PT2) of the experimental study (see **Figure 4.8b**). Besides, the following configurations were used:

- **Colour of the outdoor surface of the massive wall of the SBRS:** white.
- **Algorithm for surface convection - inside:** 1 - Adaptative Convection Algorithm. The Trombe wall algorithm is employed to design the convection in the air space of a Trombe wall system and it was validated by Ellis [127].
- **Algorithm for surface convection - inside:** 2 - Simple Combined.
- **Opening of the vents:** During the cooling season**, to** permit ventilation of the air space during, reducing the risk of overheating in the summer months.

5.4.1.2 Locations and climatic conditions

To extend the analysis beyond experimental conditions and assess the performance of the façade with the Solar Bridge Retrofit System (SBRS) in diverse environments, the simulation strategy incorporated different Portuguese winter climate zones. Lisbon (winter climate zone I1 and summer climate zone V2), Porto (winter climate zone I2 and summer climate zone V1) and Bragança (winter climate zone I3 and summer climate zone V2) were the initial chosen locations. However, to showcase a location with severe summer (V3) another Portuguese location was added: Évora (winter climate zone I1 and summer climate zone V3). This approach ensures that the research findings are more robust and widely applicable,

Table 5.6. lists each climate zone, along with the corresponding (chosen) city and weather climate file used for simulation. The results will only target th**e** Typical Design Winter Week of each location, once these weeks are representative weeks chosen to reflect typical winter conditions rather than extreme ones.

Table 5.6 Studied Portuguese locations and their respective winter and summer climate zones.

Portuguese winter (summer) climate zone	City	Weather climate file	Typical Design Winter Week
I1 (V2)	Lisbon	PRT_LISBOA_INETI.epw	12 - 18 March
I2 (V1)	Porto	PRT_Porto.085450_IWEC	29 January - 05 February
I3 (V2)	Bragança	PRT_BRAGANCA_IWEC.epw	17 - 24 February
I1 (V3)	Évora	PRT_Evora.085570_IWEC	12 - 19 February

Figure 5.11 - **Figure 5.14** show the monthly average air temperature and monthly cumulated global solar radiation on the horizontal plane In Lisbon, Porto, Bragança and Évora, respectively, according to the *epw* weather data files in each location.

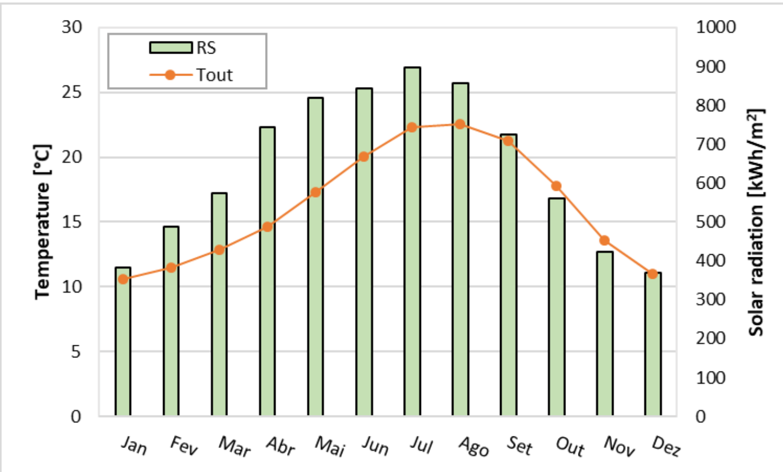


Figure 5.11 Average monthly air temperature (Tout) and monthly solar radiation on the horizontal plane in Lisbon.

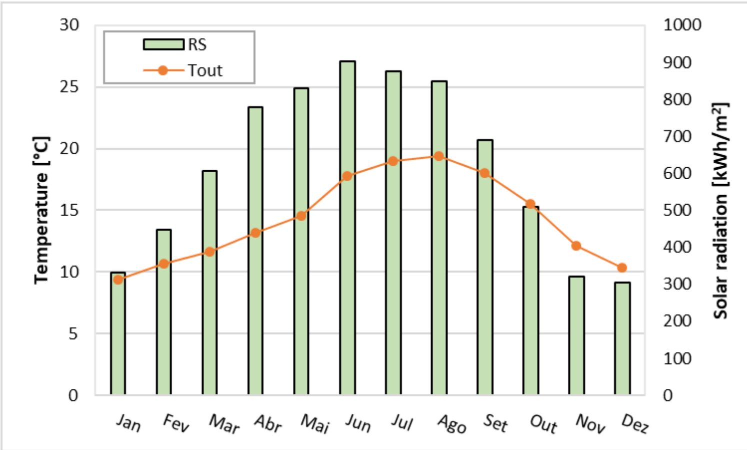


Figure 5.12 Average monthly air temperature (Tout) and monthly solar radiation on the horizontal plane in Porto.

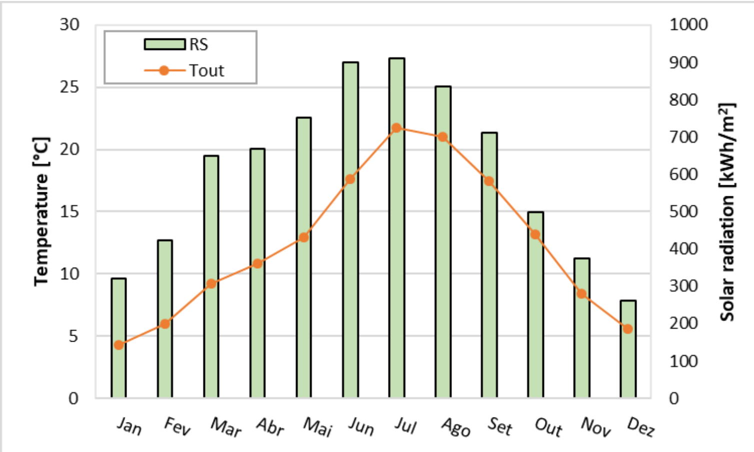


Figure 5.13 Average monthly air temperature (Tout) and monthly solar radiation on the horizontal plane in Bragança.

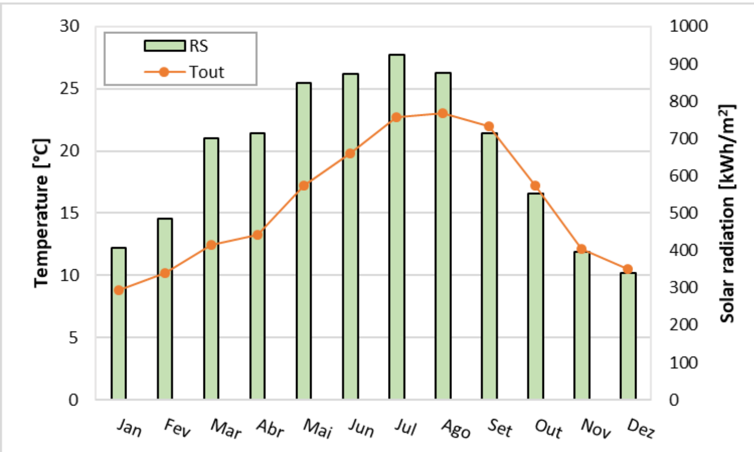


Figure 5.14 Average monthly air temperature (Tout) and monthly solar radiation on the horizontal plane in Évora.

5.4.1.3 Assessment indicators

To estimate the evolution of the indoor air temperature (Tint) for all walls' configurations, different scenarios were considered according with the simulation schematic shown in **Figure 5.15**.

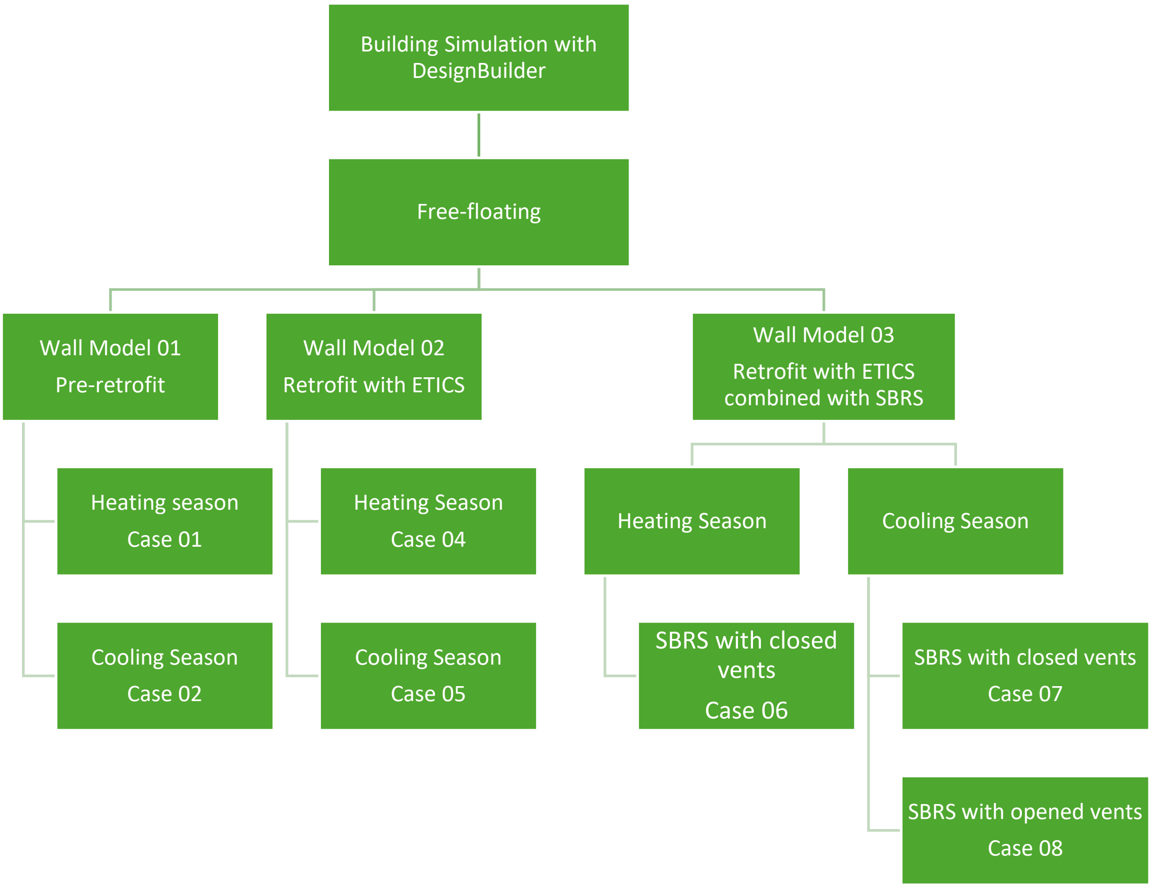


Figure 5.15 Flow chart describing the simulation plan.

5.4.2 Results of Heating Season

This section presents the numerical findings from the dynamic simulation with DesignBuilder in different Portuguese locations to portray different winter climate zones. During the heating season the vents of the SBRS are always closed.

5.4.2.1 Winter climate zone I1: Lisbon

To represent winter climate zone I1, Lisbon was chosen as representative location. The Typical Design Winter Week occurs between 12th and 18th of March. **Figure 5.16** presents the outdoor air temperature (Tout) during that week and the indoor air temperature (Tint) for each wall model.

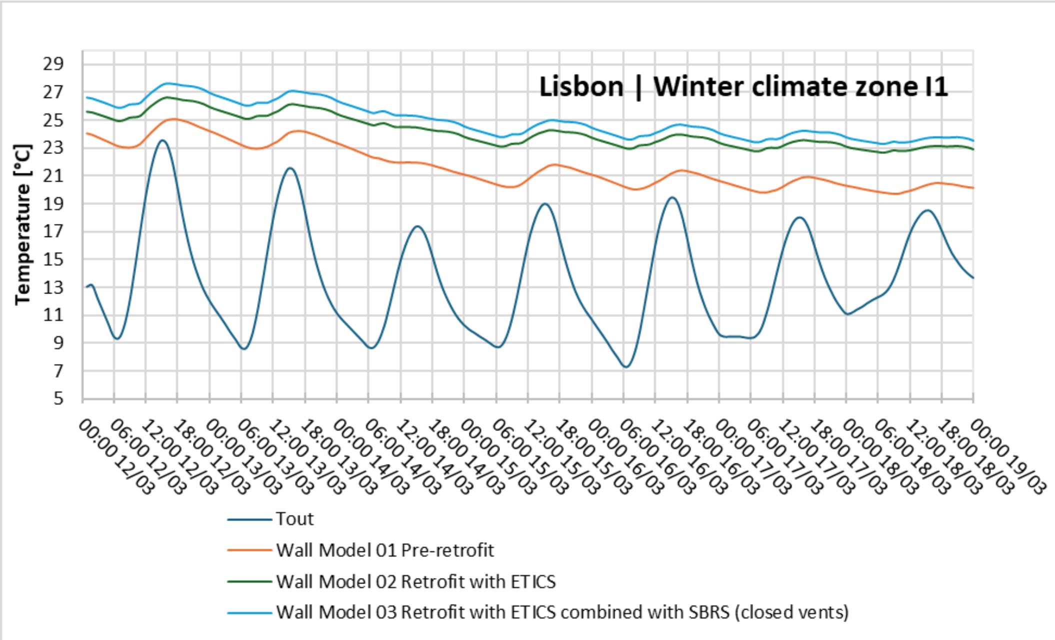


Figure 5.16 Outdoor air temperature (Tout) and indoor air temperature (Tint) for each wall model for the Typical Design Winter Week of Lisbon (I1).

During all Typical Design Winter Week of Lisbon, as expected the indoor air temperature (Tint) of the room with Wall Model 01 (pre-retrofit) is always lower than the same room with Wall Model 02 (retrofit with ETICS) or Wall Model 03 (retrofit with ETICS combined with SBRS). The average Tint was 21,7 °C, 24,2 °C and 25,0 °C for the Wall Model 01, 02 and 03, respectively. When the rooms with retrofit solutions are compared, the Tint of the room with Wall Model 03 was always higher than the one with Wall Model 02.

Regarding thermal comfort analysis, and based on commonly recommended thermal comfort ranges for winter, such as EN 16798-1 [128], which suggests a Tint range of 20–24 °C, Wall Model 01 shows temperatures that are below or slightly outside this comfort range. In contrast, Wall Model 02 and especially Wall Model 03, show average temperatures within or above the comfort range, with Wall Model 03 being the most effective in ensuring thermal comfort during the heating season.

5.4.2.2 Winter climate zone I2: Porto

To represent winter climate zone I2, Porto was chosen as representative location. The Typical Design Winter Week occurs between 29th January and 05th February. **Figure 5.17** presents the outdoor air temperature (Tout) during that week and the indoor air temperature (Tint) for each wall model.

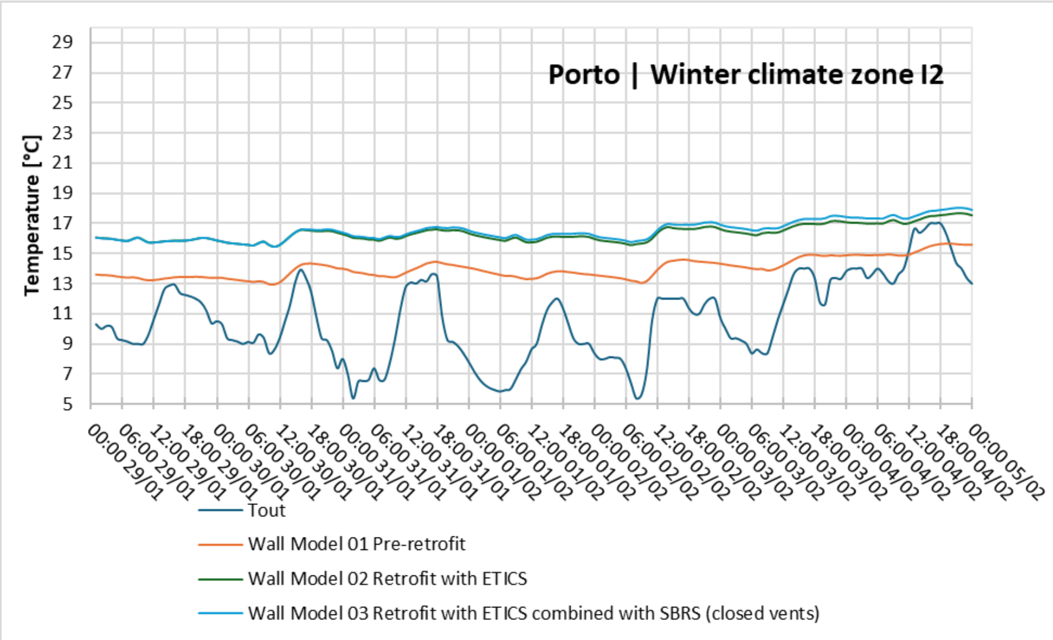


Figure 5.17 Outdoor air temperature (Tout) and indoor air temperature (Tint) for each wall model for the Typical Design Winter Week of Porto (I2).

During all Typical Design Winter Week of Porto, as expected, the indoor air temperature (Tint) of the room with Wall Model 01 (pre-retrofit) is always lower than the same room with Wall Model 02 (retrofit with ETICS) or Wall Model 03 (retrofit with ETICS combined with SBRS). The average Tint were 14,0 °C, 16,3 °C and 16,5 °C for the Wall Model 01, 02 and 03, respectively.

From a thermal comfort perspective, and based on EN 16798-1 [128], the recommended Tint range is 20-24 °C. Although none of the wall models achieved the recommended comfort range during the analysed week, it is important to emphasize that Wall Model 03 provided the closest indoor temperature to the recommended range.

5.4.2.3 Winter climate zone I3: Bragança

To represent winter climate zone I3, Bragança was chosen as representative location. The Typical Design Winter Week occurs between 17th and 24th of February. **Figure 5.18** presents the outdoor air temperature (Tout) during that week and the indoor air temperature (Tint) for each wall model.

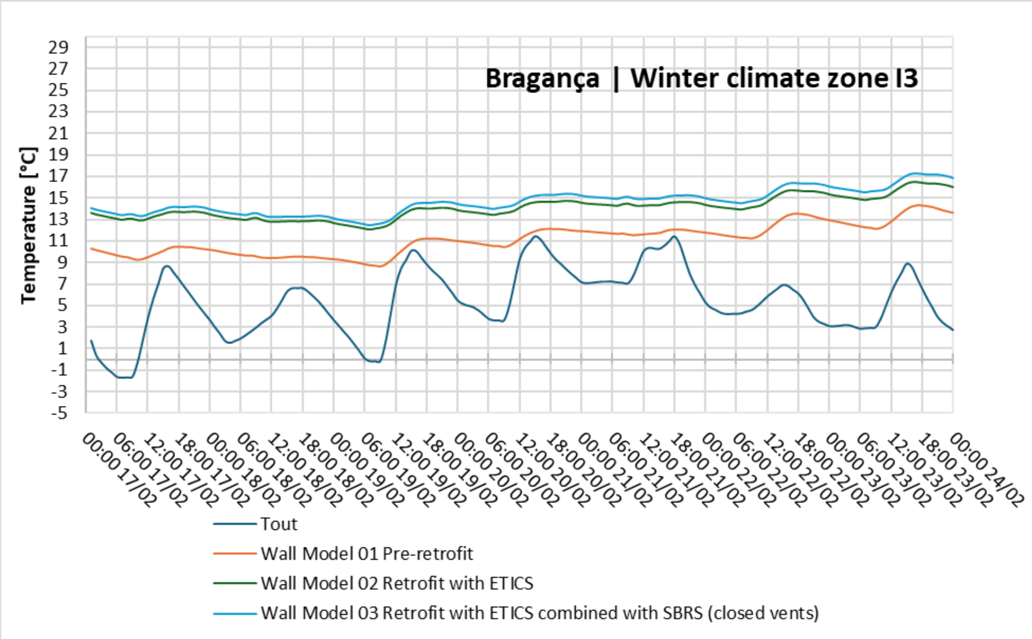


Figure 5.18 Outdoor air temperature (Tout) and indoor air temperature (Tint) for each wall model for the Typical Design Winter Week of Bragança (I3).

As observed in Lisbon and Porto, during all Typical Design Winter Week of Bragança, the indoor air temperature (Tint) of the studied room with Wall Model 03 (retrofit with ETICS combined with SBRS) was always higher than the same with Wall Model 01 (pre-retrofit) and Wall Model 02 (retrofit with ETICS). When the rooms with retrofit solutions are compared, the Tint of the room with Wall Model 03 was always higher than the one with Wall Model 02. The average Tint were 11,2 °C, 14,1 °C and 14,6 °C for the Wall Model 01, 02 and 03, respectively.

From a thermal comfort perspective, and based on EN 16798-1 [128], the recommended Tint range is 20-24 °C. None of the wall models achieved the recommended comfort range during the analysed week. Wall Model 01 (pre-retrofit) consistently fell significantly below the comfort range, while Wall Models 02 and 03 demonstrated notable improvements but still remained below the target range. Among the analysed solutions, Wall Model 03 achieved the best performance, providing a higher average indoor temperature. However, it still failed to meet the recommended comfort range. As a result, additional heating would be required to ensure thermal comfort, particularly during the coldest winter days in Bragança.

5.4.3 Results of Cooling Season

To analyse different winter climate zones, Lisbon, Porto and Bragança were selected as reference locations. However, none of these locations represent the summer climate zone V3, they only cover summer climate zones V1 and V2. For this reason, Évora was included in the summer season analysis as a reference location for climate zone V3.

5.4.3.1 Summer climate zone V1: Porto

To represent summer climate V1, Porto is the selected location. The Typical Design Summer Week occurs between 15th and 21st of July. **Figure 5.19** presents the outdoor air temperature (Tout) during that week and the indoor air temperature (Tint) for each wall model.

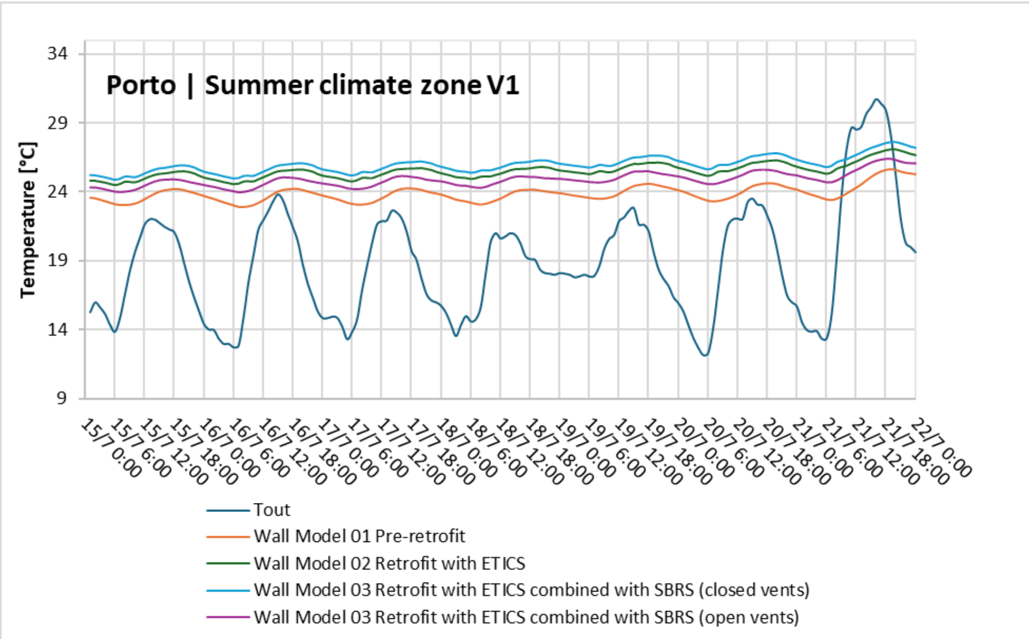


Figure 5.19 Outdoor air temperature (Tout) and indoor air temperature (Tint) for each wall model for the Typical Design Summer Week of Porto (V1).

In Porto, the outdoor air temperature (Tout), during its Typical Design Summer Week, the outdoor air temperature (Tout) ranged from 12.2 °C to 30,7 °C, with an average of 18,9 °C. Throughout the week, when comparing the three wall models, a room with Wall Model 01 (pre-retrofit) had the lowest indoor air temperature (Tint), ranging from 22.9 °C to 25.6 °C, with an average of 23.9 °C. The Tint of the room with Wall Model 02 (retrofit with ETICS) ranged from 24.5 °C to 27.0 °C, with an average of 25.5 °C. The Tint of the room with Wall Model 03 (retrofit with ETICS combined with SBRS), with open vents, ranged from 24.0 °C to

26.4 °C, with an average of 24.9 °C. As expected, when the vents were closed, Tint-values increased, ranging from 24.9 °C to 27.6 °C, with an average of 26.0 °C.

From a thermal comfort perspective, and based on EN 16798-1 [128], the recommended Tint range is 23-26 °C for the cooling season. Among the analysed models, only Wall Model 03 with open vents maintained indoor temperatures exclusively within this range. Wall Model 01 had a minimum Tint of 22.9 °C, falling just 0.1 °C below the recommended minimum. Both Wall Model 02 and Wall Model 03 with closed vents exhibited Tint values exceeding 26 °C, with Wall Model 02 reaching a peak of 27 °C and Wall Model 03 with closed vents reaching 27.6 °C.

5.4.3.2 Summer climate zone V2: Lisbon and Bragança

To represent summer climate V2, both Lisbon and Bragança portray a location with this summer climate. The Typical Design Summer Week of Lisbon and Bragança occur between 8th and 12th of August and between 29th of June and 06th of July, respectively. **Figure 5.20** and **Figure 5.21** present the outdoor air temperature (Tout) during that week and the indoor air temperature (Tint) for each wall model for Lisbon and Bragança, respectively.

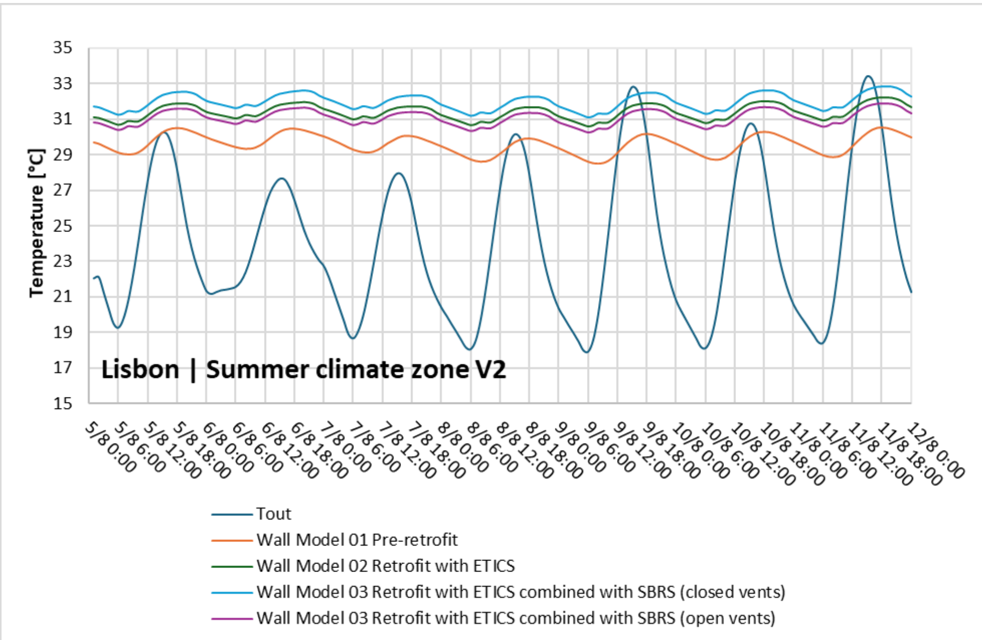


Figure 5.20 Outdoor air temperature (Tout) and indoor air temperature (Tint) for each wall model for the Typical Design Summer Week of Lisbon (V2).

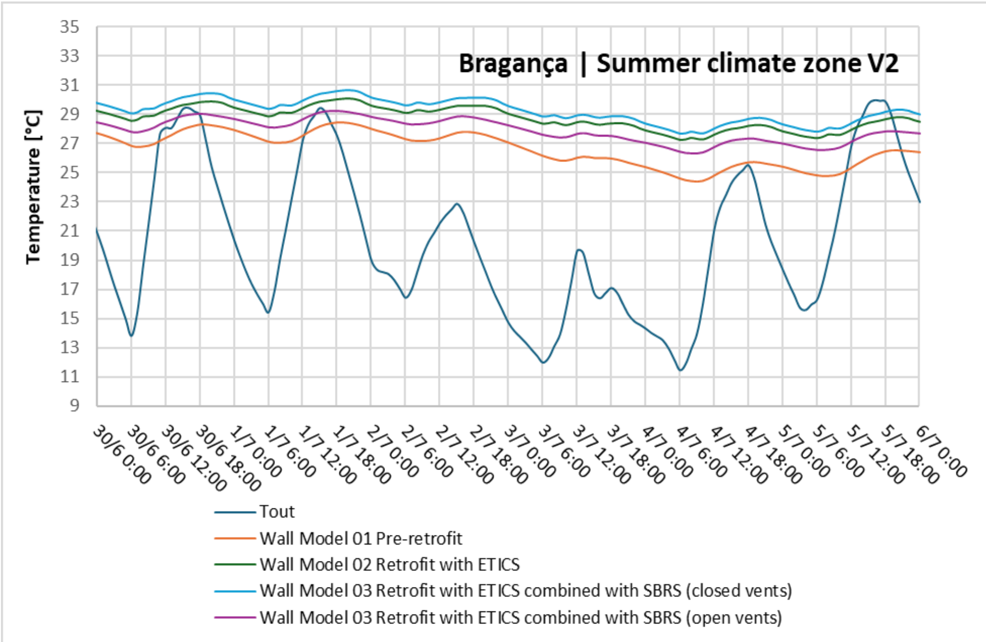


Figure 5.21 Outdoor air temperature (Tout) and indoor air temperature (Tint) for each wall model for the Typical Design Summer Week of Bragança (V2).

In Lisbon, during its Typical Design Summer Week, the outdoor air temperature (Tout) ranged from 17.9 °C to 33.4 °C, with an average of 23.9 °C. As observed in Porto, when comparing the three wall models, the room with Wall Model 01 (pre-retrofit) had the lowest indoor air temperature (Tint), while the room with Wall Model 03 (retrofit with ETICS combined with SBRS) with the closed vents, had the highest Tint. The Tint of the room with Wall Model 01 ranged from 28.5 °C to 30.5 °C, with an average of 29.6 °C. The Tint of the room with Wall Model 02 (retrofit with ETICS) ranged from 30.6 °C to 32.2 °C, with an average of 31.4 °C. The Tint of the room with Wall Model 03 (retrofit with ETICS combined with SBRS), with open vents, ranged from 30.3 °C to 31.9 °C, with an average of 31.1 °C. When the vents were closed, Tint values increased, ranging from 31.1 °C to 32.8 °C, with an average of 32.8 °C.

As mentioned before, from a thermal comfort perspective, and based on EN 16798-1 [128], the recommended Tint range is 23-26 °C for the cooling season. None of the wall models achieved the recommended comfort range during the week under analysis. All retrofit solutions exhibited higher Tint values compared to the pre-retrofit solution (Wall Model 01), as the more insulating envelope solutions reduced heat losses during summer—a factor that is typically beneficial in this season. Among the retrofit options, Wall Model 03 with open vents demonstrated the lowest Tint values. Although it performed the best in terms of indoor temperature by providing a lower average Tint, it still did not reach the recommended comfort range. As a result, additional cooling measures would be necessary to ensure thermal comfort, particularly during the hottest days of summer

In Bragança, during its Typical Design Summer Week, the outdoor air temperature (Tout) ranged from 11.5 °C to 29.9 °C, with an average of 20.6 °C. As observed in the previous locations (Porto and Lisbon), when comparing the three wall models, the room with Wall Model 01 (pre-retrofit) had the lowest indoor air temperature (Tint), while the room with Wall Model 03 (retrofit with ETICS combined with SBRS) with the closed vents, had the highest Tint. The Tint of the room with Wall Model 01 ranged from 24.4 °C to 28.5 °C, with an average of 26.7 °C. The Tint of the room with Wall Model 02 (retrofit with ETICS) ranged from 27.2 °C to 30.1 °C, with an average of 28.8 °C. The Tint of the room with Wall Model 03 (retrofit with ETICS combined with SBRS), with open vents, ranged from 26.3 °C to 29.2 °C, with an average of 27.9 °C. When the vents were closed, Tint values increased, ranging from 27.7 °C to 30.7 °C, with an average of 29.3 °C.

As mentioned before, the recommended Tint range for the cooling season is 23-26 °C [128]. Wall Model 01 ranged below, within and above the recommended ranged. The average Tint of the room with Wall Model 01 was also above (26.7 °C; + 0.7 °C above the maximum standard). None of the retrofit wall models reached the recommended comfort range during the week under analysis. Among the retrofit options, the solution with the lowest Tint-values were the Wall Model 03 with open vents. Although it performs the best in terms of indoor temperature, providing a lower average temperature, it still does not meet the comfort range. Therefore, additional cooling would be required to achieve thermal comfort, especially during the hottest days of the summer.

5.4.3.3 Summer climate zone V3: Évora

To represent summer climate V3, Évora is the selected location. The Typical Design Summer Week occurs between 9th and 16th of September. **Figure 5.22** presents the outdoor air temperature (Tout) during that week and the indoor air temperature (Tint) for each wall model.

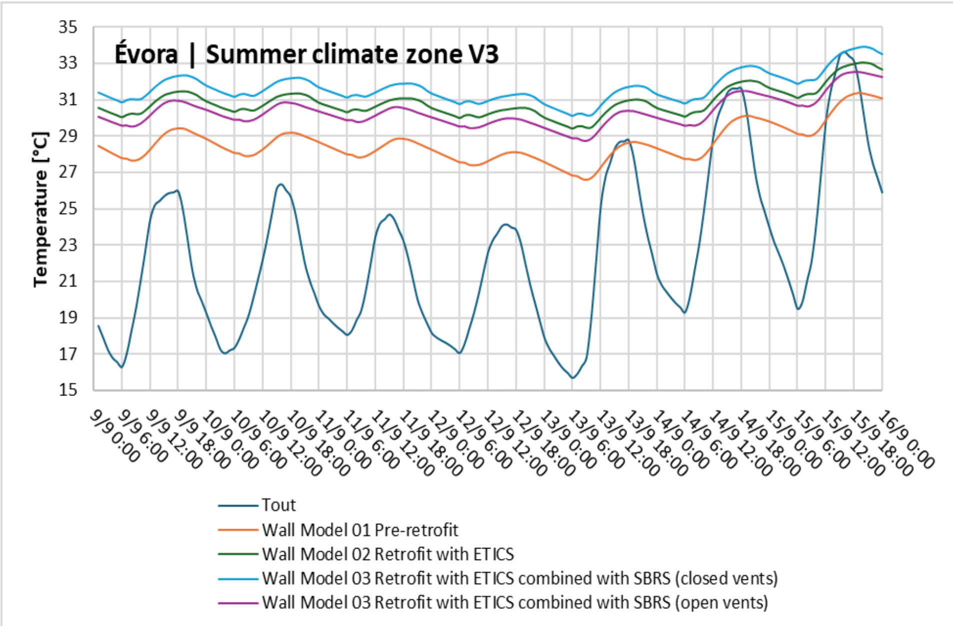


Figure 5.22 Outdoor air temperature (Tout) and indoor air temperature (Tint) for each wall model for the Typical Design Summer Week of Évora (V3).

In Évora, during the Typical Design Summer Week, the outdoor air temperature (Tout) ranged from 15.7 °C to 33.6 °C, with an average of 22.6 °C. As observed in the previous locations (Porto, Lisbon and Bragança), when comparing the three wall models, the room with Wall Model 01 (pre-retrofit) had the lowest indoor air temperature (Tint), while the room with Wall Model 03 (retrofit with ETICS combined with SBRS) with the closed vents, had the highest Tint. The Tint of the room with Wall Model 01 ranged from 26.6 °C to 31.3 °C, with an average of 28.6 °C. The Tint of the room with Wall Model 02 (retrofit with ETICS) ranged from 29.4 °C to 33.0 °C, with an average of 30.9 °C. The Tint of the room with Wall Model 03 (retrofit with ETICS combined with SBRS), with open vents, ranged from 28.7 °C to 32.5 °C, with an average of 30.3 °C. When the vents were closed, Tint values increased, ranging from 30.1 °C to 33.9 °C, with an average of 31.6 °C.

From a thermal comfort perspective, and based on EN 16798-1 [128], the recommended Tint range is 23-26 °C for the cooling season. As observed in the previous locations, none of the wall models reach the recommended comfort range during the week under analysis. Among the retrofit options, the solution with the lowest Tint values were the Wall Model 03 with open vents. Although it performs the best in terms of Tint, providing a lower average temperature, it still does not meet the comfort range. Therefore, additional cooling would be required to achieve thermal comfort, especially during the hottest days of the summer.

5.5 Discussion and brief conclusion

The numerical study of the Solar Bridge Retrofit System (SBRS) provided valuable insights into its performance during both heating and cooling seasons.

During the heating season:

- **SBRS functions effectively as a heat gain technology**, surpassing its primary role of mitigating winter heat losses due to structural thermal bridges. This conclusion aligns with the results of experimental studies. In this chapter, isoflux diagrams from BISTRA showed that the thermal bridge effect reverses in Wall Model 03 (retrofit with ETICS combined with SBRS), compared to Wall Model 01 (pre-retrofit), resulting in heat gains rather than heat losses through the concrete column. Meanwhile, the isoflux diagram of Wall Model 02 (retrofit with ETICS) showed a more uniform temperature distribution across the wall, covering both the thermal bridge area and the surrounding masonry wall
- The numerical results of DesignBuilder showed that, across **all studied Portuguese locations, a room with Wall Model 03 (retrofit with ETICS combined with SBRS) performed better than a room with Wall Model 01 (pre-retrofit) or with Wall Model 02 (retrofit with ETICS).**

During the cooling season:

- **Regardless of the Portuguese location** (Bragança, Évora, Lisbon or Porto), **a room with Wall Model 03 (retrofit with ETICS combined with SBRS) with open** vents outperformed other retrofit solutions, maintaining slightly lower indoor air temperatures (Tint) than Wall Model 02. Tint was consistently 0.3 °C to 0.8 °C lower in Wall Model 03 with open vents.
- **Regardless of the Portuguese location (Bragança, Évora, Lisbon or Porto), Wall Model 03 with closed vents is not recommend**, as it leads to higher Tint values during the summer. These numerical findings align with experimental results, which suggest that opening vents during the cooling season is beneficial.

Overall, the numerical study of the SBRS demonstrated:

- Enhancement of winter thermal performance while offering adaptability for summertime conditions.

- Suitability across all Portuguese climate zones for both heating and cooling season, provided that vents are included in its design

6

SUMMARY OF THIS PHD WORK

This chapter presents the summary of this PhD research project, namely the research scope, advising team and the resulting science communication and achievements.

6.1 Advising scope

This PhD work aimed to assess the potential of passive solar technologies in the thermal retrofit of residential buildings within Mediterranean climate. Its objective was to further research for retrofit solar strategies in Portugal by aiming at developing a retrofit scheme of the building's envelope through adoption of an external transparent skin to increase indirect-solar gains and mitigate structural thermal bridges, which was named Solar Bridge Retrofit System, or simply SBRS,

The research was motivated by the apparent lack of information regarding the potential use of transparent skin solutions in retrofitting design projects in Portugal. And, was is expected that this PhD work will lead to the promotion of a new retrofit technology in the Portuguese residential building context.

6.2 Advising team

The PhD work is integrated in the Doctoral Program in Eco Construction and Rehabilitation within the PhD Program in Civil Engineering and has been advised by:

- Doctor Daniel Aelenei, Professor at Department of Civil Engineering of NOVA FCT,

and co-advised by two Professor from the Department of Civil Engineering, Architecture and Environment of Instituto Superior Técnico, University of Lisbon (IST UL), namely:

- Doctor Maria da Glória de Almeida Gomes;
- Doctor António Heleno Domingues Moret Rodrigues.

6.3 Science communication

During the PhD work the following papers were published:

- D. Aelenei, S. Brito-Coimbra, M. Glória Gomes, and A. Moret Rodrigues (2021) "Solar Bridge Retrofit System: An innovative solution to renovate structural thermal bridge areas," Energy Building, vol. 236, p. 110784, 2021, doi: https://doi.org/10.1016/j.enbuild.2021.110784.
- S. Brito-Coimbra, D. Aelenei, M. Gloria Gomes, and A. Moret Rodrigues (2021) "Building Façade Retrofit with Solar Passive Technologies: A Literature Review," Energies, vol. 14, no. 6, p. 1774, https://doi.org/10.3390/en14061774.
- S. Brito-Coimbra, D. Aelenei, M. Gloria Gomes, and A. Moret Rodrigues (2023) "Experimental Design for Building Retrofit Studies: The Assessment of the Thermal Behaviour of a Solar Passive Retrofit Solution" (2023) Testing and Experimentation in Civil Engineering, RILEM Bookseries, vol 41, p. 291 - 301, https://doi.org/10.1007/978-3-031-29191-3_25.

During the PhD work were presented:

- A poster, named ""Thermal rehabilitation of buildings using solar passive techniques" at 1st Doctoral Conference in Civil Engineering - EDIFICE 2018 on 7th March 2018 (NOVA University – Campus Caparica).

- A poster, named “Thermal Rehabilitation of Buildings using Solar Passive Techniques" at EcoCoRe Summer School on 22th June 2018 (NOVA University – Campus Caparica).
- An oral communication “Thermal Rehabilitation of Buildings using Solar Passive Techniques” at 2nd Doctoral Conference in Civil Engineering - EDIFICE 2019 on 13th March 2019 (NOVA University – Campus Caparica).
- An oral communication, named “The use of External Transparent Skin in the correction of Structural Thermal Bridges”, at EcoCoRe Summer School 19 on 6th September 2019 (UMinho – Campus Guimarães).
- A poster, named “Limiting structural thermal bridges through solar passive retrofit - A Prototype Design of a Solar Bridge Retrofit System (SBRS)”, at FAÇADES 2019 - South Challenges and beyond on 22th November 2019 (NOVA University – Campus Caparica).
- An oral communication (online), named “The thermal performance of the Solar Bridge Retrofit System during the heating and cooling season”, EDIFICE 2021, on 26th May 2021.
- A poster, named "A Solar Passive System to Retrofit Structural Thermal Bridge Areas", at European Façade Network Conference - Teaching Façades for a Sustainable Future on 14th June 2022 (Lisbon).

6.4 Achievements

During the PhD work were presented, the PhD student was award with:

- **Best Poster Prize** at 1st Doctoral Conference in Civil Engineering - EDIFICE 2018 on 7th March 2018 (NOVA University – Campus Caparica).
- **Best Poster Prize in the 1st year category** at EcoCoRe Summer School on 22th June 2018 (NOVA University – Campus Caparica).
- **2nd Best Poster** at European Façade Network Conference on 14 June 2022 (Lisbon).

7

CONCLUSIONS

This PhD work addressed the challenges of retrofitting the thermally inefficient Portuguese residential building stock, specifically focusing on buildings built between 1970 and 1990, prior to introduction of the first thermal code. These buildings suffer from significant energy loss due to structural thermal bridges in load-bearing concrete elements. By leveraging the solar potential in mainland Portugal, this work introduced and validated the Solar Bridge Retrofit System (SBRS), an innovative passive solar solution (indirect solar gain mechanism) inspired by the unvented Trombe wall. Unlike the traditional Trombe wall, which is typically associated with masonry surfaces, SBRS rather collects and stores the heat at the level of thermal bridge areas, which are known to cause significant heat losses during the heating season.

The findings confirm that the SBRS offers a promising retrofit strategy for mitigating the thermal bridge effect, particularly during the heating season. The system's design, which integrates an external transparent skin over structural components, demonstrated effective heat gain potential, improving the thermal performance of façades while complementing traditional insulation methods (ETICS). Notably, double-glazing outperformed single-glazing in enhancing heat gains. Besides, numerical study showed that, across all studied Portuguese locations (Bragança, Lisbon, or Porto), a room with Wall Model 03 (retrofit with ETICS combined with SBRS) performed better than a room with Wall Model 01 (pre-retrofit) or with Wall Model 02 (retrofit with ETICS).

During the cooling season, the experimental results showed that the SBRS proved adaptable by adjusting vent configurations, thus mitigating excessive heat gains, particularly with a white wall configuration. These results emphasize the importance of managing the SBRS to meet different seasonal requirements. The significance of the SBRS with vents was further demonstrated by the numerical results. Regardless of the Portuguese location (Bragança, Évora, Lisbon, or Porto), SBRS with closed vents was not recommended, as it led to higher indoor air temperatures (Tint) during the summer. However, when SBRS included open vents, it consistently outperformed other retrofit solutions, maintaining slightly lower Tint values than Wall Model 02. Tint was consistently 0.3 °C to 0.8 °C lower in Wall Model 03 with open vents.

Overall, the SBRS shows significant potential as an effective and flexible retrofit solution for Portuguese buildings from the 1970–1990 period. Its application not only addresses critical wintertime heat losses but also allows for cooling season adaptability. This research provides valuable experimental data to validate numerical models, contributing to the development of innovative construction techniques that can improve energy efficiency and thermal comfort in aging residential buildings.

7.1 Future work

This PhD study lays the groundwork for the Solar Bridge Retrofit System (SBRS) as a transformative approach to retrofitting Portuguese residential buildings. However, further research is essential to address existing limitations, optimize performance, and expand its applicability. The following directions are proposed for future investigations:

1. **Reassessing with scaled-up test conditions:** Rerun studies with all façades constructed using double brick walls (instead of only the South-facing wall) and ensuring the test cell dimensions are larger, resembling the size of a typical room in a residential building. By doing this, the effect of thermal inertia could be better analysed.
2. **Humidity levels in the air cavity of the SBRS:** Investigate the humidity levels within the SBRS air cavity and assess its potential Impact on performance and durability.
3. **Material optimization:** Explore alternative materials for the external transparent skin, such as advanced glazing or phase-change materials, to enhance thermal performance. Emphasis should be placed on eco-friendly, low-carbon materials to minimize the system's environmental impact.
4. **Geometric modifications of the SBRS:** Study the impact of different pillar dimensions and air cavity of the SBRS, to enhance thermal performance. Besides, different vents size could also be analysed and their placement at different heights of the SBRS.

5. **Thermal comfort adaptations:** Refine the SBRS design to improve its ability to maintain thermal comfort across diverse seasonal conditions, ensuring year-round performance optimization.
6. **Investigation of alternative orientations:** Assess the performance of the SBRS on walls with orientations other than south-facing (e.g., east- and west-facing façades) to evaluate its adaptability and effectiveness in varying spatial configurations.
7. Global evaluation of the SBRS by studying it in other Mediterranean climate regions: Study the performance of the SBRS in other global locations with Mediterranean climates, such as Southern Spain (e.g., Seville), the state of California in the United States of America, Central Chile, Western Cape of South Africa, and parts of Australia. This would provide insights into its potential for broader international application.
8. **Long-term monitoring and user interaction:** Conduct extensive long-term monitoring of buildings retrofitted with SBRS under real-world conditions to gather comprehensive data on thermal and energy performance. Study user interactions with adjustable features, such as vents, to improve usability and overall system efficiency.
9. **Climate change impact studies: Develop studies considering future climate scenarios and their impact on SBRS performance. This includes simulating increased frequency of extreme weather events and higher average temperatures to evaluate system resilience and adaptability.**
10. **Economic analysis:** Perform detailed cost-benefit analyses, including energy savings, initial investment, and payback periods. Evaluate financial incentives or policy measures to promote widespread adoption of the SBRS in different contexts.
11. **Scalability and industrialization:** Investigate methods to simplify and scale up the production and installation of SBRS components. Modular designs or pre-assembled kits could make the system more accessible, fostering its large-scale adoption for retrofitting existing building stock.

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