EXPERIMENTAL AND NUMERICAL SIMULATION OF THE THERMAL PERFORMANCE OF LIGHT STEEL RESIDENTIAL BUILDINGS

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ABSTRACT

In this paper the passive thermal performance of a light steel residential building is studied. A numerical model is implemented and experimentally validated. Subsequently, this calibrated model is used to assess the importance of several parameters (ventilation, internal gains, overhangs shading, windows shade devices and glazing) in the thermal performance of this building. It is concluded that a calibrated numerical model can effectively be used to define a control strategy to optimize the thermal performance of light steel residential buildings, coupled with automatic control of ventilation, shading and insulation levels, with minimum energy input (near-passive condition).

Keywords: Energy efficiency, Thermal performance, Light steel, Residential buildings

INTRODUCTION

Sustainable development is nowadays one of the major concerns of humankind. As it is widely known, sustainable development has three pillars: economic, social, and environmental. Given the recent climate changes, global warming, polar ice melting and sea level rise, the governments and policymakers are more conscious of the importance of the environmental protection requirements. The *Intergovernmental Panel on Climate Change* (IPCC, 2007) established scientific-based scenarios for climate change for the next 100 years that globally predict increases of the global mean air temperature in the range of 2.0 to 4.5ºC. Carbon dioxide is the most important anthropogenic greenhouse gas and its emissions have grown since pre-industrial times, with an increase of 70% between 1970 and 2004. Fossil fuel use is the primary source of the increased atmospheric concentration of carbon dioxide since the pre-industrial times. Besides the environmental sustainability problems, the burning of fossil fuels is not sustainable also from the economic point of view, since it is a non-renewable source of energy leading to a significant increase in the prices while the reserves go down, as happened recently in the first half of 2008.

According to the United Nations Environmental Programme (UNEP, 2007), the building sector accounts for 36% of all energy use in Europe, while residential buildings account for 27.5%. In general terms, four major categories of residential energy consumption can be identified: heating, cooling, lighting and other. It has been proven that the share of energy consumption necessary to satisfy thermal comfort criteria (heating and cooling) is substantial and ranges from 55% to 74%, depending on the climatic region. Pérez-Lombard et al. (2008) performed a review on buildings energy consumption and concluded that "*Energy consumption of buildings in developed countries comprises 20–40% of total energy use and is above industry and transport figures in EU and USA.*" Furthermore, there is a growing need to improve people's standards of comfort, also in the thermal domain. Therefore, immediate action in the building sector is essential in order to avoid hazardous climate change.

The European Commission adopted the Energy Performance Building Directive (EPBD) 2002/91/EC of 16 December 2002 introducing the obligation of energy certification of buildings and revealing the European Union concerns about this issue, *"Increased energy efficiency constitutes an important part of the package of policies and measures needed to comply with the Kyoto Protocol and should appear in any policy package to meet further commitments."* However, there are researchers that state that this factor is not enough since it only regards the operational energy consumed in buildings, neglecting other phases of the life cycle, i.e. the embodied energy (Szalay, 2007).

In fact, given the vital importance of climate change and the major impact of buildings energy consumption on it, many researchers are actively addressing this subject. In Sweden, Adalberth (1997a) suggested a methodology for a life-cycle energy analysis and applied it to three prefabricated single-unit dwellings (Adalberth, 1997b). He found that 85% of total energy usage is required during the management phase leading to conclude that is essential to produce dwellings that require small amounts of energy during this phase. A Canadian research (Cole, 1999) examined the embodied energy and greenhouse gas emissions associated with the on-site construction of alternative structural building assemblies based in different materials: wood, steel and concrete. Significant differences were found between the energy and greenhouse gas emissions associated with the construction of these structural assemblies, with concrete typically involving higher quantities.

Numerical simulations of the energy performance of buildings are crucial at the design stage allowing to address several scenarios that help finding the most efficient solutions for energy conservation. In the last decades, a large number of building energy simulation programs have been enhanced and developed. Recently, Crawley et al. (2008) presented an overview of twenty major building energy simulation programs comparing its features and capabilities in fourteen different categories. They concluded that *"there was a relatively new level of attention and interest in publishing validation results"*. EnergyPlus, version 1.2.2 (2005), was one of the computer software packages for simulating building energy consumption that was analysed.

Independently of which software is used, it is necessary to compare the simulation results with real measured data, allowing to verify the accuracy of the predictions and, if necessary, to calibrate the model. Tronchin and Fabbri (2008) compared the energy performance simulation results of an Italian single family house, using three different software models, with the real energy consumption. They found significant differences between the predictions provided by these numerical tools. Pan et al. (2007) studied the energy performance of a high-rise commercial building in Shanghai (China) using a calibrated DOE-2 energy model. The calibration of the model was based on the comparison between simulation results and *in situ* building measured energy use. Using the calibrated model it was possible to achieve a more accurate evaluation of the building energy savings with the energy conservation measures to be implemented in the retrofitting project.

Felippín et al. (2008) studied the energy improvement of a conventional dwelling in Argentina through thermal simulation. Initially, they compared the predicted results with *in situ* monitored values obtained inside several dwellings of this single family house. Then, several refurbishment measures related with passive solar heating, envelope thermal insulation and shading devices were simulated. These changes allowed predicting around 66% of energy consumption savings for heating and about 54% for cooling.

In Portugal, the most popular external wall system in buildings consists of masonry walls constituted by a double pane brick walls with an air gap between, containing the thermal insulation: expanded (EPS) or extruded (XPS) polystyrene (CIB, 2007). The most popular brick materials are clay units, horizontally perforated, which represent more than 90% of the units used in walls. However, this type of solution presents several drawbacks (CIB, 2007), from problems at design and construction stages and also some special difficulties, e.g. cavity walls mechanically weak and incorrectly constructed, singular points around openings not studied, among others. Lightweight steel construction provides an alternative with some interesting advantages: light weight, exceptionally solid in relation to weight, excellent stability of shape in case of humidity, rapid on-site erection, easy to prefabricate and present considerable potential for the recycling and reuse of all the materials used (LSK, 2005).

Despite having some advantages over the traditional masonry wall system, cold formed steel framed walls are not currently well disseminated and studied, particularly in Portugal. In this paper, the thermal performance of a Portuguese light steel single-family residential building is analysed. With this goal, the authors monitored the main functional compartments of a real light steel residential house (case study) built in Portugal under real conditions of use during the summer/autumn period under passive thermal conditions. A detailed numerical model was implemented using the EnergyPlus (2008) software to simulate the thermal behaviour of this dwelling. The comparative analysis of prediction and measurement results is performed for two distinct periods: occupied and unoccupied house. Finally, using the calibrated numerical model of the building, a parametric study was carried out to assess the importance of some parameters in the thermal performance of this light steel residential building: ventilation, internal gains, overhangs shading, windows shade devices and glazing.

CASE STUDY: LIGHT STEEL RESIDENTIAL BUILDING

General Description

The case study focuses on a single-family dwelling (four occupants) with 2 main floors, with an area of 165 m^2 each, and a smaller top floor with an area of 115 m^2, as illustrated in Figure 1. This residential building is located in Aveiro, Portugal, near the Portuguese Atlantic coast (Figure 2).

Figure 1. *Front view and rear view of the dwelling.*

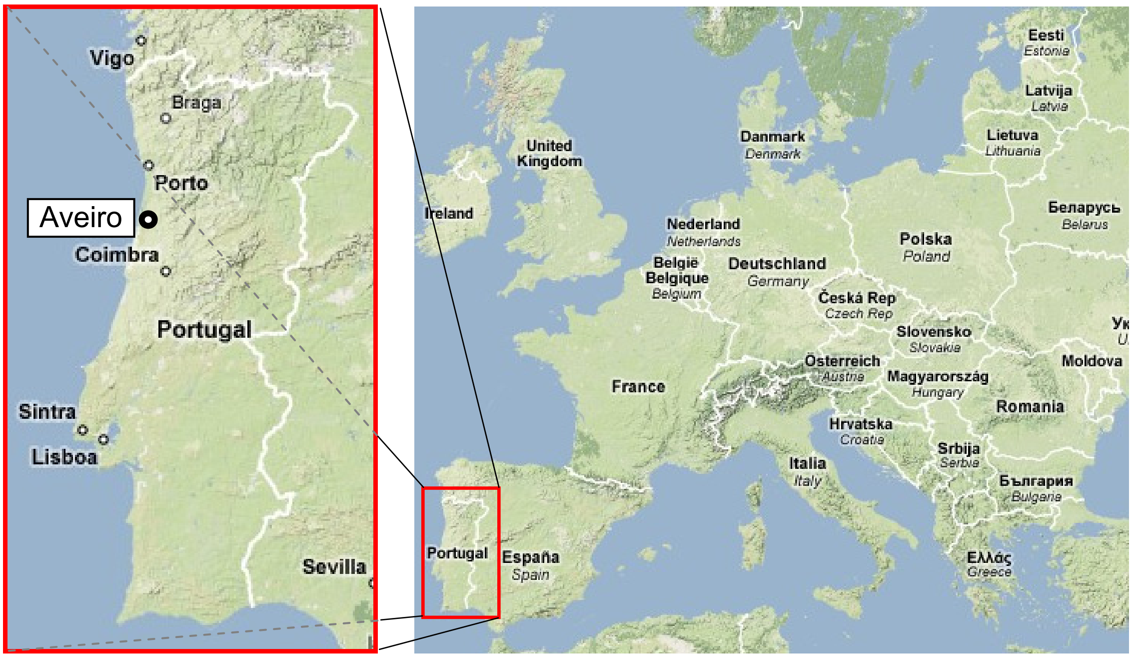


Figure 2. *Location of the case study site: Aveiro, Portugal.*

The total internal net space is 361 m^2. The ground floor comprises a living-dining room, a small office, a kitchen, a small pantry, two bathrooms, corridor and stairs (Figure 3). The first floor has 4 bedrooms, 4 bathrooms and stairs. The top floor has one master office and one bathroom. The main facade of the house faces south.

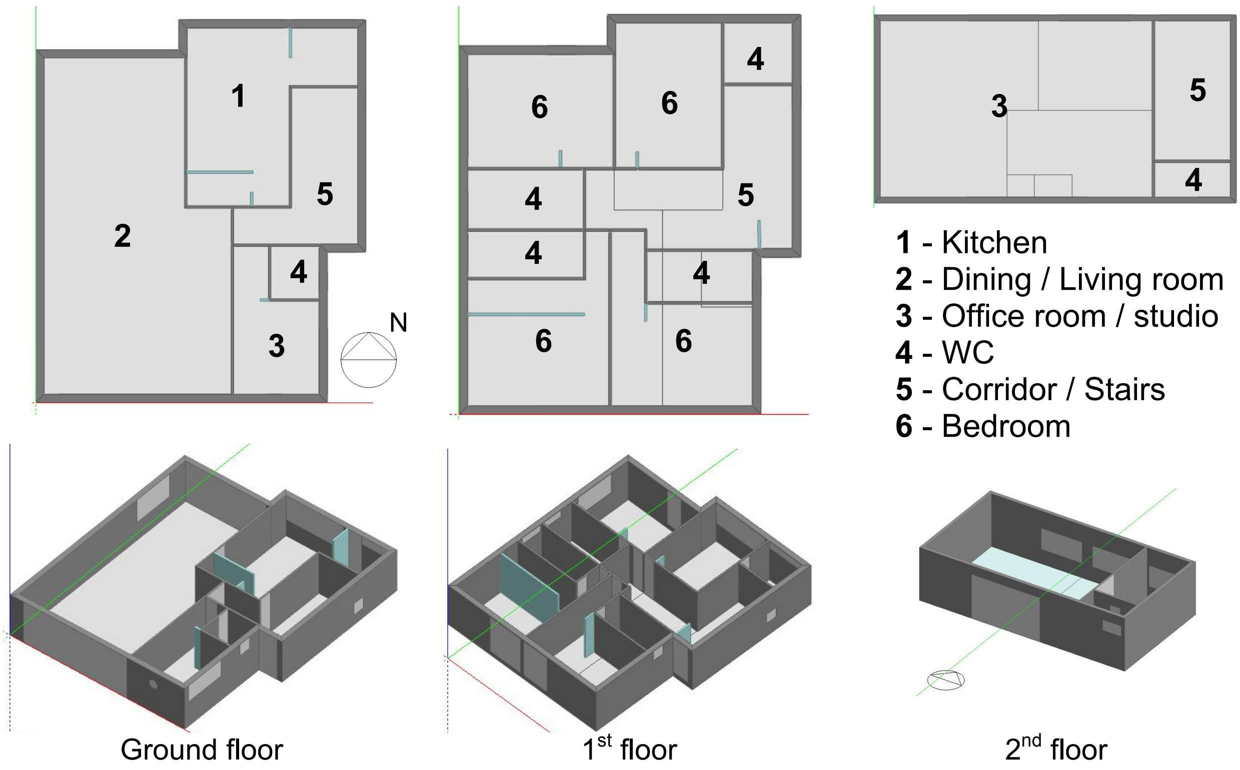


Figure 3. *Layout of the floors.*

The structure of this building consists of cold formed steel profiles. The external walls are made of a 33 mm thick Exterior Insulation and Finish System (EIFS), an outside layer of Oriented Strand Board (OSB) panels, 11 mm thick, and an inside layer of gypsum boards with a thickness of 15 mm. The gap between the two panels is filled with rock wool 140 mm thick. The internal walls are made of gypsum boards with a thickness of 15 mm and a layer of rock wool with a thickness of 70 mm.

The slabs are constituted by a wooden flooring (10 mm), over a 100 mm lightweight concrete, above the OSB composite panels (15 mm), with a 100 cm air gap and an intermediate layer of rock wool 70 mm thick, and a bottom layer of gypsum boards 15 mm thick. In the ground floor there is wooden flooring (20 mm) over a concrete paviour (120 mm), a layer of gravel (150 mm) and a tile bedding (200 mm).

The terrace is made of a top layer of ceramic tiles (10 mm) over a lightweight concrete (40 mm), above an OSB panels 18 mm thick, an air gap (100 mm) and an intermediate layer of rock wool 140 mm thick, and a bottom layer of gypsum board 15 mm thick. The roof is constituted by ceramic tiles (15 mm) above the 11 mm thick OSB layer, an air gap (100 mm) and an intermediate rock wool layer (140 mm), and a bottom layer of gypsum boards (15 mm).

The window frames are in PVC with double pane clear glass (air) 6/14/4 mm, while the ground floor exterior doors are made of wood (35 mm thick). Table 1 indicates the geometric characteristics of the building main construction elements and the corresponding thermal properties. The thermal and optical properties of windows are presented in Table 2.

Table 1. Thermal transmittances of the building main construction components.

Construction components	Material	Thickness (mm)	U (W/m^2.°C)
External walls	Gypsum board Rock wool OSB Exterior Insulation and Finish System (EIFS)	15 140 11 33	0.218
Internal walls	Gypsum board Rock wool Gypsum board	15 70 15	0.479
Roof	Gypsum board Rock wool Air gap OSB Air gap Ceramic tiles	15 140 100 11 50 15	0.102
Terrace	Gypsum board Rock wool Air gap OSB Lightweight concrete Ceramic	15 140 100 18 40 10	0.127
Internal floor	Wooden flooring Lightweight concrete OSB Air gap Rock wool Gypsum board	10 100 18 100 140 15	0.121
Ground floor	Wooden flooring Concrete paviour Gravel Tile bedding	20 120 150 200	0.964
Doors	Wood	35	2.823

Table 2. Thermal and optical properties of windows

	U (W/m^2.°C)	Total Solar Transmission (SHGC)	Direct Solar Transmission
Double pane clear glass 6/14/4mm Air	2.733	0.723	0.648
PVC frames	3.476	----	----

Experimental Measurements

The experimental temperature measurements were carried out inside four main compartments (Figure 4): living room (ground floor), northeast and southwest bedrooms (first floor), and office studio (second floor). The temperature monitoring took place during the 2008 summer season, between July 25 and October 25. During most of this time the house was occupied by 4 persons. However, during the holiday's period of this family (August 18 to September 7) the house was closed and unoccupied.

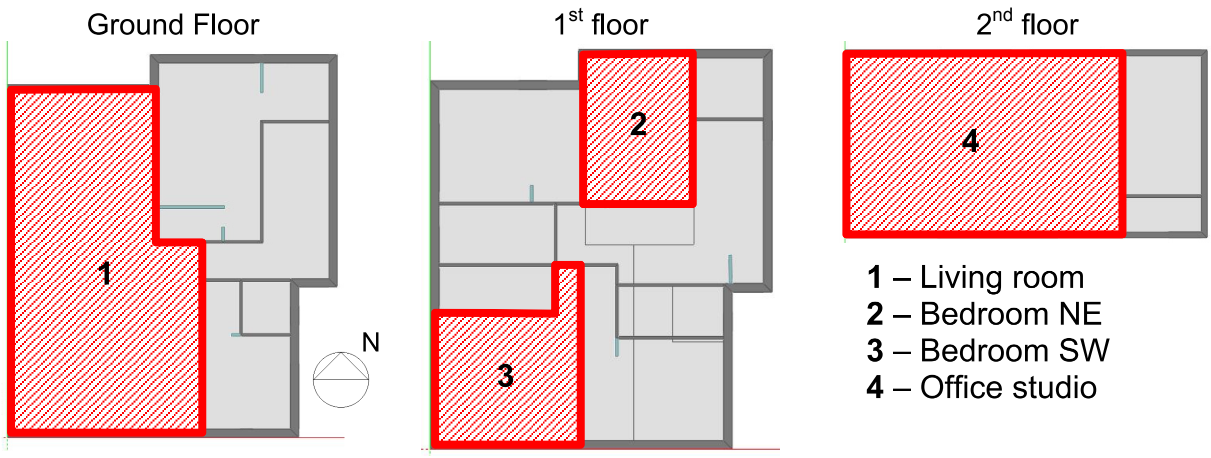


Figure 4. *Location of the instrumented compartments.*

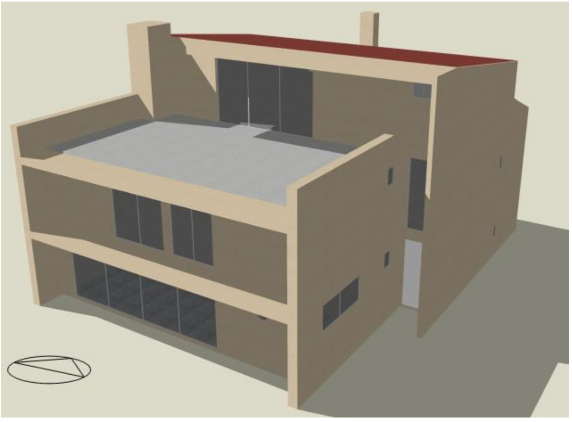
The equipment used in this experimental campaign consisted of four Tinytag Ultra 2 thermo-hygrometer loggers (model TGU-4500). The data acquisition was performed on an hourly basis. The exterior climatic conditions were obtained in the nearest meteorological station build in the same city and belonging to the University of Aveiro.

Numerical simulation of the thermal behaviour of the building

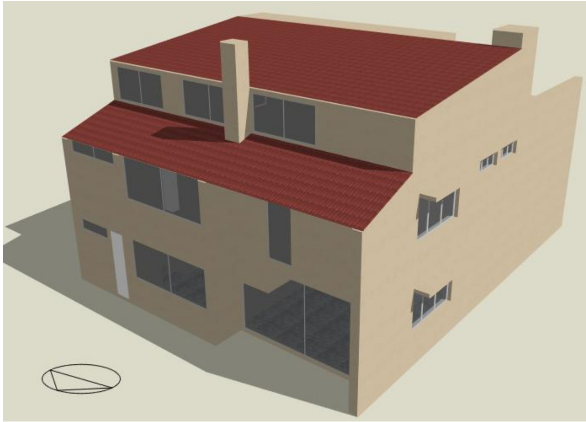
The model was implemented using the DesignBuilder (2008) software which uses the EnergyPlus (2008) software as the engine for the dynamic thermal simulation. EnergyPlus is an energy analysis and thermal load simulation program, with several important physical models and computational features, such as: integrated simultaneous solution; sub-hourly, user-definable time steps; heat balance based solution; transient heat conduction; improved ground heat transfer modelling; combined heat and mass transfer; thermal comfort models; anisotropic sky model; advanced fenestration calculations; day lighting controls; loop based configurable HVAC systems and atmospheric pollution calculations, etc. These features allow obtaining precise and realistic simulation results. EnergyPlus has been extensively validated and is rated as a reference simulation tool for dynamic thermal simulation (Crawley et al., 2008).

Modelling and analysis options

The model of the building is presented in Figure 5, where two different aerial exterior views can be seen. This model was assembled using 15 thermal zones, corresponding to the main internal partitions of the building. The ground floor has four thermal zones; the first floor has eight thermal zones, and finally the top floor has two zones (see Figure 3). The stairways and corridors form a single thermal zone common to the three floors.



a) Southern and eastern views



b) Northern and western views

Figure 5. *Elevation views of the building model.*

As previously mentioned, during the monitored period, the building was unoccupied for three consecutive weeks. During this period, no internal heat gains and no natural ventilation were considered. During the occupied period, according to the schedule supplied by the residents, presented in Table 3, it was assumed that the house was occupied by four persons with typical luminance requirements and standard internal gains.

Table 3. Occupancy schedules during weekdays (WD) and weekend (WE) for main compartments: Liv – Living room; Kit – Kitchen; Bed – Bedroom; Bat – Bathroom.

Hour	% of maximum for each profile							
	LivWD	LivWE	KitWD	KitWE	BedWD	BedWE	BatWD	BatWE
0-1	0	0	0	0	100	100	0	0
1-2	0	0	0	0	100	100	0	0
2-3	0	0	0	0	100	100	0	0
3-4	0	0	0	0	100	100	0	0
4-5	0	0	0	0	100	100	0	0
5-6	0	0	0	0	100	100	0	0
6-7	0	0	0	0	100	100	0	0
7-8	0	0	0	0	75	100	25	0
8-9	0	0	25	0	25	100	50	0
9-10	0	0	75	25	0	50	25	25
10-11	0	25	0	50	0	0	0	25
11-12	0	50	0	50	0	0	0	0
12-13	0	50	0	0	0	0	0	0
13-14	0	0	0	50	0	0	0	0
14-15	0	25	0	25	0	0	0	0
15-16	0	50	0	0	0	0	0	0
16-17	0	50	0	0	0	0	0	0
17-18	50	50	0	0	0	0	0	0
18-19	25	25	25	25	0	0	0	0
19-20	0	0	100	50	0	0	0	0
20-21	50	25	25	75	0	0	25	0
21-22	50	25	25	25	0	0	0	0
22-23	50	50	0	0	0	0	0	0
23-24	0	0	0	0	100	100	0	0

The natural ventilation rate was 0.6 air changes per hour (minimum value imposed by the Portuguese code [RCCTE, 2006]). The North East bedroom was unoccupied, while the South West bedroom was occupied by the married couple and the other two rooms were occupied by the children. The exterior climatic conditions were simulated using the weather data obtained in the University of Aveiro meteorological station. The simulations were performed on an hourly basis. A comparative analysis of the results obtained experimentally and predicted by the DesignBuilder model is presented in the following section.

COMPARATIVE ANALYSIS OF RESULTS

Unoccupied Period

In this section, the results obtained during the first week of September 2008 are presented. In this period the house was unoccupied. Figure 6 shows the outside dry bulb temperatures, as well as measured and predicted inner air temperatures in the following compartments: the living room on the ground floor; the two bedrooms (NE and SW) on the first floor; and the office studio on the second floor.

As expected, this house exhibits a good thermal behaviour showing small air temperature fluctuations inside the monitored compartments when compared to the outside fluctuations. There is a good agreement between the predictions and the measurements inside the living room (Figure 6a) and in the office studio (Figure 6d). However, the predictions exhibit lower temperatures when compared with the measured temperatures in the bedrooms (Figures 6b and 6c). Table 4 shows the root mean square error (RMSE) and

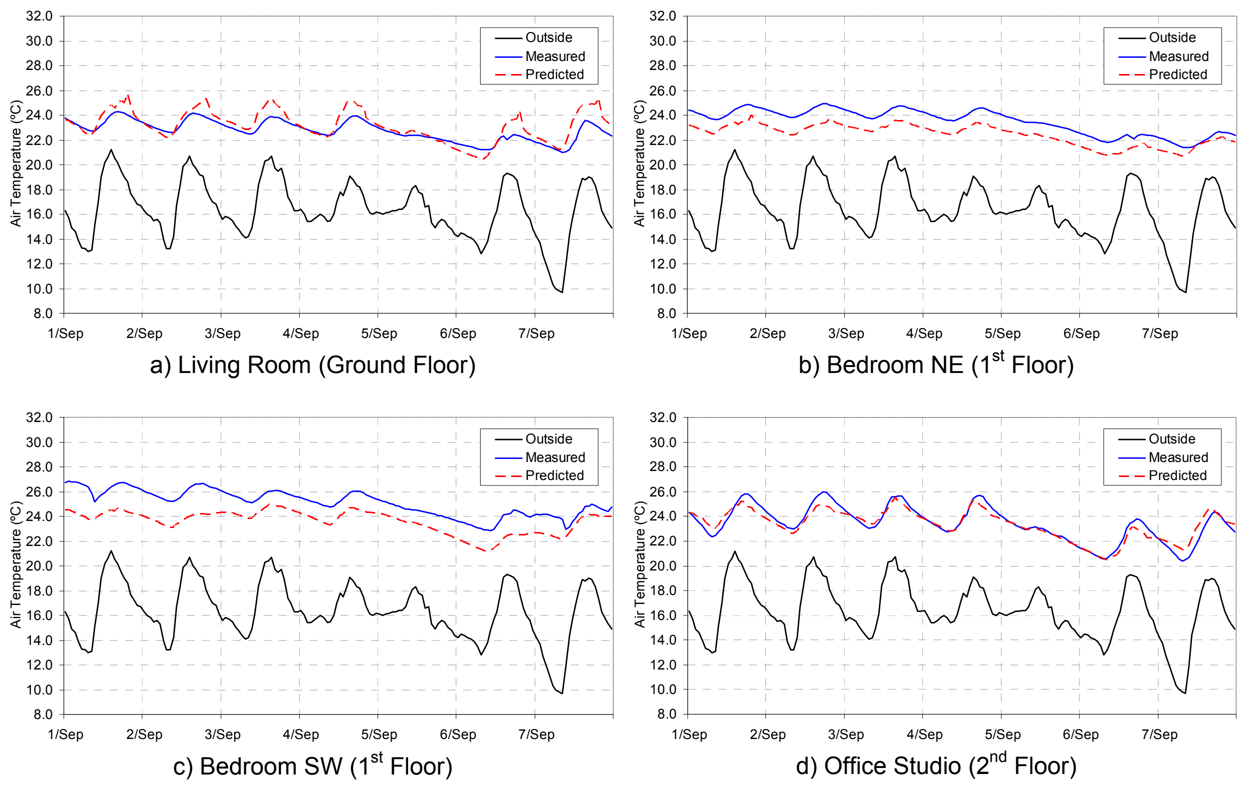


Figure 6. *Temperature variation inside the main compartments: unoccupied period.*

the mean temperatures (MT) for each compartment. The best agreement between the air temperature measurements and the predictions occurs in the office studio (RMSE = 0.5ºC) while the worst agreement take place in the SW bedroom (RMSE = 1.6ºC). During this period, the coolest compartment was the living room with a mean temperature of 22.8ºC, while the hottest was the SW bedroom (MT = 25.1ºC), with an average air temperature 2.3ºC higher.

Table 4. Root mean square error (RMSE) and mean temperature (MT) measured and predicted inside main dwellings (1/Sep – 7/Sep).

		RMSE (ºC)	MT (ºC)		RMSE (ºC)	MT (ºC)
Living Room	Measured Predicted	0.7	22.8 23.1	**Bedroom NE**	1.1	23.5 22.4
Bedroom SW	Measured Predicted	1.6	25.1 23.6	**Office Studio**	0.5	23.4 23.3

Occupied Period

The air temperature results obtained between 4th and 10th August (occupied period) are presented next and are illustrated in Figure 7 and Table 5. As for the previous case, the best agreement between the air temperature predictions and the measured data was observed in the ground and top floor compartments (RMSE = 0.7ºC), closely followed by the NE bedroom (RMSE = 0.8ºC) and by the SW bedroom (RMSE = 1.0ºC). The living room and the SW bedroom also remain the coolest and the hottest dwellings with a recorded mean air temperature of 23.6 and 25.5ºC, respectively. This trend was also predicted by the

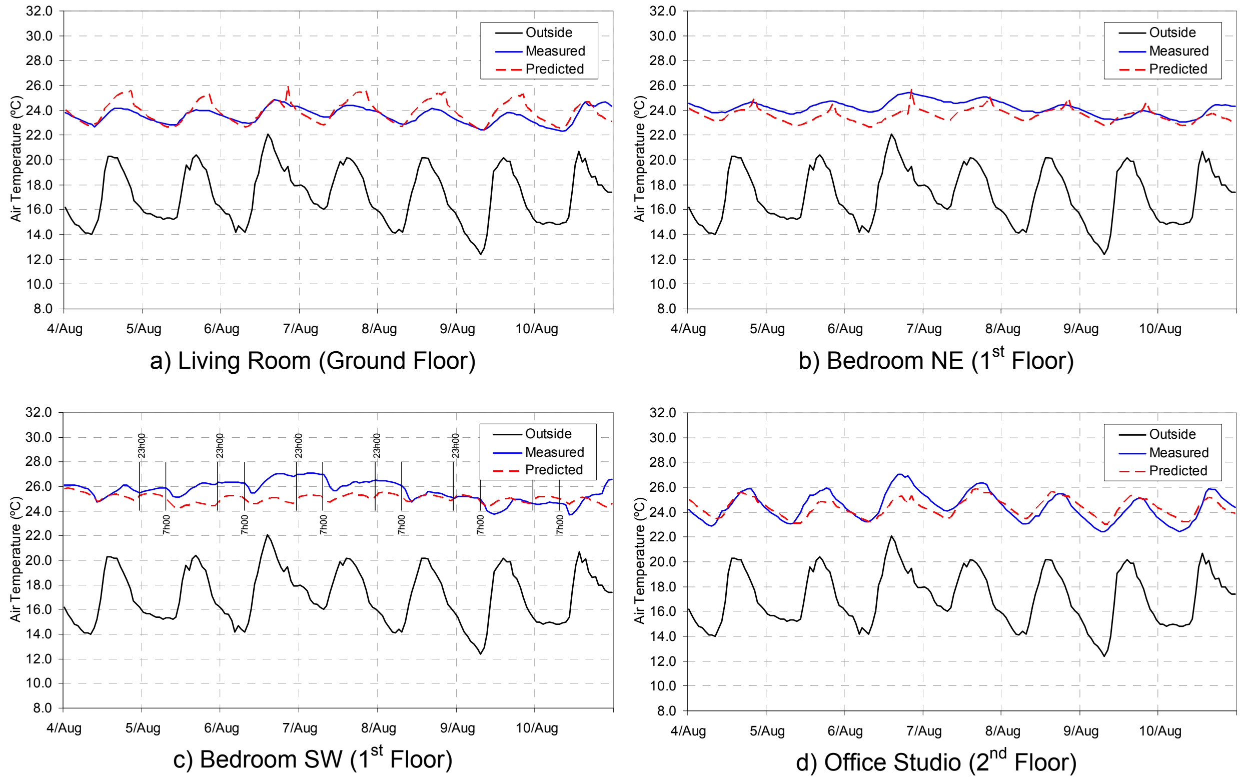


***Figure 7.** Temperature variation inside the main compartments: occupied period.*

DesignBuilder model and may be justified by two factors: (1) the higher thermal inertia in the ground floor (lower temperatures); and (2) by the solar heat gains in the bedroom window south oriented and by the reduced thermal loss given the interior confinement of the slab pavement and two interior partition walls (higher temperatures).

By comparing the variation of air temperature between the unoccupied and the occupied period in the master bedroom (figures 6c and 7c), it is possible to observe irregular fluctuations (not driven by the exterior temperature) during the occupied period (Figure 7c). In fact, at night there is a systematic interior air temperature increase around 23h, 24h, when the couple goes to bed and closes the bedroom. In the morning, around 7h, there is a systematic temperature fall when they wake-up and ventilate the room. As expected, these features were not observed for the unoccupied period (Figure 6c), where the inside air temperature follows more closely the trend of the outside temperature.

Table 5. Root mean square error (RMSE) temperature differences and mean temperature (MT) measured and predicted inside the main compartments (4/Aug – 10/Aug).

		RMSE (ºC)	MT (ºC)		RMSE (ºC)	MT (ºC)
Living Room	Measured Predicted	0.7	23.6 23.8	**Bedroom NE**	0.8	24.2 23.6
Bedroom SW	Measured Predicted	1.0	25.5 25.5	**Office Studio**	0.7	24.4 24.4

PARAMETRIC STUDY

Introduction

In order to analyse the importance of certain variables in the thermal performance of the building, a parametric study was carried out using the calibrated numerical model described previously.

The climate in the Aveiro region is strongly influenced by the proximity of the Atlantic Ocean and presents relatively constant conditions during the warmer half of the year (mid-spring – summer – mid-autumn season). In order to cover the range of climatic conditions for this period, the parametric study considers three distinct climatic records: an average situation represented by the first week of September and two additional situations: maximum and minimum conditions, approximately corresponding to a period of return of one week every year. Figure 8 illustrates the three climatic scenarios.

In addition, in order to reduce the level of uncertainty associated with the presence of the residents, the parametric study was performed assuming unoccupied conditions. The following parameters were considered: ventilation, internal heat gains, overhangs shading, windows shade devices and glazing. Table 6 describes the adopted twelve scenarios.

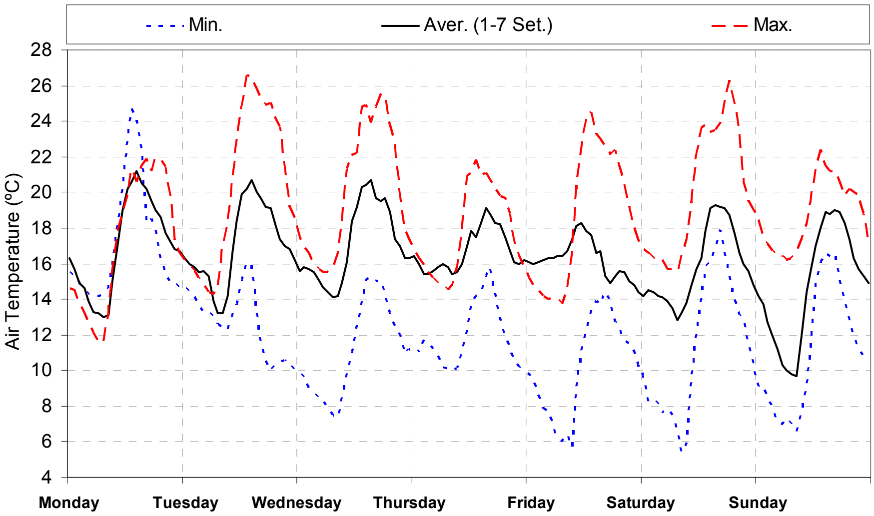


Figure 8. *Adopted climatic scenarios.*

Table 6. Definition of different scenarios.

Parameters	Scenarios	Description
Reference	Scenario 1	Reference scenario: unchanged calibrated model (unoccupied period)
Ventilation	Scenario 1	0.0 air changes per hour
	Scenario 2	0.6 air changes per hour
	Scenario 3	1.2 air changes per hour
Internal Heat Gains	Scenario 1	No internal heat gains
	Scenario 4	4.0 Watts per square meter
	Scenario 5	8.0 Watts per square meter
Overhangs Shading	Scenario 1	All overhangs of the calibrated model
	Scenario 6	No overhangs
	Scenario 7	No horizontal overhangs (only vertical overhangs)
	Scenario 8	No vertical overhangs (only horizontal overhangs)
Window Shading Devices	Scenario 1	Interior medium translucent shade roll
	Scenario 9	No shade devices
	Scenario 10	Exterior medium translucent shade roll
Windows Glazing	Scenario 1	Double pane clear glass 6/14/4mm air
	Scenario 11	Single pane clear glass 6mm
	Scenario 12	Double pane low-emissivity electrochromic glass reflective bleached 6/13/6mm argon

The values obtained for the twelve scenarios and three climatic conditions in terms of mean temperature (MT) and standard temperature deviation (STD) in each room are presented in Annex A. These results are discussed and presented in more detail in the following sub-sections. First, each parameter will be analysed individually for the average climatic scenario (first week of September) and for each main functional compartment. Subsequently, an overview of all scenarios will be performed for all building and for the three climatic conditions.

Ventilation

Unintentional air infiltration due to imperfections in the building envelope (e.g. cracks and joints) and intentional natural ventilation (e.g. open windows and doors, ducts, ventilators) may have a significant influence in the thermal performance of the buildings. The effect of air renewal is simulated by means of three different simulation scenarios with distinct constant ventilation rates: 0.0, 0.6 and 1.2 air changes per hour.

As expected, given the lower outside air temperature, increasing the ventilation rate leads to a decrease of the inner temperature. The average inside temperature reduction for 0.6 ac/h rate (minimum rate imposed by the Portuguese code – RCCTE, 2006) reached 1.4ºC (-6%) in SW bedroom (Figure 9c and Table A3) and 2.3ºC (-10%) doubling this ventilation rate (Scen. 3) for average climatic conditions.

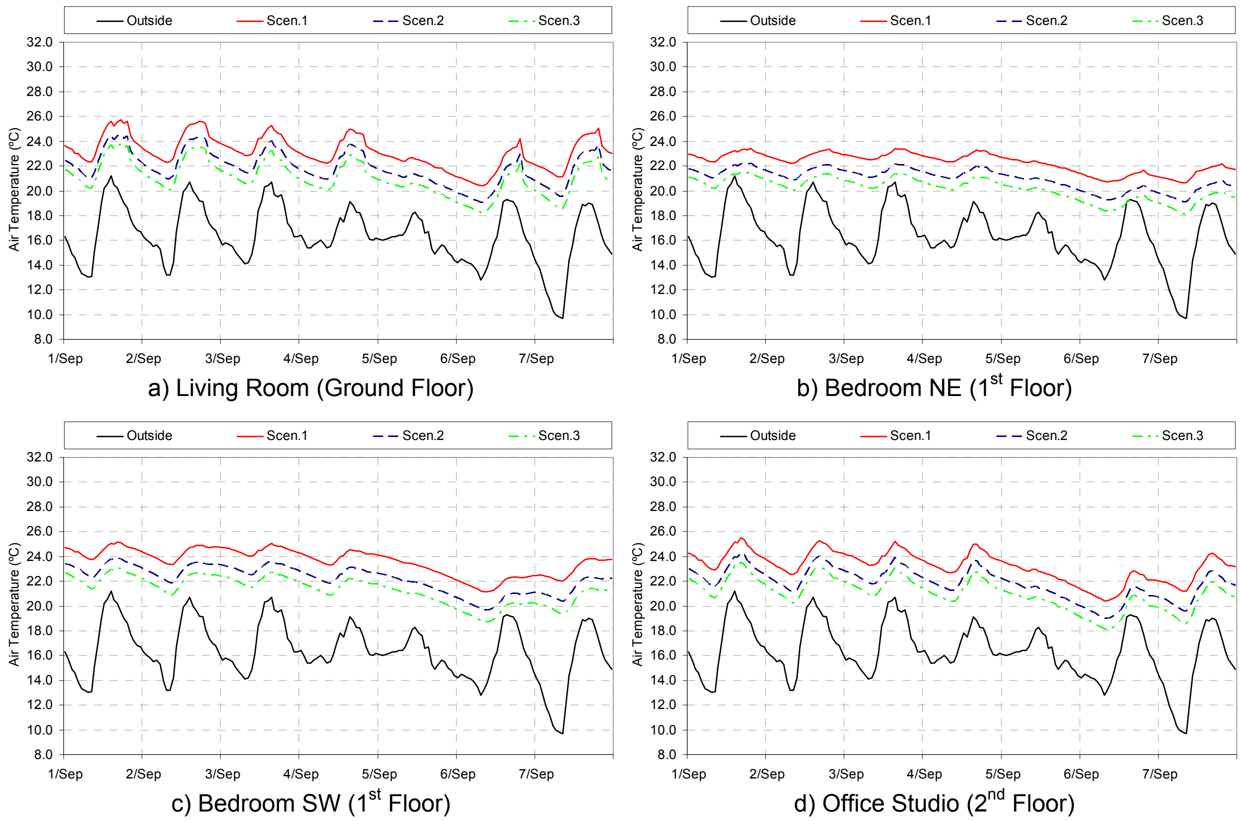


Figure 9. *Temperature variation inside main dwellings: Scen.1 - No ventilation; Scen.2 - 0.6 ac/h; Scen.3 - 1.2 ac/h.*

Internal Heat Gains

Heat gains provided by: interior lighting; office equipment; human bodies; and cooking appliances, can change the interior temperature and influence the thermal behaviour of buildings. To assess the influence of this parameter besides the reference scenario (no internal heat gains – Scen.1), two uniform heat gain rates were simulated: 4.0 W/m^2 (the value predicted by the Portuguese code – RCCTE, 2006 – for a residential house) and 8.0 W/m^2 (scenarios 4 and 5 respectively). These heat gains were considered constant over 24 hours.

Figure 10 illustrates the results for the first week of September. As expected, there is an increase in the interior temperatures (0.8ºC and 1.7ºC) for an interior heat gain rises of 4.0 and 8.0 W/m^2, respectively. These maximum temperature increases occur for both scenarios in the NE bedroom (see Table A2).

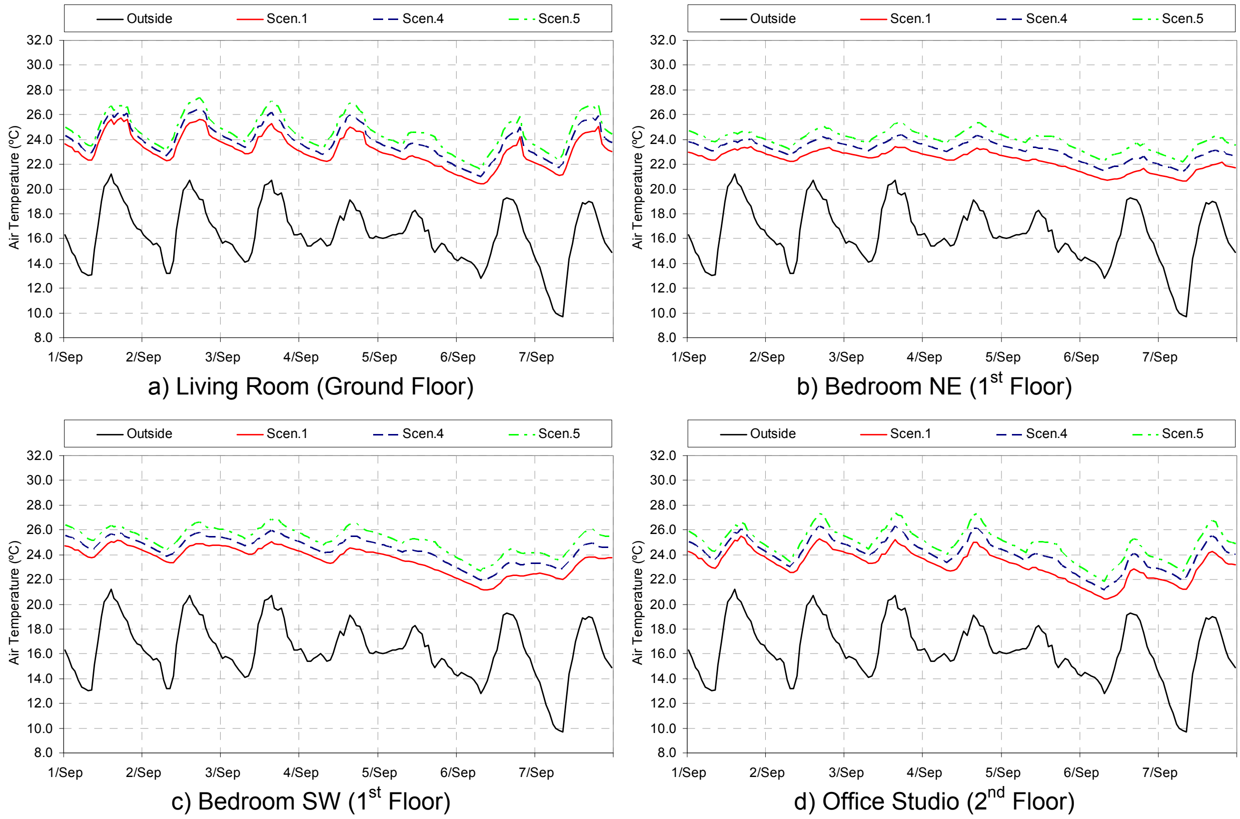


Figure 10. *Temperature variation inside main dwellings: Scen.1 - No Internal Gains; Scen.4 – 4.0 W/m^2; Scen.5 - 8.0 W/m^2.*

Overhangs Shading

Solar heat gains through the windows and doors glazing may have a considerable impact in the thermal performance of buildings, particularly in facades exposed South and West (north hemisphere). In the others facades, the solar gains are lower but also exist, even in a northern orientated glazing due to diffuse radiation. Solar heat gains may have a positive or a negative influence on the thermal performance of a building: in the heating season, they may reduce the heating energy demand; however, in the cooling season the opposite happens due to the possibility of overheating of the building. Therefore it is very important at the design stage to correctly define the glazed openings dimension, exposure and shading strategy.

In this section, the effect of exterior shading provided by overhangs in the thermal performance of the case study residential house is assessed. Figure 11 illustrates the results obtained for three different scenarios besides the reference one (all overhangs – Scen.1): no overhangs (Scen. 6); no horizontal overhangs (Scen. 7); and no vertical overhangs (Scen. 8). As before, the mean temperatures and standard temperature deviation values for these scenarios are presented in Annex A. As expected, when there are no overhangs (Scen.6) the mean temperature in this building increases by up to 4.4ºC (+19%) as predicted for the SW bedroom (Figure 11c, Table A3). However, the importance of vertical and horizontal overhangs is not the same, the latter being more efficient. When the shade is provided only by horizontal overhangs (Scen.8) the temperature increases only 0.5ºC (+2%) at SW bedroom, while in scenario 7 (only vertical overhangs) the temperature raises 3.9ºC (+17%) in the same dwelling.

Besides the overhangs geometry, the importance of the glazed openings orientation is also illustrated in these results. In the NE bedroom (Figure 11b), with a north exposed window, the increase of temperature is lower and there is no significant increase in the daily thermal amplitude, given the glazing exposition to only diffuse solar radiation. The absence of horizontal overhangs clearly leads to the overheating of the dwellings near midday, particularly when there are south exposed windows, significantly overcoming the summer comfort temperature (25ºC) fixed by the Portuguese code (RCCTE, 2006).

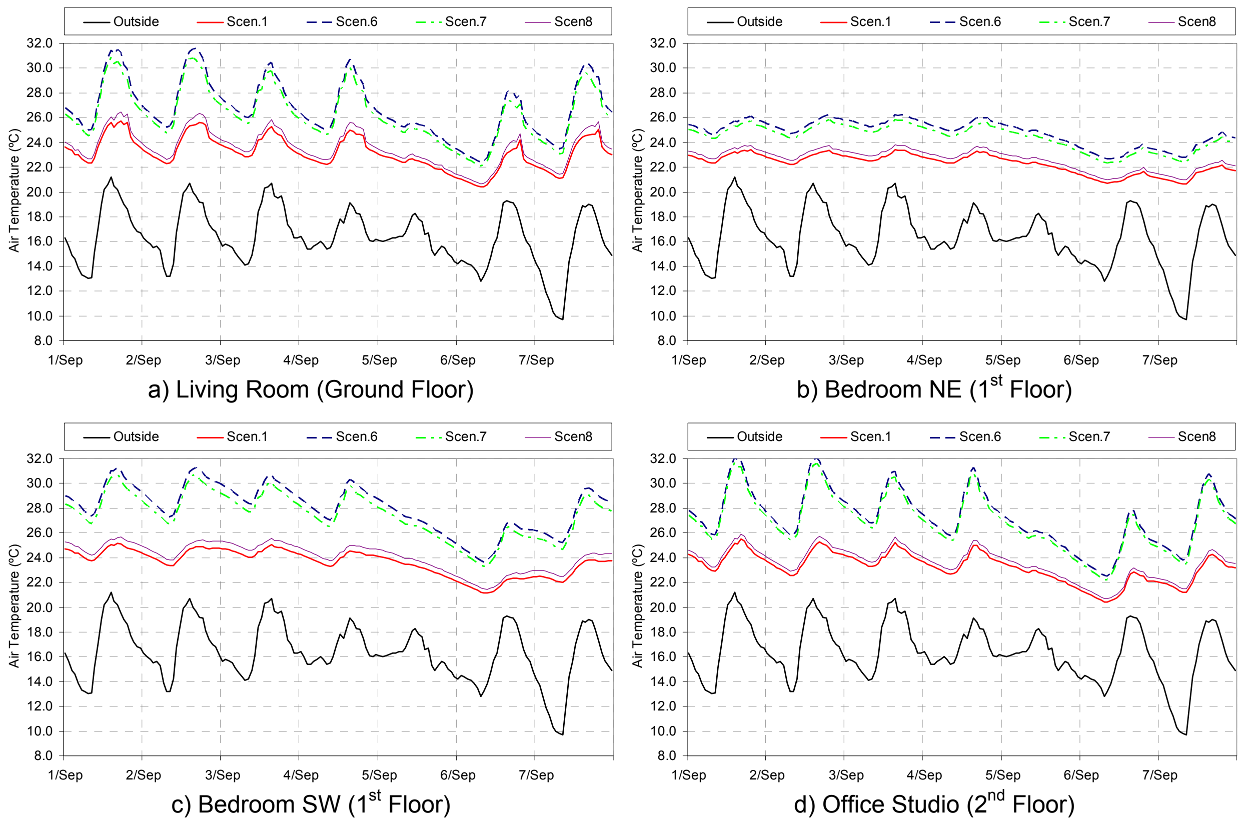


Figure 11. *Temperature variation inside main dwellings: Scen.1 - All overhangs; Scen.6 - No overhangs; Scen.7 - No horizontal overhangs; Scen.8 - No vertical overhangs.*

Windows Shading Devices

Besides the fenestration shading provided by overhangs, some times is very useful to use windows shading devices, e.g. shade rolls, venetian blinds, drapes and curtains, in order to control daylight and solar gains. In this section, the importance of the windows shading devices in the thermal performance of this light steel residential building is studied. Three different shading devices scenarios were modelled: interior medium translucent shade roll (Scen.1 – reference case); no shading devices (Scen.9); and exterior medium translucent shade roll (Scen.10). Figure 12 shows the results. When there is no windows shading devices (Scen.9) the mean temperature increases 0.6 and 0.8ºC in the bedrooms even with the exterior shading provided by the overhangs. When the shade roll is placed externally (Scen.10) the thermal efficiency increases resulting in an average decrease of 1.7ºC in the temperature predicted inside the living room of the ground floor (Figure 12a, Table A1).

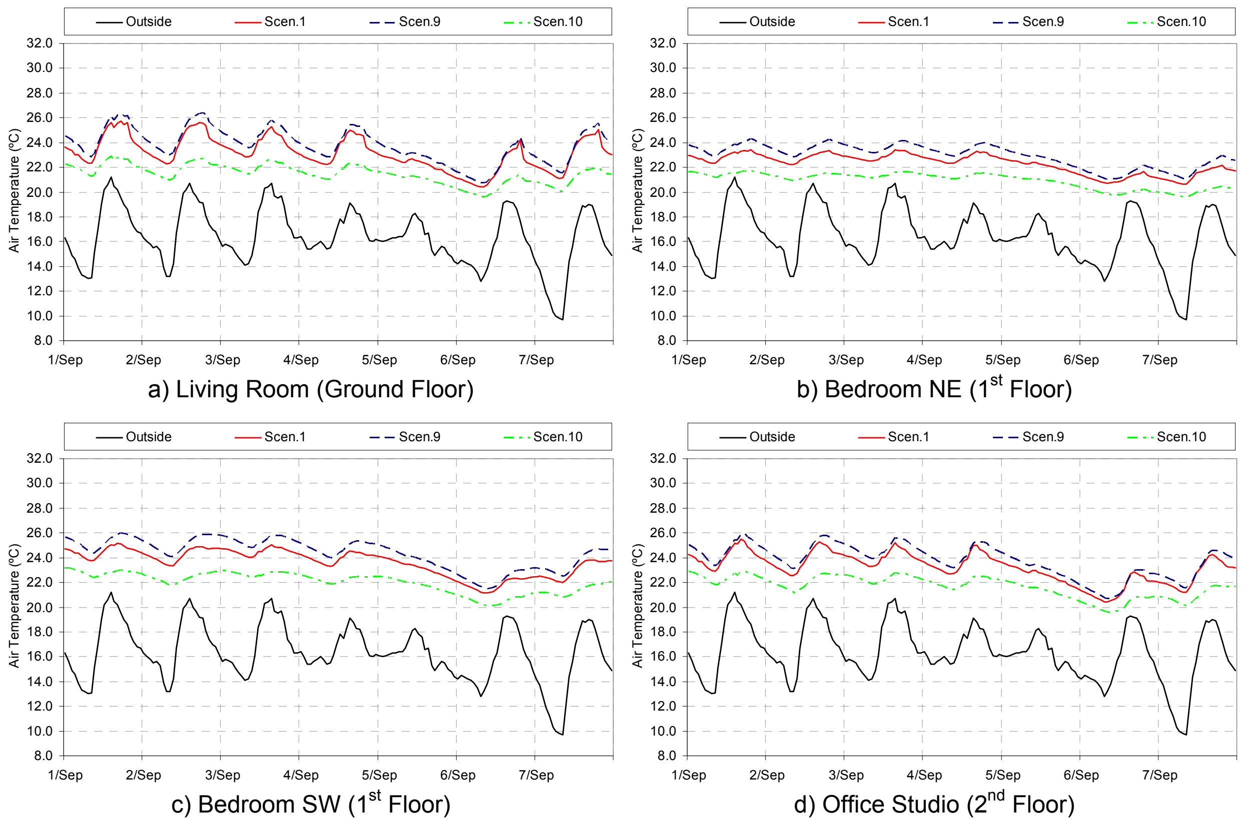


Figure 12. *Temperature variation inside main dwellings: Scen.1 - Interior medium translucent shade roll; Scen.9 - No shade devices; Scen.10 - Exterior medium translucent shade roll.*

Windows Glazing

As already observed in this work, an important amount of heat could be lost or gained trough the glazed openings. Therefore, besides adequate shading, it is essential to select windows with adequate thermal and optical properties. In this section, the importance of windows glazing properties in the thermal performance of this case study residential building is analysed. Three different windows glazing scenarios were modelled, namely: double pane clear glass 6/14/4mm air (Scen.1 – reference case); single pane clear glass 6mm (Scen.11); and double pane low-emissivity electrochromic glass reflective bleached 6/13/6mm argon (Scen.12). The thermal and optical properties of these glazed windows are presented in Table 7. All window frames have the same geometry and are constituted by the same material (PVC). The obtained results for each scenario are presented in Figure 13.

Table 7. Thermal and optical properties of windows for different scenarios.

		U (W/m^2.°C)	Total Solar Transmission (SHGC)	Direct Solar Transmission
Scen.1	Dbl Clr 6/14/4mm Air	2.733	0.723	0.648
Scen.11	Sgl Clr 6mm	6.121	0.810	0.775
Scen.12	Dbl LoE Elec Ref Bleached 6/13/6mm Arg	1.322	0.425	0.322

The worst performance glazing window (Scen.11) leads to a decrease on the mean temperature (0.8ºC in the living room), as a result of the lower outside temperature and the higher heat loss through the windows. In scenario 12 (higher glazing performance) the average temperature slightly decreases (0.1 and 0.2ºC). However, the daily temperatures amplitude decreases given the lower solar transmission, leading to a decline in the maximum temperatures.

An additional scenario was modelled based on scenario 1 (Dbl Clr 6/14/4mm), with argon gas filling the gap between the glass panes instead of air. The differences found in the thermal performance of this building using this gas types (air/argon) were not significant (not illustrated).

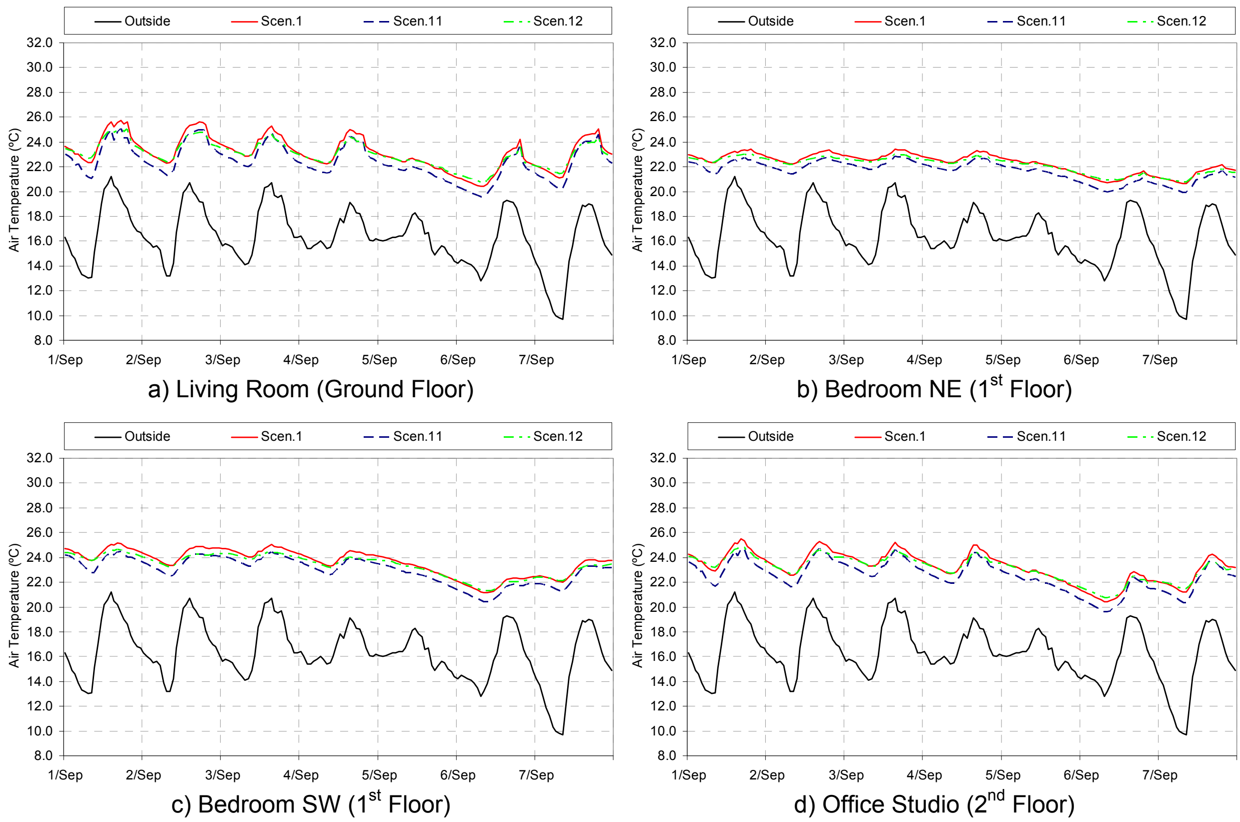
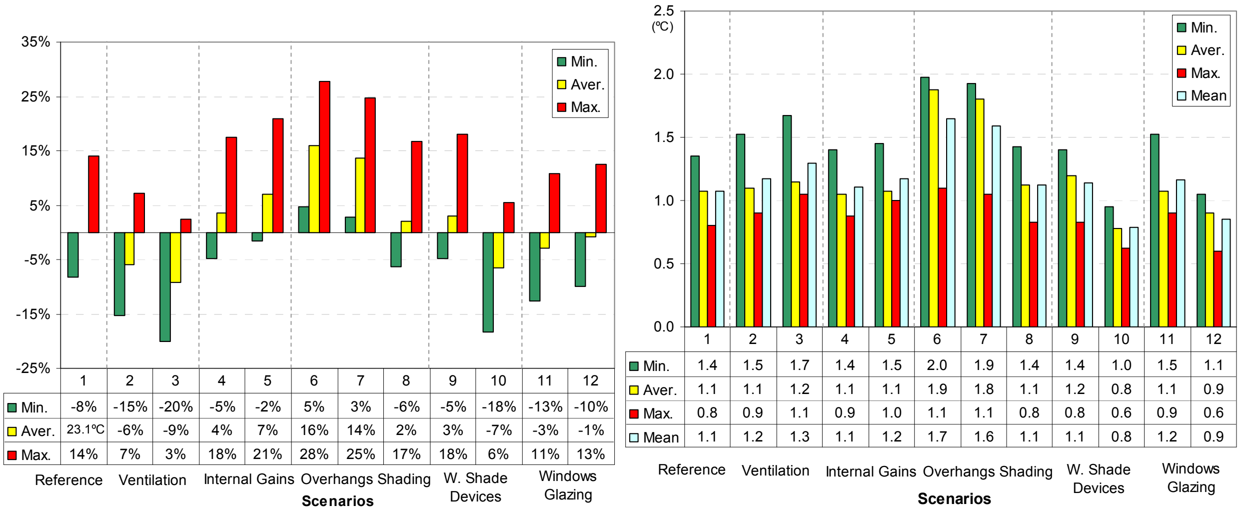


Figure 13. *Temperature variation inside main dwellings: Scen.1 - Dbl Clr 6/14/4mm Air; Scen.11 - Sgl Clr 6mm; Scen.12 - Dbl LoE Elec Ref Bleached 6/13/6mm Arg.*

Results Overview

Figure 14 summarizes the results for the twelve scenarios and three climatic conditions in terms of mean temperature differences and standard temperature deviation. The values presented in this figure are not for a single compartment but for whole house and were obtained by an average of the results for the analysed compartments. The percentages related to the mean temperature differences (Figure 14a) were obtained in relation to the mean temperature (23.1ºC) of the reference case scenario using the average climatic conditions.



	1	2	3	4	5	6	7	8	9	10	11	12
Min.	-8%	-15%	-20%	-5%	-2%	5%	3%	-6%	-5%	-18%	-13%	-10%
Aver.	23.1ºC	-6%	-9%	4%	7%	16%	14%	2%	3%	-7%	-3%	-1%
Max.	14%	7%	3%	18%	21%	28%	25%	17%	18%	6%	11%	13%

	1	2	3	4	5	6	7	8	9	10	11	12
Min.	1.4	1.5	1.7	1.4	1.5	2.0	1.9	1.4	1.4	1.0	1.5	1.1
Aver.	1.1	1.1	1.2	1.1	1.1	1.9	1.8	1.1	1.2	0.8	1.1	0.9
Max.	0.8	0.9	1.1	0.9	1.0	1.1	1.1	0.8	0.8	0.6	0.9	0.6
Mean	1.1	1.2	1.3	1.1	1.2	1.7	1.6	1.1	1.1	0.8	1.2	0.9

a) Mean temperature differences b) Standard temperature deviation

***Figure 14.** Results of the parametric study (average temperature of all studied compartments).*

The parameter with higher influence in the thermal performance of this light steel residential building is the overhangs shading, i.e. when there is no overhangs (Scen. 6) the temperature inside the house increases 16% (+3.7ºC) for the average climatic conditions (first week of September). Ventilation (1.2 ac/h - Scen. 3) is able to reduce the temperature by 9% (-2.1ºC) assuming the same climatic conditions. The parameter with lower impact in the passive thermal performance of this dwelling was found in scenario 12 (windows glazing: double pane low-emissivity electrochromic glass reflective bleached 6/13/6mm argon) with a temperature decrease of only 1% (-0.2ºC). However these openings are already shadowed by the overhangs and by the interior translucent shade roll.

The three climatic scenarios, typical of summer/autumn for this location, originate a temperature fluctuation of about 22% (5.1ºC). For the reference case (no ventilation), with maximum temperature conditions, the summer comfort temperature (25ºC) is violated 95% of the time. However, with a ventilation of 1.2 ac/h (scenario 3), the summer comfort temperature (25ºC) is only violated 12.5% of the time. This clearly shows the relevance of adequate ventilation during the cooling season.

CONCLUSIONS

The thermal performance of a Portuguese light steel single-family residential building was analysed in this paper. A detailed numerical model was implemented using the EnergyPlus (2008) software to simulate the thermal behaviour of this dwelling. This model was calibrated and validated by comparison with the data obtained in a real light steel residential house (case study) built in Portugal under real conditions of use during the summer/autumn period under passive thermal conditions. Only the four main functional compartments were monitored. Using the previously calibrated numerical model, a parametric study was carried out to assess the importance of some parameters (ventilation, internal gains, overhangs shading, windows shade devices and glazing) in the thermal performance of this light steel residential building. Three climatic conditions were used: minimum, average and maximum exterior temperature.

The following conclusions can be stated. Firstly, the use of numerical models to simulate the real thermal behaviour of buildings is nowadays possible. User friendly and reliable dynamic simulation programs are available allowing the incorporation of advanced techniques in everyday design.

Secondly, light steel residential houses with adequate construction details may exhibit satisfactory thermal performance with minimum energy input as long as a series of parameters are adequately controlled. These include ventilation, shading and a right combination of thermal properties of the materials of the building envelop. The first two must be operated in direct dependence from the prevailing temperature and solar radiation. This implies dynamic simulation capabilities and automation, so that ventilation and shading can be instantly adjusted to achieve optimal thermal conditions. In addition, because of the lower thermal inertia of the building, coupled with good insulation of the building envelop, the building verifies the comfort targets for the summer season under almost passive conditions.

Current work is progressing to define strategies for optimal operation of light steel residential buildings and the verification of winter temperature conditions.

ACKNOWLEDGEMENTS

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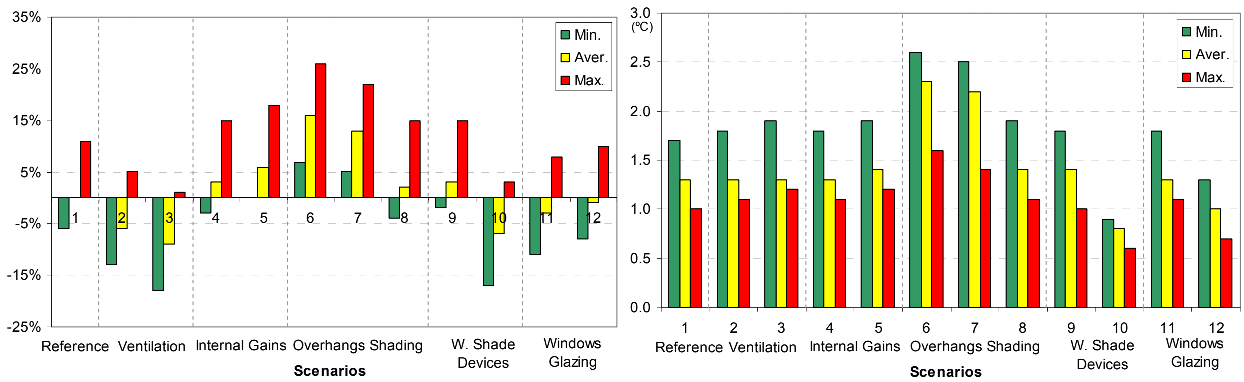
ANNEX A

Table A1. Standard temperature deviation (STD) and mean temperature (MT) inside Living Room for different scenarios.

		MT (ºC) Δt (ºC \ %)									STD (ºC)		
		Min.			**Aver.**			**Max.**			**Min.**	**Aver.**	**Max.**
Reference	Scen.1	21.8	-1.4	-6%	**23.2**	---	---	25.8	2.6	11%	1.7	1.3	1.0
Ventilation	Scen.2	20.2	-3.0	-13%	21.9	-1.3	-6%	24.3	1.1	5%	1.8	1.3	1.1
	Scen.3	19.1	-4.1	-18%	21.0	-2.2	-9%	23.4	0.2	1%	1.9	1.3	1.2
Internal Gains	Scen.4	22.4	-0.8	-3%	23.9	0.7	3%	26.6	3.4	15%	1.8	1.3	1.1
	Scen.5	23.1	-0.1	0%	24.6	1.4	6%	27.3	4.1	18%	1.9	1.4	1.2
Overhangs Shading	Scen.6	24.9	1.7	7%	26.8	3.6	16%	29.2	6.0	26%	2.6	2.3	1.6
	Scen.7	24.3	1.1	5%	26.3	3.1	13%	28.4	5.2	22%	2.5	2.2	1.4
	Scen.8	22.2	-1.0	-4%	23.6	0.4	2%	26.6	3.4	15%	1.9	1.4	1.1
W. Shade Devices	Scen.9	22.7	-0.5	-2%	23.8	0.6	3%	26.6	3.4	15%	1.8	1.4	1.0
	Scen.10	19.2	-4.0	-17%	21.5	-1.7	-7%	23.8	0.6	3%	0.9	0.8	0.6
Windows Glazing	Scen.11	20.6	-2.6	-11%	22.4	-0.8	-3%	25.0	1.8	8%	1.8	1.3	1.1
	Scen.12	21.4	-1.8	-8%	23.0	-0.2	-1%	25.5	2.3	10%	1.3	1.0	0.7

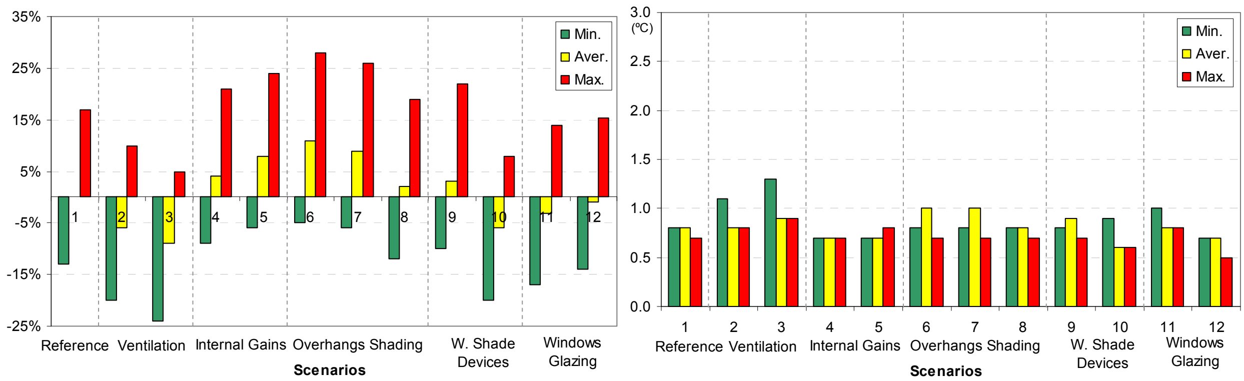


a) Mean temperature differences b) Standard temperature deviation

Figure A1. *Results of the parametric study inside Living Room.*

Table A2. Standard temperature deviation (STD) and mean temperature (MT) inside Bedroom NE for different scenarios.

		MT (ºC) Min.	Δt (ºC)	Δt (%)	MT (ºC) Aver.	Δt (ºC)	Δt (%)	MT (ºC) Max.	Δt (ºC)	Δt (%)	STD (ºC) Min.	STD (ºC) Aver.	STD (ºC) Max.
Reference	Scen.1	19.4	-2.9	-13%	**22.3**	---	---	26.1	3.8	17%	0.8	0.8	0.7
Ventilation	Scen.2	17.9	-4.4	-20%	21.0	-1.3	-6%	24.5	2.2	10%	1.1	0.8	0.8
	Scen.3	16.9	-5.4	-24%	20.2	-2.1	-9%	23.4	1.1	5%	1.3	0.9	0.9
Internal Gains	Scen.4	20.2	-2.1	-9%	23.1	0.8	4%	26.9	4.6	21%	0.7	0.7	0.7
	Scen.5	21.0	-1.3	-6%	24.0	1.7	8%	27.7	5.4	24%	0.7	0.7	0.8
Overhangs Shading	Scen.6	21.2	-1.1	-5%	24.8	2.5	11%	28.5	6.2	28%	0.8	1.0	0.7
	Scen.7	20.9	-1.4	-6%	24.4	2.1	9%	28.1	5.8	26%	0.8	1.0	0.7
	Scen8	19.7	-2.6	-12%	22.7	0.4	2%	26.5	4.2	19%	0.8	0.8	0.7
W. Shade Devices	Scen.9	20.1	-2.2	-10%	22.9	0.6	3%	27.1	4.8	22%	0.8	0.9	0.7
	Scen.10	17.8	-4.5	-20%	20.9	-1.4	-6%	24.1	1.8	8%	0.9	0.6	0.6
Windows Glazing	Scen.11	18.5	-3.8	-17%	21.6	-0.7	-3%	25.4	3.1	14%	1.0	0.8	0.8
	Scen.12	19.2	-3.1	-14%	22.1	-0.2	-1%	25.7	3.4	15%	0.7	0.7	0.5

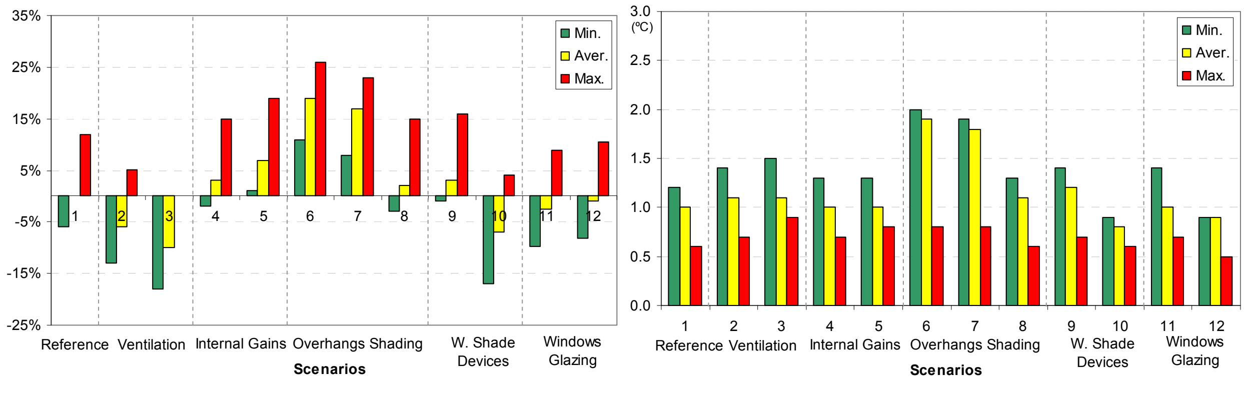


a) Mean temperature differences b) Standard temperature deviation

Figure A2. *Results of the parametric study inside Bedroom NE.*

Table A3. Standard temperature deviation (STD) and mean temperature (MT) inside Bedroom SW for different scenarios.

		MT (ºC) Δt (ºC \ %)						STD (ºC)		
		Min.		**Aver.**		**Max.**		**Min.**	**Aver.**	**Max.**
		22.3		**23.6**		26.4		1.2	1.0	0.6
Reference	Scen.1	-1.3	-6%	---	---	2.8	12%			
		20.6		22.2		24.8		1.4	1.1	0.7
	Scen.2	-3.0	-13%	-1.4	-6%	1.2	5%			
		19.4		21.3		23.7		1.5	1.1	0.9
Ventilation	Scen.3	-4.2	-18%	-2.3	-10%	0.1	0%			
		23.1		24.4		27.2		1.3	1.0	0.7
	Scen.4	-0.5	-2%	0.8	3%	3.6	15%			
		23.8		25.2		28.0		1.3	1.0	0.8
Internal Gains	Scen.5	0.2	1%	1.6	7%	4.4	19%			
		26.2		28.0		29.8		2.0	1.9	0.8
	Scen.6	2.6	11%	4.4	19%	6.2	26%			
		25.6		27.5		29.1		1.9	1.8	0.8
	Scen.7	2.0	8%	3.9	17%	5.5	23%			
		22.8		24.1		27.1		1.3	1.1	0.6
Overhangs Shading	Scen8	-0.8	-3%	0.5	2%	3.5	15%			
		23.4		24.4		27.4		1.4	1.2	0.7
	Scen.9	-0.2	-1%	0.8	3%	3.8	16%			
		19.5		22.0		24.6		0.9	0.8	0.6
W. Shade Devices	Scen.10	-4.1	-17%	-1.6	-7%	1.0	4%			
		21.3		23.0		25.7		1.4	1.0	0.7
	Scen.11	-2.3	-10%	-0.6	-3%	2.1	9%			
		21.7		23.4		26.1		0.9	0.9	0.5
Windows Glazing	Scen.12	-1.9	-8%	-0.2	-1%	2.5	11%			

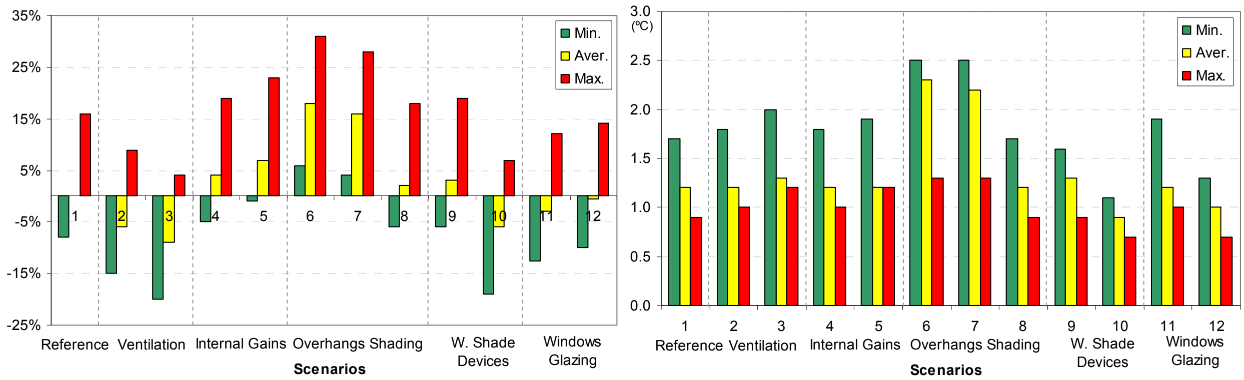


a) Mean temperature differences b) Standard temperature deviation

Figure A3. *Results of the parametric study inside Bedroom SW.*

Table A4. Standard temperature deviation (STD) and mean temperature (MT) inside Office Studio for different scenarios.

		MT (ºC) Min.	Δt (ºC)	Δt (%)	MT (ºC) Aver.	Δt (ºC)	Δt (%)	MT (ºC) Max.	Δt (ºC)	Δt (%)	STD (ºC) Min.	STD (ºC) Aver.	STD (ºC) Max.
Reference	Scen.1	21.3	-1.9	-8%	**23.2**	---	---	26.8	3.6	16%	1.7	1.2	0.9
Ventilation	Scen.2	19.7	-3.5	-15%	21.8	-1.4	-6%	25.2	2.0	9%	1.8	1.2	1.0
	Scen.3	18.6	-4.6	-20%	21.0	-2.2	-9%	24.1	0.9	4%	2.0	1.3	1.2
Internal Gains	Scen.4	22.1	-1.1	-5%	24.1	0.9	4%	27.7	4.5	19%	1.8	1.2	1.0
	Scen.5	22.9	-0.3	-1%	24.9	1.7	7%	28.5	5.3	23%	1.9	1.2	1.2
Overhangs Shading	Scen.6	24.5	1.3	6%	27.3	4.1	18%	30.3	7.1	31%	2.5	2.3	1.3
	Scen.7	24.1	0.9	4%	26.9	3.7	16%	29.7	6.5	28%	2.5	2.2	1.3
	Scen8	21.7	-1.5	-6%	23.6	0.4	2%	27.3	4.1	18%	1.7	1.2	0.9
W. Shade Devices	Scen.9	21.9	-1.3	-6%	23.8	0.6	3%	27.6	4.4	19%	1.6	1.3	0.9
	Scen.10	18.7	-4.5	-19%	21.7	-1.5	-6%	24.8	1.6	7%	1.1	0.9	0.7
Windows Glazing	Scen.11	20.3	-2.9	-13%	22.5	-0.7	-3%	26.0	2.8	12%	1.9	1.2	1.0
	Scen.12	20.9	-2.3	-10%	23.1	-0.1	0%	26.5	3.3	14%	1.3	1.0	0.7



a) Mean temperature differences b) Standard temperature deviation

Figure A4. *Results of the parametric study inside Office Studio.*