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Modeling the Evolution of Construction Solutions in Residential Buildings' Thermal Comfort

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Abstract: The evolution of the construction sector over the years has been marked by the replacement of high thermal inertia mass constructions by increasingly lighter solutions that are subject to greater thermal fluctuations and, consequently, thermal discomfort. To minimize these effects, energy demanding space conditioning technologies are implemented, contributing significantly to the sector's share of global energy consumption. Enhanced constructive solutions involving phase-change materials have been developed to respond to the constructive thermal inertia loss, influencing buildings' thermal and energy performance. This work aims to model the evolution of the construction over the last decades to understand to what extent constructive characteristics influence the occupants' thermal comfort. For this purpose, typical and enhanced solutions representing distinct constructive periods were simulated using the EnergyPlus® software through its graphical interface DesignBuilder® and the thermal comfort of the different solutions was evaluated using the adaptive model for thermal comfort EN16798-1. The main results reveal that more restraining regulatory requirements are indeed mitigating thermal discomfort situations. However, overheating phenomena can rise, creating worrying consequences in the short-medium term. Thus, countries with mild climates such as Portugal, must pay special attention to these effects, which may be aggravated by climate change.

Keywords: thermal comfort; energy and thermal performance of buildings; dynamic simulation; constructive solutions

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1. Introduction

1.1. Motivation and Background

Energy efficiency in buildings is currently at the center of the European Union (EU) agenda due to the untapped potential for energy demand reduction, without which the 2030 and 2050 energy targets are almost unachievable, in particular, in the framework of the European Green Deal. At a global scale, buildings are responsible for about 36% of the total final energy demand and 40% of direct and indirect carbon dioxide emissions [1]. At the EU level, the building stock is responsible for about 40% of the final energy consumption, making it the largest energy demanding sector and a preferential target for decarbonization policies (Figure 1) [2]. Despite the efforts to enhance the energy efficiency of the sector, according to estimations, an increase in energy consumption of about 20% until 2050 should be expected [3]. The increasing ownership rates of electrical devices alongside the amount of time spent inside buildings and the increasingly restrictive thermal comfort requirements, have contributed significantly to this trend [4,5].

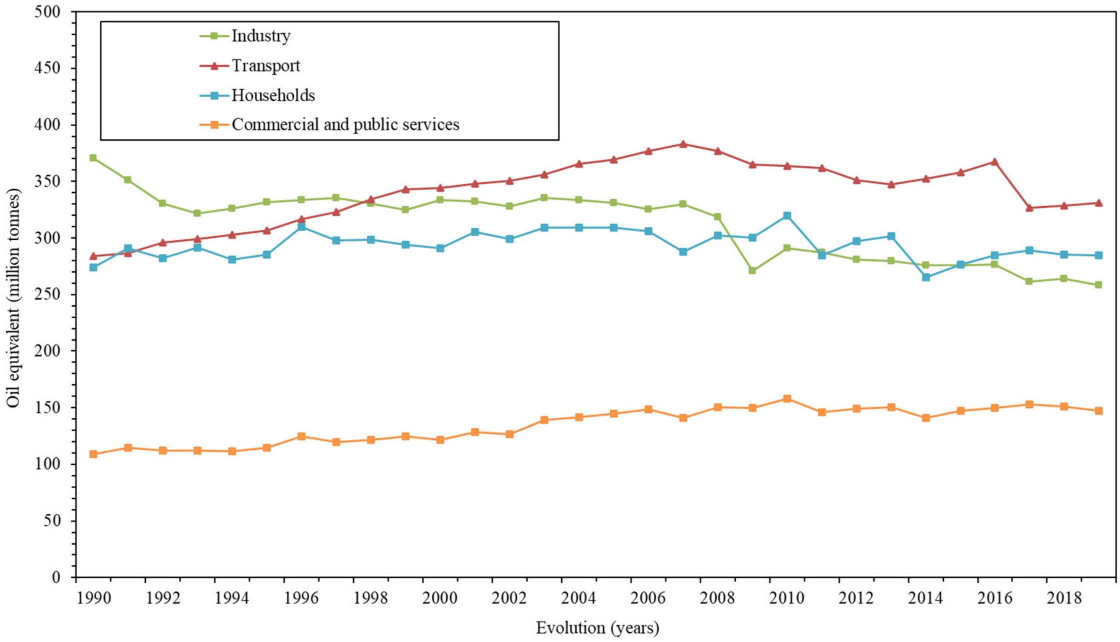


Figure 1. Final energy consumption per sector, European Union (EU)-28 [6].

The EU buildings' policy framework has been evolving since the beginning of the 1990s, when a wide range of measures was put into motion to actively improve buildings' energy performance. Currently, the Energy Performance of Buildings Directive (EPBD) (Directive 2018/844/EU) [7] alongside the Energy Efficiency Directive (Directive 2018/2002/EU), are the most important European regulations on the buildings sector. Despite the current regulatory framework, most of the European existing buildings (about 75% of which are residential [4]) were built before the first thermal regulations and the percentage of new constructions (after 2000) is quite small [8]. The thermal properties of the built stock are assured by the heat transfer coefficients (*U-values*) of the corresponding constructive elements, which differ considerably across EU countries [9]. Over the years, the values have decreased as a result of consecutive thermal performance improvement policies. Due to the harsh winter weather conditions, Northern and Central European countries have a long tradition of incorporating insulating materials in construction, explaining the high thermal resistance of construction elements. On the other hand, the mild weather of Mediterranean countries led to the thermal quality of buildings being neglected, which is verified by higher *U-values* [10].

Portugal was chosen as a case study due to the high levels of energy poverty and the recognized lack of thermal quality in buildings [11]. More than two thirds of the existing Portuguese residential buildings (67.7%) were built before 1990, when the first Portuguese buildings thermal performance legislation (RCCTE-Decree-Law 40/90 [12]) was published [13]. Portugal, as other European countries, is characterized by an aged residential building stock with poor thermal characteristics, low penetration of space conditioning systems alongside with the low efficiency of the existing ones, and highest levels of energy poverty (according to the European Energy Poverty Observatory, more than 20% of the population is not able to adequately warm their homes) [14]. Regarding construction, Portugal followed the trend of the remaining European countries and has been improving the thermal characteristics of the main constructive elements (Figure 2). The greatest reductions in *U-values* coincide with the publication of buildings' thermal performance regulations summarized in Table A1 of the Appendix A. However, despite the comprehensive regulatory framework and the milder climate situation, heating energy consumption needs in Portugal are relatively high, reflecting the poor thermal performance of buildings [15]. The lack of insulation materials in construction as well as the scarcity of adequate heating systems (in 2011, the majority of residential buildings were either heated by inefficient mobile heating devices or by open wood fireplaces [16] and in 2015, only 15.7% of the dwellings had air-conditioning systems [17]) contributes seriously to the country's relatively high heating and cooling needs.

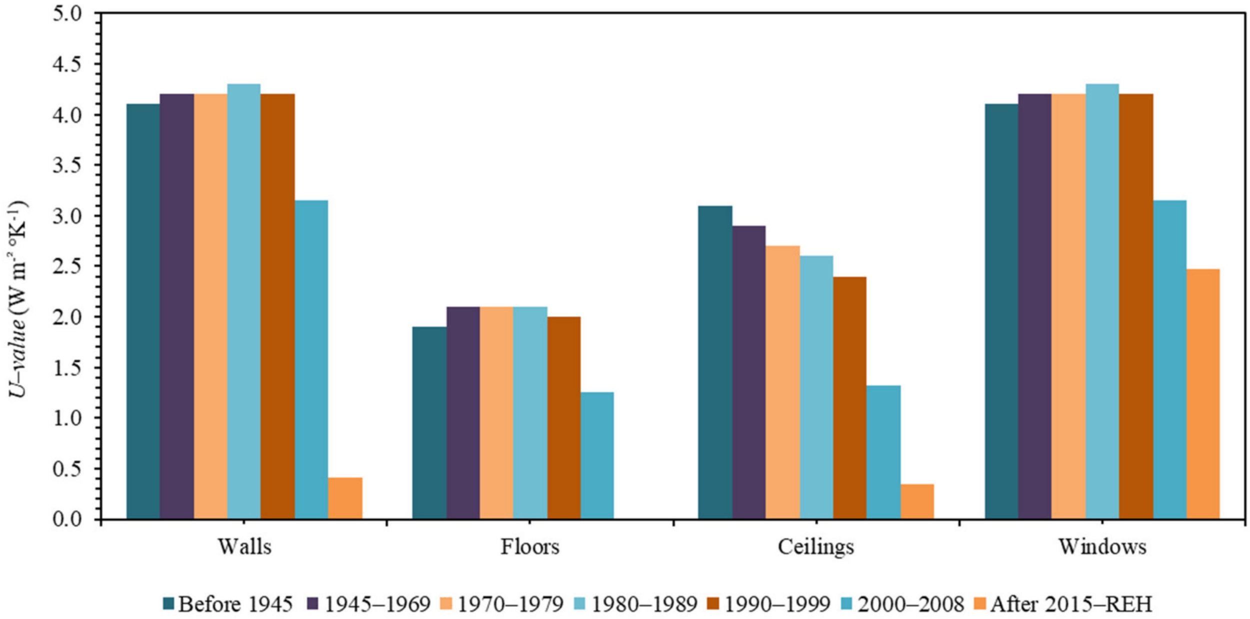


Figure 2. Evolution of the *U-values* of the main constructive elements in Portugal (Retrieved from: http://www.entranze.enerdata.eu/#/u-values.html (accessed on 24 September 2020)).

Previous authors have studied the Portuguese building stock quality but with other purposes. For instance, the study of Simões et al. [18] sought to quantify and map energy poverty in Portugal and Magalhães and Leal [19] aimed at determining the space heating deficit across the country. Unfortunately, little has been exploited regarding how the nature of constructive solutions may indeed influence the thermal comfort of residential buildings.

1.2. Evolution of Constructive Solutions and Thermal Comfort

For many years, construction was dependent on the existing natural resources in the different regions and in the prevailing climatic conditions [20,21]. In the last century, the use of regional natural materials was reduced, being massively replaced by brick and cement [21]. In addition to the materials, techniques have also evolved. For instance, the changes in the construction of external walls are extreme, leading to a considerable decrease in buildings' thermal inertia and a consequent worsening of thermal comfort conditions (Figure 3). The high-thickness cloths of stone masonry were replaced over the years by lighter and cheaper materials, such as brick [22]. In the 1980s, thermal insulation materials started to be introduced and, since then, different outside and inside thermal insulation systems have been developed to cope with increasing thermal performance requirements [23]. Roofing [24,25], flooring [26] and glazing spans [27,28] solutions have also evolved, and it is currently common the usage of insulating materials to increase the thermal resistance of these constructive elements.

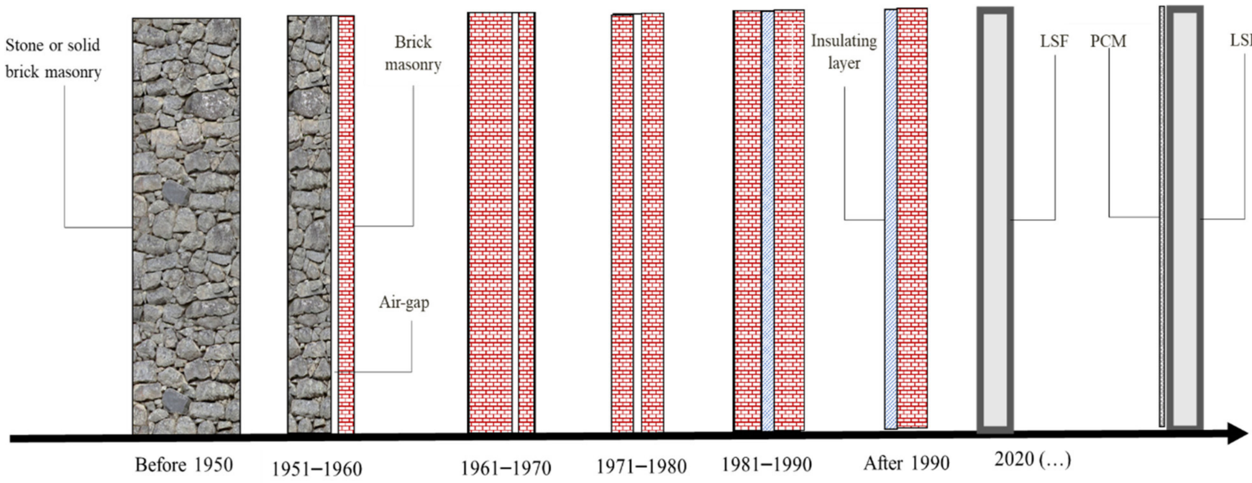


Figure 3. Evolution of external wall constructive solutions.

More recently, lightweight steel-framed (LSF) systems have been attracting interest as these prefabricated modular steel structures are assembled on site, reducing significantly both construction time and costs [29,30]. However, the low thermal mass is one of the most relevant drawbacks of these constructions, giving rise to noteworthy daily temperature oscillations (particularly felt in Mediterranean climates) which, in turn, cause high thermal discomfort [31]. Several strategies can be used to improve the thermal resistance of LSF elements, being the use of phase-change materials (PCMs) one of them. In refurbishment processes, PCM boards can be added to walls, without changing considerably the existing design, while in new constructions several options are available, namely by encapsulating these materials in the building elements [30,32]. PCMs have unique properties that allow them to increase the thermal inertia of buildings without increasing the weight of the structures [32,33].

A building's thermal comfort influences the welfare, health and productivity of its occupants and, therefore, it has been a topic widely addressed both from the literature and legislation standpoints [34]. Constructive solutions play a key role in occupants' thermal comfort as they must allow adequate indoor-outdoor heat transfer [35], ensuring that heat losses through the envelope in winter are minimized, whereas solar gains through glazing spans and internal loads are enhanced [35]. Conversely, in the summer, solar gains entering buildings by both opaque and glazed elements must be minimized, and internal loads should be removed [36]. However, the evolution of constructive solutions has been accompanied by a loss of thermal mass, yielding a negative influence on the buildings' thermal performance [37], thereby opposing the increase in thermal comfort requirements. Thus, the evaluation of buildings thermal characteristics gains special relevance as constructive elements can be responsible for minimizing heat gains and losses, and for creating thermal inertia, contributing to enhance thermal comfort.

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), thermal comfort can be defined as "*that condition of mind which expresses satisfaction with the thermal environment*" [38]. According to this description, comfort conditions are thus variable from person to person and influenced by physical and physiological processes, in addition to cultural, environmental and personal factors [5]. The individual's metabolic activity, clothing or the performed activities impact thermal comfort perception as well as physical parameters, such as air temperature and speed and relative humidity [34]. Several metrics for assessing human thermal comfort have been proposed in scientific literature over the last decades aiming to describe as accurately as possible human thermal perception regarding the thermal environment to which people are exposed [39]. In the scope of this work, the EN16798-1 [40] is used to examine the simulation results and to compare comfort levels.

1.3. Contribution and Organization

The present paper reviews the evolution of the construction sector over several decades, showing how different constructive solutions influence the thermal quality of buildings. The effect of the most frequent construction solutions on the thermal comfort of residential buildings is exploited, as well as the improvements produced by enhanced solutions, including PCM. The results are intended to serve as a starting point for sectoral entities and policy makers in the definition of improved thermal and energy buildings performance measures and in the enhancement of people's thermal comfort conditions.

The remainder of the paper is organized as follows. In Section 2, the proposed methodology is described. Simulation results are displayed and discussed in Section 3. Finally, Section 4 presents the final remarks stressing the main conclusions and leaving clues to future work on the topic.

2. Methodology

The implemented methodology is divided into three main steps (Figure 4). The first one (Step 1) aims to characterize the thermal performance of a constructive solution chosen as the reference (Scenario A), which is fully described in Section 2.1. The reference model was validated and duly calibrated through onsite indoor temperature and relative humidity data gathered with the building running in a free-flow basis. Monitoring sensors were placed in each thermal zone of the reference building, ensuring a continuous record of the air temperature and relative humidity. The position of the sensors inside the rooms was defined in order to avoid direct sun exposure from the glazed areas in accordance with ISO 7726 [41]. The monitoring acquisition system is logged at 10 min intervals and averaged hourly and has as accuracy of 0.5 °C and a resolution of 0.1 °C.

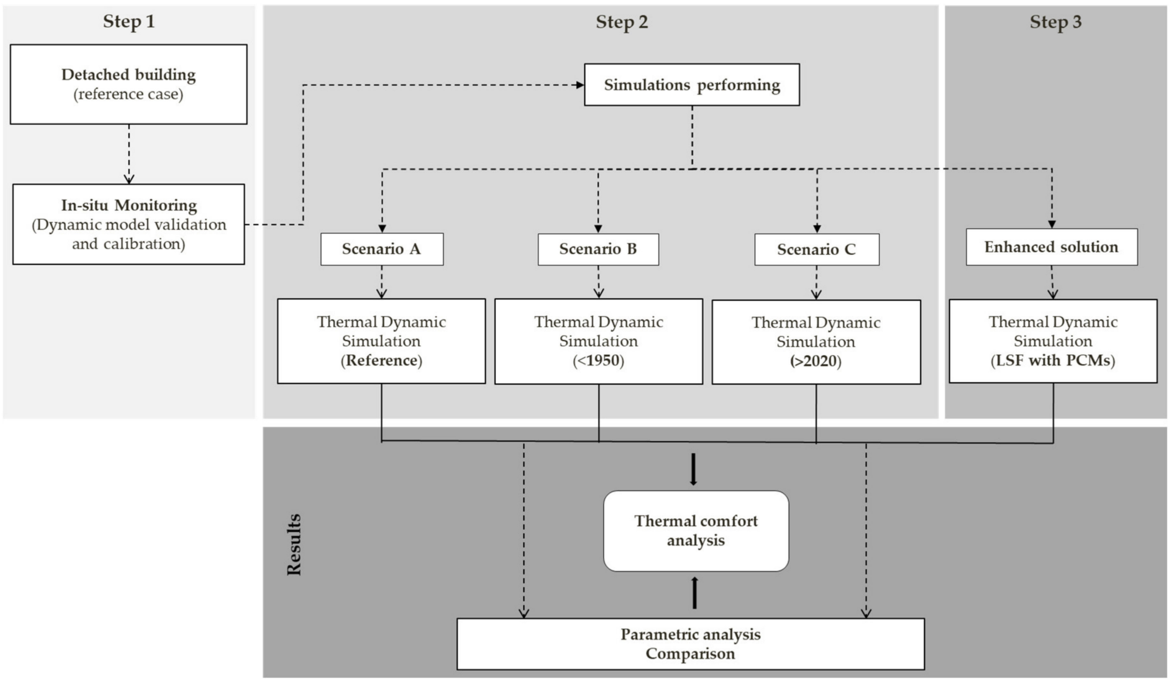


Figure 4. Schematic of the followed methodology.

After validating the reference case, different constructive solutions, representing different constructive periods, were simulated (Step 2). Solutions were defined as discrete parameters (materials and thicknesses were changed between scenarios) but the layout and internal loads of the reference case were maintained across simulations. The window solutions as well as outdoor doors were also maintained for a real understanding of the behavior on the opaque envelope level. Two scenarios were simulated to exploit two very distinctive constructive solutions, namely:

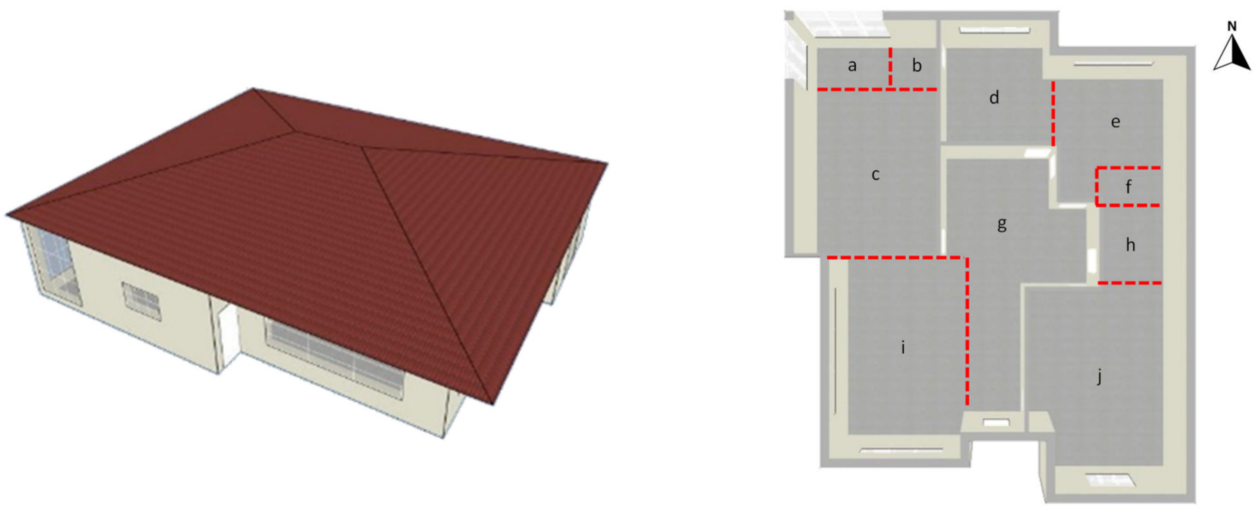
- Scenario B—representing the period before 1950 characterized by high-thickness solid brick walls without insulation;
- Scenario C—representing the most recent thermal requirements announced in the recent Portuguese Decree-Law 101-D/2020 [42].

These two scenarios alongside the reference one allow to represent the main construction techniques. Moreover, due to a growing tendency of prefabricated construction systems as faster and economic building solutions, a LSF structure was also modeled (enhanced solution—Step 3). PCM solutions are combined in the inner surfaces of external walls and ceiling to reduce the risk of overheating (due to the reduction of the thermal inertia) and maximize the potential of the charge and discharge process for the indoor environment. Lastly, the results of all scenarios are compared, and recommendations are listed to aid designers when choosing construction solutions, to deal with the lack of thermal inertia, as well as to demystify several issues in the research community. More details on the constructive solutions are presented in Section 2.3.

2.1. Case Study

2.1.1. Building Characterization

The reference building used as case study was built in 2003, it has a total floor area of 176 m^2 and is composed by one inhabitable floor and an attic (Figure 5). The building has a sunroom (*a*), used for storage and as a laundry room, a pantry (*b*), a kitchen (*c*), three bedrooms (marked as *d*, *e* and *j*), an entrance hall (*g*), a living room (*i*) and two bathrooms (*f* and *h*).



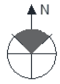
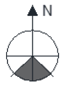
a—sunroom *b*—pantry *c*—kitchen *d*—bedroom 1
e—bedroom 2 *f*—bathroom 1 *g*—distribution hall *h*—bathroom 2
i—living room *j*—bedroom 3

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

Figure 5. Rendered images of the case study building: (**a**) 3d model; (**b**) ground floor blueprints.

Table 1 presents the building window-to-wall ratio by orientation. The largest glazed surfaces are North and West oriented but 17.81% of the window-to-wall ratio is South-oriented, which allows it to take advantage of solar gains in the living room and in the bedroom 3. In the summer, more efficient shading techniques are required in these rooms to prevent overheating.

Table 1. Glazing surfaces and window-to-wall ratio of the case study.

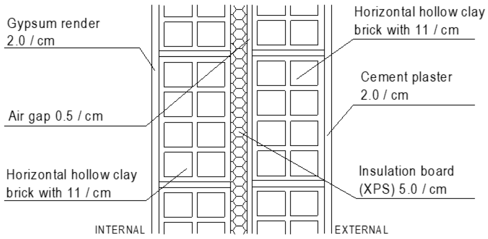
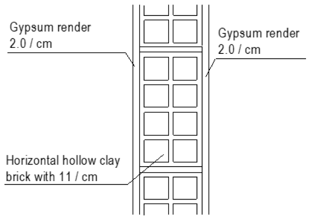
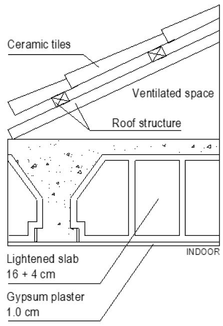
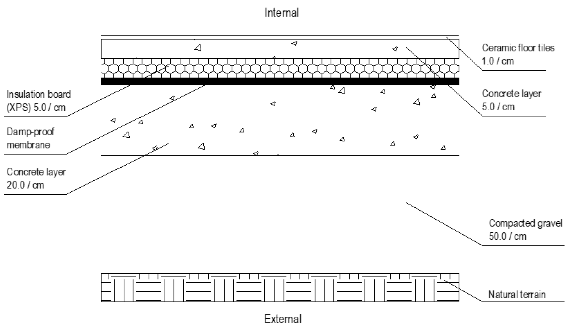
	Gross Wall Area (m^2)	Window Opening Area (m^2)	Window-Wall Ratio (%)
	49.00	14.30	29.18
	61.60	0.34	0.55
	49.00	9.01	18.40
	61.60	12.24	19.86
Total	221.20	35.89	16.22

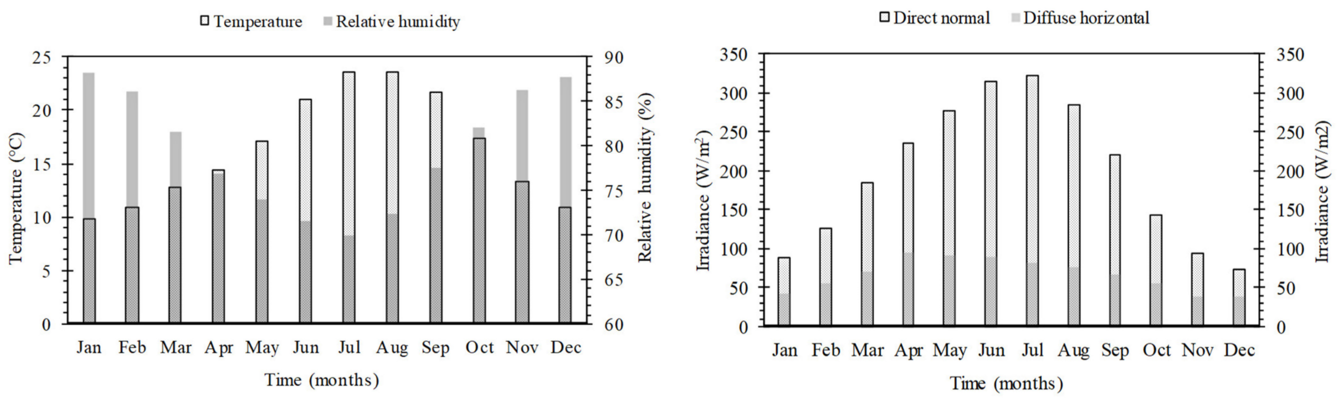
The reference constructive solution is described as follows. The building's envelope walls are composed of a double hollow clay brick with air gap and insulation in the middle. The interior partition is made by single-layered brick walls, rendered with gypsum on both sides. The ground floor is supported by a thick layer of compacted gravel and concrete. A damp-proof membrane protects the flooring insulation board, to which the interior ceramic floor is glued. The pitched roof is composed by an exterior coating of ceramic tiles supported by a roof structure. A slab separates the indoor space and the roof structure, creating between both an attic. In these elements, the existence of thermal bridges was considered. The calculation method used to determine the thermal bridges depends on the type of bridge encountered (linear and punctual thermal bridges) and the *U-values* of the constructive solutions presented in Table 2 already include linear thermal bridges in columns and beams. For windows, a thermal transmission coefficient of $U_{w,installed}$ = 2.44 W m^{-2} K^{-1} and a solar heat gain coefficient of 0.56 were used. In turn, a thermal transmission coefficient of $U_{w,installed}$ = 1.40 W m^{-2} K^{-1} was considered for external doors. These values consider the *U*-value of the frame (U_f) and the glass edge thermal bridge (Ψ_g) in accordance with ISO 10077 [43] and the installation thermal bridge ($\Psi_{install}$) in accordance with EN ISO 10211 [44]. In order to optimize the sensitivity analysis, an average value, $U_{w,installation}$, was assumed.

2.1.2. Climate Data

Beyond the constructive features, heat transmission in buildings depends strongly on climatic variables (namely outdoor temperature, solar radiation, wind speed and relative humidity); the altitude at which the building is located and the building orientation. In Portugal, due to its geographical situation in the northern hemisphere, the South orientation is the one that receives the most solar radiation and therefore, this orientation should be preferred for maximizing solar gains. Despite being a small country, Portugal is divided into three heating climate zones (I_1, I_2, I_3) and three cooling climate zones (V_1, V_2, V_3). The case study dwelling is located in Barrocal, a civil parish of the municipality of Pombal, district of Leiria, central region of Portugal. Due to its location, the reference building is located on the climatic zone I_2 V_2. Data on temperature, relative humidity and solar irradiance from a local weather station belonging to the Portuguese Water Resources Information System (SNIRH—https://snirh.apambiente.pt/ (accessed on 18 August 2020)) was used in the simulations (Figure 6).

Table 2. Case study constructive solutions.

Building Element	Constructive Solution	*U-Value* (W m^{-2} K^{-1})
External walls		0.44
Internal partition walls		4.29
Pitched roof		0.58
Ground floor slab		0.59



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

Figure 6. Weather data for Pombal region: (**a**) average monthly air temperature and relative humidity; (**b**) average monthly solar irradiance.

2.2. Dynamic Simulation: Numerical Model Definition

The model is developed resourcing to DesignBuilder® software to simulate the whole building thermal and energy balance. The EnergyPlus® software is the calculation engine behind the DesignBuilder®, which has a graphical interface to reproduce the model geometry, as well as the building features and thermal zoning, in a user-friendly fashion. A detailed multi-zone model was assembled considering four thermal zones (Figure 7), corresponding to the main internal compartments according to the zoning orientation. The ground floor has three thermal zones (TZ01, TZ02 and TZ03) and the attic comprise itself another thermal zone, in this case, an unheated space (TZ04). The zoning was defined with the following correspondence to the internal partitions: TZ01—hall and kitchen; TZ02—living room and distribution hall; TZ03—bedrooms; TZ04—attic.

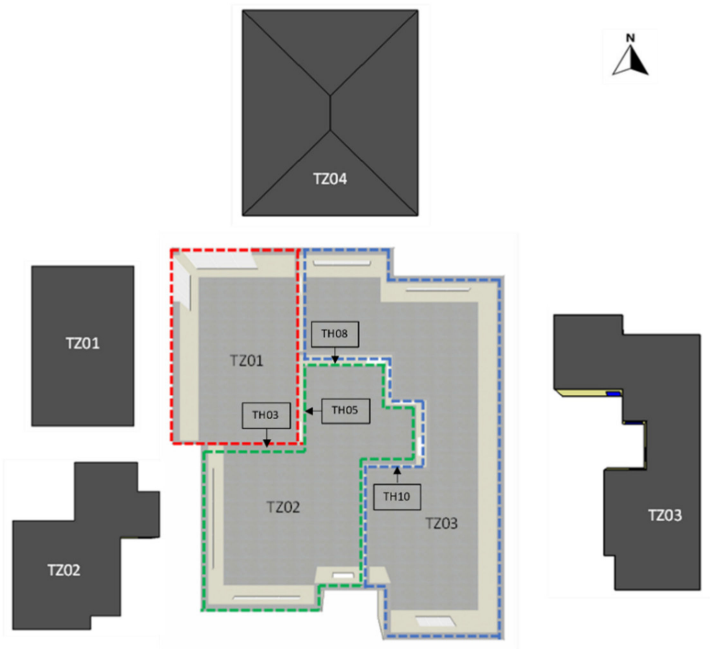


Figure 7. Layout of the indoor thermal zones (TZ01, TZ02 and TZ03) and positioning of the monitoring sensors (TH03, TH05, TH08 and TH10).

Also, the occupation patterns were considered. The building is occupied with a household of two adults and two children. The typical weekly occupation agenda is presented in Table 3. During the remaining hours, the zones are assumed to be unoccupied.

Table 3. Occupancy schedule defined detailed by thermal zone.

Thermal Zone	Occupancy				
	Level of Occupancy (%)	Profile			
		Weekday		Weekend	
TZ01	50	On-From	7.00 to 8.00	On-From	8.00 to 9.00
	100		8.00 to 9.00		9.00 to 10.00
	100		12.30 to 14.30		13.00 to 15.00
	50		19.00 to 20.00		19.00 to 20.00
	100		20.00 to 21.00		20.00 to 21.00
TZ02	100		21.00 to 22.00		21.00 to 23.00
	50		22.00 to 00.00		22.00 to 00.00
TZ03	50		22.00 to 00.00		22.00 to 00.00
	100		00.00 to 07.00		00.00 to 08.00
TZ04	0		Always-off		Always-off

A constant value of 1.57 W m^{-2} was adopted for all thermal zones (excluding TZ04) to simulate the internal gains correspondent to the electric devices and lighting. During the summer season, to prevent overheating, exterior shading with medium reflectivity slats were used during the day. The shutters have a 0.80 reflectance coefficient, a thermal conductivity of 0.90 W m^{-2} K^{-1} and a thickness of 1 mm. Finally, air infiltration and natural ventilation were considered in simulations by assuming a constant rate of 0.3 ACH.

2.3. Scenarios

As mentioned previously, different constructive solutions were investigated, and the results were compared with the reference ones. The considered constructive solutions are thoroughly described in Table 4. The same internal partition walls were used in all the simulations.

Table 4. Scenarios constructive solutions.

Scenarios	Building Element	Constructive Solution	*U-Value* (W m^{-2} K^{-1})
B	External walls	Massive granite solution with 80 cm of thickness. In the inner surface of the wall 2 cm of mortar was considered.	2.09
	Pitched roof	Ceramic roof tiles supported by a wood structure.	2.35
	Ground floor slab	Ceramic floor tiles supported by a miscellaneous of materials including gravel, stone and air lime with a thickness of 20 cm.	2.26
C	External walls	Metallic modular system with 5 cm of thermal insulation (expanded polystyrene) plus 5 cm of acoustic insulation (glass wool) coated by wood panels.	0.36
	Pitched roof	Metallic modular system with 6 cm of thermal insulation (extruded polystyrene) plus 4 cm of acoustic insulation (glass wool) coated by wood panels in the inner surface and metallic sheet in the outer surface.	0.33
	Ground floor slab	Concrete slab with 6 cm of thermal insulation (extruded polystyrene).	0.55
Enhanced solution	External walls	Metallic modular system with 5 cm of thermal insulation plus 5 cm of acoustic insulation coated by wood panels and BioPCM (a non-toxic, non-corrosive, biodegradable patented family of phase-change materials) in the inner surface.	0.36
	Pitched roof	Metallic modular system with 6 cm of thermal insulation plus 4 cm of acoustic insulation coated by wood pannels in the inner surface plus BioPCM and metallic sheet in the outer surface.	0.33
	Ground floor slab	Concrete slab with 6 cm of thermal insulation (extruded polystyrene).	0.50

For the enhanced solution, PCM with different melting temperature values were tested to reduce the high levels of overheating. Commercial solutions provided by BioPCM® were selected (Table 5), considering PCM with different melting points within the same group.

Table 5. Used phase-change material (PCM): main properties.

PCM Reference	Thickness (m)	Melting Point (°C)	Total Energy Storage (J g^{-1})
BioPCM® M_{91}/Q_{25}_0.037	0.037	25	322
BioPCM® M_{91}/Q_{27}_0.037		27	322
BioPCM® M_{91}/Q_{29}_0.037		29	350

3. Results and Discussion

3.1. Hygrothermal Monitoring Assessment and Model Validation

As explained before, the reference building monitoring results are key to calibrate the numerical model. Figure 8 shows the detailed air temperature, monitored and simulated, of the main thermal zones as well as the exterior air temperature during the monitoring period. The spaces were monitored from 1 August through 31 August 2019, according to the household's convenience. The exterior weather data were collected from a local weather station.

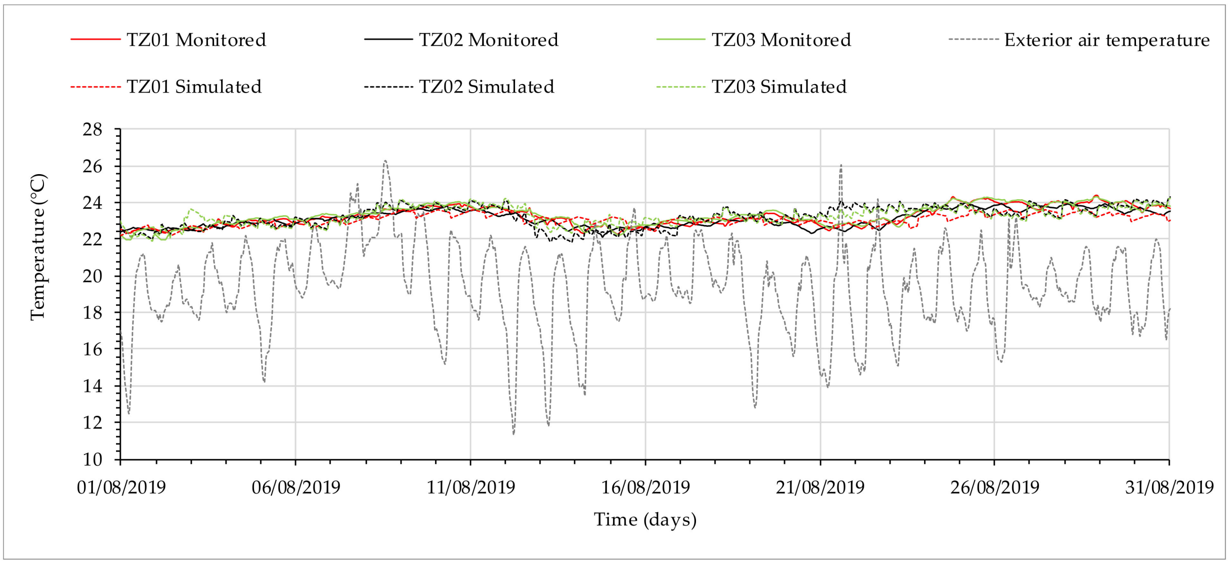


Figure 8. Mean air temperature monitoring results.

The model was validated by comparing the differences between the monitored and simulated indoor air temperatures. The weather file used in simulations was modified to contain the real site data collected from the local weather station. Figure 9 shows the results of the output correlation factor, r^2, between the real and simulated data for the building. Overall, for temperatures between 22 °C and 24 °C, the deviation between the simulated results and the monitored data is small, with the cloud of points tending to a symmetric relation with a maximum deviation of 1 °C. The good of fitness (GOF) index depicted in Figure 9 is 2.04 which, compared with the ASHRAE Guideline [45] that recommends a GOF value below 11% for trials acceptance, means that the model can be validated.

3.2. Parametric Analysis

3.2.1. Scenario A—Reference

Figure 10 displays the temperature behavior of the reference model on an annual basis. The temperature variation is depicted in detail for each thermal zone of the building. From the plot, TZ01 and TZ02 display a similar behavior over the year, reaching the highest temperatures between the period ranging from the beginning of June until the end of September. In turn, the lowest temperatures are observed during the months of December, January and February. Although the global behavior of the TZ03 is similar when compared with TZ01 and TZ02, throughout the year, the daily swing of temperature is considerably lower in this thermal zone.

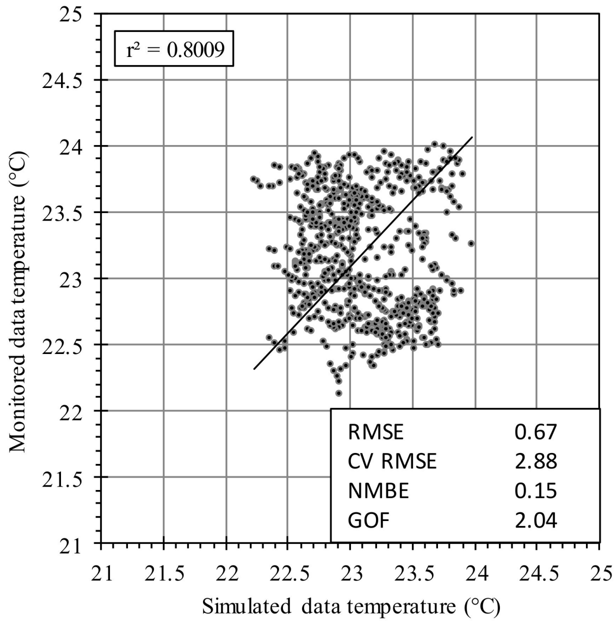


Figure 9. Correlation factor regarding simulated and monitored data.

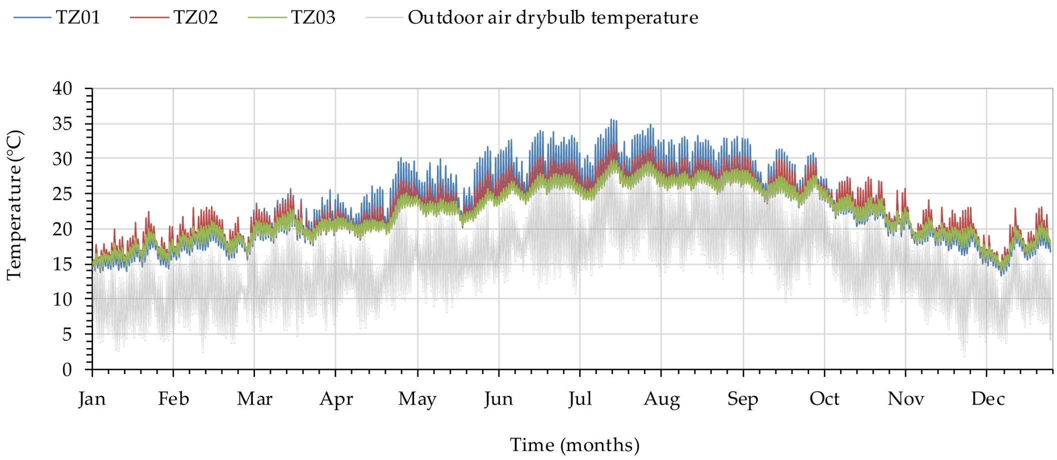


Figure 10. Annual temperature of the reference building (indoor and outdoor air dry-bulb temperature).

The indoor thermal comfort was evaluated according to the adaptive comfort method with the accepted deviation of the indoor operative temperature defined by EN 16798-1 [40] category II with normal level of expectation from the users. Thus, the recommended standard indoor operative temperatures are presented for buildings without mechanical cooling systems, according to the temperature limits depicted in Figure 11. For the heating season, the temperature limits were 20–25 °C according to the standard. Moreover, the thermal discomfort during the winter (underheating) is represented by the total number of hours (expressed in an annual percentage) correspondent to a temperature in the thermal zone below 20 °C. The thermal discomfort by overheating was evaluated with equal methodology, using the upper limit of the EN 16798-1 [40]. By analyzing Figure 11, it is possible to observe that indoor temperature goes under the lower limit comfort threshold (underheating) and exceeds the upper limits (overheating). This result allows it to be concluded that the reference construction conditions are not sufficient to guarantee adequate levels of thermal comfort on their own and need to be improved (e.g., with more insulation) or with the help of mechanical air-conditioning systems, especially during the heating season.

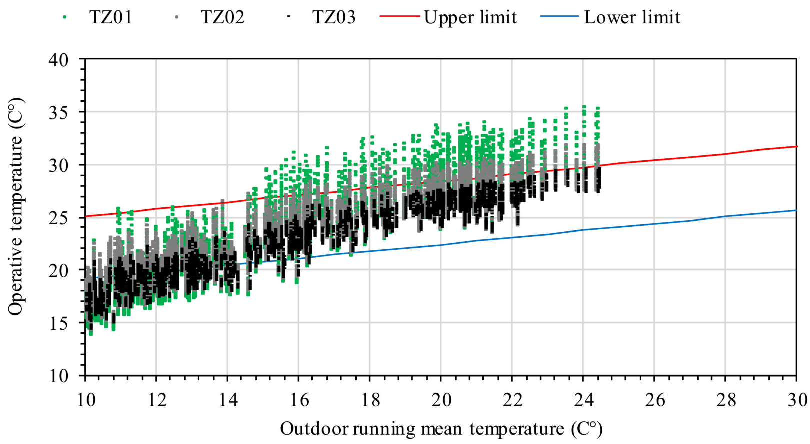


Figure 11. Thermal comfort analysis using EN16798-1 for the reference scenario.

During the winter, the thermal discomfort caused by underheating is considerable in all thermal zones (Table 6). These results reflect, on the one hand, the poor orientation of the building, which does not allow us to take advantage of solar gains in the winter, and, on the other hand, the inadequacy of construction solutions. Thus, it can be concluded that to maintain this building within acceptable comfort ranges throughout the year, a heating system is necessary. Also, in the summer, overheating situations are detected in TZ01 and TZ03. The results in TZ01 are worsened by the existence of the sunroom, which creates an exaggerated heating effect. In TZ02, the effects are negligible.

Table 6. Thermal discomfort—Reference scenario.

Thermal Zone	Thermal Discomfort (%) *	
	Winter	Summer
TZ01	34.18	14.26
TZ02	30.01	0.06
TZ03	34.69	5.27

* These values represent the total number of hours of discomfort, expressed in an annual percentage.

3.2.2. Scenario B

Figure 12 displays the deviations between the comfort thresholds and the simulation results. At first glance, worse conditions of discomfort should be expected due to the large number of results below the lower comfort limit. Indeed, in the winter, the underheating discomfort worsened considerably in the three thermal zones (Table 7). In turn, TZ01 was the only thermal zone in risk of overheating in the summer and, even in this zone, the risk is low.

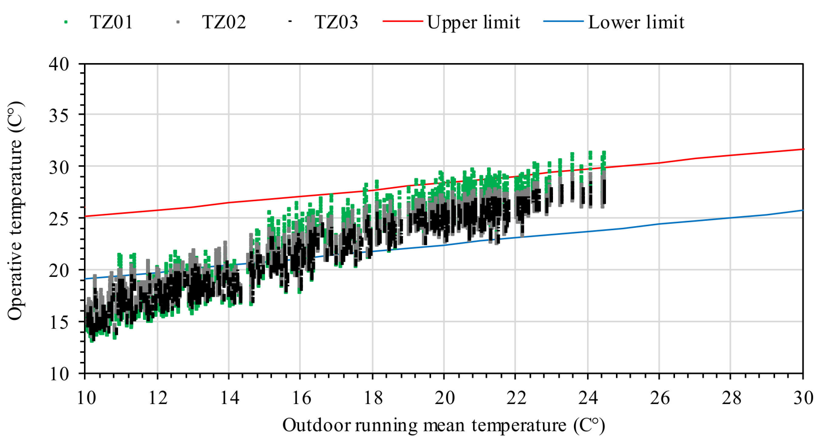


Figure 12. Thermal comfort analysis using EN16798-1 for Scenario B.

Table 7. Thermal discomfort—Scenario B.

Thermal Zone	Thermal Discomfort (%)	
	Winter	Summer
TZ01	49.71	1.83
TZ02	50.66	0.00
TZ03	54.13	0.00

Comparing both scenarios (A and B) the results obtained reveal several differences in the overall building thermal behavior with an increase of about 20% in the discomfort during the winter season. However, both scenarios present high levels of underheating discomfort and an almost negligible overheating discomfort during the summer season. Despite the differences in the constructive solutions, the low levels of insulation in both scenarios give rise to these results in the winter. In turn, during the summer season, the high inertia of both solutions allows the building to absorb and release solar energy, maintain it within the comfort limits.

3.2.3. Scenario C

Figure 13 illustrates the simulation results for Scenario C. It is possible to expect significant levels of thermal discomfort, both due to underheating and overheating, since the cloud of points representing the simulated temperatures is well below and above the standard temperature thresholds.

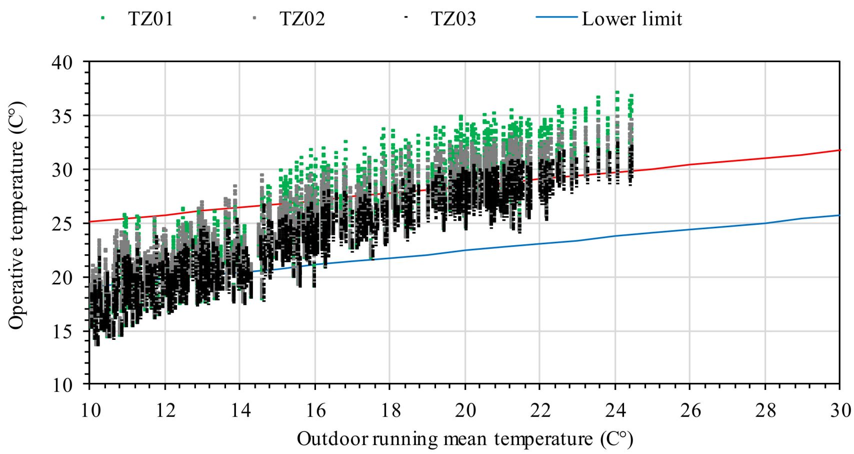


Figure 13. Thermal comfort analysis using EN16798-1 for Scenario C.

The low thermal inertia of the constructive system considered explains the high levels of overheating obtained in the summer and underheating in the winter (Table 8). Comparing this solution with the reference one, a slight reduction in the discomfort by underheating is noticed, which may be due to the small increase in the thermal resistance of the envelope elements (walls and roof). However, the reduction of thermal inertia has a great influence on overheating, with values far above those recorded in the reference situation.

Table 8. Thermal discomfort—Scenario C.

Thermal Zone	Thermal Discomfort (%)	
	Winter	Summer
TZ01	31.37	22.10
TZ02	27.64	17.09
TZ03	31.28	13.14

3.2.4. Enhanced Solution

To improve the thermal performance of low thermal inertia constructive solutions, presenting a consequential risk of overheating (as noticed in the results of Scenario C), an enhanced solution containing PCM was tested. At this level, the strategy includes the use of PCM incorporated into the walls and ceilings of the constructive solution of Scenario C. PCM were applied behind the plasterboard for both constructive solutions (exterior walls and ceiling), expecting these materials to be able to buffer the temperature swing in the cooling season during the day to prevent overheating.

In the present step, the conduction transfer function (CTF) model for the algorithm of surface heat balance calculation methodology was used [46]. Figure 14 displays the simulation results for the different PCM.

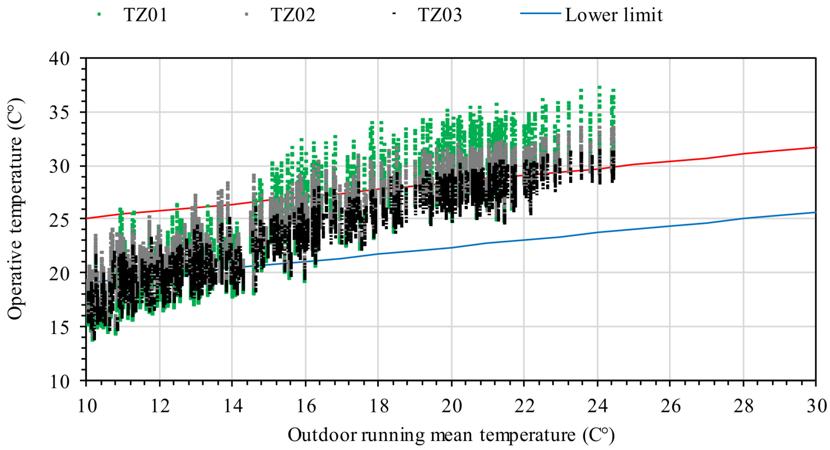


Figure 14. Thermal comfort analysis using EN16798-1 for the enhanced solution with BioPCM® M_{91}/Q_{25}_0.037.

Due to the similar results, as well as the density of the points depicted in the plot, only BioPCM® M_{91}/Q_{29}_0.037 is represented in Figure 14. However, in terms of effective discomfort values, the different melting points have different effects, as shown in Table 9. Running the simulations with PCM with different melting point values revealed that the overheating rate during the summer season decreases about 7% in all thermal zones. The results of the BioPCM® M_{91}/Q_{29}_0.037 are slightly better and, therefore, this material is a suitable option to be applied to control the overheating risk in construction associated to a low thermal inertia. Despite the improvements in overheating, the effects in underheating are almost negligible.

Table 9. Results obtained for PCM solutions with different melting point values.

Material	Thermal Zone	Thermal Discomfort (%)	
		Winter	Summer
BioPCM® M_{91}/Q_{25}_0.037	01	34.37	19.52
	02	30.26	14.64
	03	34.87	10.64
BioPCM® M_{91}/Q_{27}_0.037	01	34.44	18.50
	02	30.49	12.68
	03	35.67	7.64
BioPCM® M_{91}/Q_{29}_0.037	01	35.30	16.58
	02	30.95	10.15
	03	36.59	5.87

4. Conclusions

This research study has tackled thermal comfort evaluation due to changes in the constructive envelope solutions of a residential building. In the experimental work, scenarios representing construction solution from buildings built in 1950 until the present were evaluated, including an improved solution containing phase-change materials. The building under study was monitored during a month and results were used for dynamic model calibration purposes. Finally, the thermal comfort as well as the PCM improvements were simulated using the standard EN 16798-1. PCM was intended for indoor application of low thermal mass constructions located at warm climates, namely Southern European climates.

The whole building dynamic simulations revealed that Scenario B is the one producing worst underheating discomfort results in winter (56% more when compared with Scenario A). Although the buildings with greater thermal inertia and mass are capable of smoothing the thermal fluctuations between indoors and outdoors, they still lack thermal insulation to provide adequate thermal conditions to the occupants. In turn, this scenario is also the one generating better (lowest) overheating results (discomfort decreases almost 6 times when compared to the reference scenario) due to the effect of thermal inertia on the smoothing of temperatures. The results of Scenario C are slightly better than the reference ones in the heating season, due to the slight improvement in the thermal performance of the envelope (underheating risk reduced by 9.5%). On the other hand, the risk of overheating increases significantly (almost three-fold) due to the considerable loss of thermal inertia in the considered construction solution. The placement of PCM in these so-called "light" solutions gives the building additional inertia and mitigates the risk of overheating (10.8% considering the mean of all thermal zones), but only partially. Taking these results into account, it can be concluded that the construction is evolving towards lighter solutions and relies on solutions, such as PCM, to solve the lack of thermal inertia, providing a favorable thermal regulation effect with a significant reduction in the overheating rate. Within this study, a correct selection of the melting point of the PCM is mandatory to fully attain the charging and discharging process on a daily cycle, thus reducing overheating. Although the performance of these materials is somewhat limited and may not be enough to avoid situations of overheating, these passive materials and solutions should be highly incentivized to improve the thermal behavior of the lightweight constructions systems.

In addition, the thermal performance requirements of the building elements have evolved with effective benefits in the thermal and energy performance of the built stock. However, the increase in construction thermal resistance can produce undesirable effects that are not being properly considered, such as overheating. Therefore, countries with mild climates, such as southern European countries, must be prepared to address this issue, which may worsen as a result of climate change.

The promising results achieved can be improved with further research focusing on the optimization of the ventilation rate, which is essential to assure the fully discharging process of the PCM. Furthermore, the construction solution costs should be evaluated, aiming not solely at thermal comfort but also to optimize the energy demand. Therefore, different design solutions should be studied in the case of the new goals to cover these objectives in future research work.

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Appendix A

Table A1. Portuguese legislation on thermal and energy performance of buildings (non-exhaustive list).

Regulation	Line of Action
Decree-Law 40/90	Portuguese thermal building legislation (RCCTE) imposing requirements on the design of new buildings and large renovations.
Decree-Law 78/2006	Portuguese energy certification system and indoor air quality (SCE).
Decree-Law 79/2006	Regulation on conditioning systems in buildings (RSECE).
Decree-Law 80/2006	Regulation of buildings' thermal behavior (RCCTE).
Decree-Law 118/2013	Recast of SCE. Portuguese energy performance regulation for residential buildings (REH) and Portuguese energy performance regulation for commercial buildings (RECS).
Ordinance 349-A/2013 (amended by Ordinances 115/2015 and 39/2016)	Defines the SCE competences, regulates the activities of the SCE technicians, establishes the categories of buildings for energy certification purposes, as well as the types of pre-certificates and SCE certificates.
Ordinance 349-B/2013 (amended by Ordinances 379-A/2015, 319/2016 and 98/2019)	Defines the methodology for determining the energy performance class for the typology of pre-certificates and SCE certificates, as well as the technical and efficiency requirements of the systems for new buildings and buildings subject to large interventions.
Ordinance 349-D/2013 (amended by Ordinances 17-A/2016 and 42/2019)	Establishes the design requirements for the thermal quality and the efficiency of the technical systems of new buildings, buildings subject to large interventions and overall existing buildings.
Order 15793-I/2013 (Amended by Order 3777/2017)	Establishes the methodologies for determining the annual nominal energy requirements for space heating and cooling and for water heating as well as the global annual primary energy needs.
Order 15793-J/2013	Rules for the determination of buildings' energy class.
Ordinance 297/2019	Amends the Ordinance 349-B/2013 and establishes a special regime for refurbishment interventions in existing buildings.
Decree-Law 95/2019	Applicable regime for building refurbishment.
Decree-Law 101-D/2020	Establishes the requirements applicable to buildings to improve their energy performance and regulates the Energy Certification System for Buildings.

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