Article

Contribution of Portuguese Vernacular Building Strategies to Indoor Thermal Comfort and Occupants' Perception

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Abstract: Solar passive strategies that have been developed in vernacular architecture from different regions are a response to specific climate effects. These strategies are usually simple, low-tech and have low potential environmental impact. For this reason, several studies highlight them as having potential to reduce the demands of non-renewable energy for buildings operation. In this paper, the climatic contrast between northern and southern parts of mainland Portugal is presented, namely the regions of Beira Alta and Alentejo. Additionally, it discusses the contribution of different climate-responsive strategies developed in vernacular architecture from both regions to assure thermal comfort conditions. In Beira Alta, the use of glazed balconies as a strategy to capture solar gains is usual, while in Alentejo the focus is on passive cooling strategies. To understand the effectiveness of these strategies, thermal performances and comfort conditions of two case studies were evaluated based on the adaptive comfort model. Field tests included measurement of hygrothermal parameters and surveys on occupants' thermal sensation. From the results, it has been found that the case studies have shown a good thermal performance by passive means alone and that the occupants feel comfortable, except during winter where there is the need to use simple heating systems.

1. Introduction

1.1. State of the Art

From the start, man had the need to seek shelters that could guarantee the best conditions of security and protection against the elements. With the transition from nomadic to sedentary, man started to build its own shelters and began, by sensory and empirical ways, to get a sense of the relationship between climate, building features and physical well-being. Thus, through generations across the world, diverse vernacular building techniques and forms have been developed and improved in order to better respond to different climate constraints and, consequently, to provide better thermal comfort conditions [1,2]. In the absence of advanced technological solutions to achieve comfort conditions, vernacular buildings were built using low-tech passive strategies that take advantage of available endogenous resources and other criteria such as: insolation; orientation; geometry; form; and materials, among others [3–5]. The relevance of vernacular features is still valid today being now the basis of sustainable building design [6].

However, since Modernism, this vernacular knowledge is often forgotten in building design and now most buildings are built from industrially-produced materials and are very dependent on mechanical air conditioning systems to ensure indoor comfort conditions [2,7]. As a result of standardisation of buildings, mechanical systems and indoor climates, air-conditioning is routinely installed and operated even if not necessary [8]. Additionally, the use of these systems led to a condition of thermal monotony that was delineated and maintained based on norms of thermal comfort that configure standardized and homogenous "comfort zones", that are now contested due to its energy-intensity [8]. Following this modern paradigm, nowadays, topics such as comfort, energy and environmental impacts are inseparable. Thus, if a building relies mainly on active systems to provide healthy and comfortable conditions for occupants, it will have a larger portion of energy consumption for heating and cooling [9,10]. Energy consumption is also a key issue in terms of the environmental life-cycle impacts of buildings, mainly during the operational stage [11]. The study conducted by Passer *et al.* [11] shows that technical building equipment has a notable influence on the overall life-cycle environmental impacts of buildings. It is also shown that a passive house provides the lowest contribution in terms of such equipment as far as life-cycle assessment results are concerned, mainly due to the fact that there is little need for conventional ventilation and air-conditioning equipment [11]. Therefore, to reduce the use of mechanical equipment, passive strategies should be considered into building design from the start [12].

On this subject, it is relevant to look at vernacular architecture because it is intrinsically bound up with the local conditions and its strategies were developed overtime to mitigate the effects of climate and to provide the best possible comfort conditions. The strategies used in vernacular constructions are usually passive, low-tech and not dependent on non-renewable energy, which makes them suitable for contemporary construction, especially for passive building design [13]. According to some authors, vernacular architecture could contribute towards reducing energy consumption through the use of passive solar techniques and local materials that should continue to be improved and adapted in

accordance with specific territories and climate [13–16]. This statement is confirmed by several quantitative studies on the thermal performance of vernacular buildings. Although they were conducted in different parts of the world, they have reported similar conclusions. These studies have shown that vernacular buildings can achieve acceptable comfort standards throughout much of the year by passive means alone [5,6,17–19]. In some cases, indoor air temperatures remained almost constant with no need for air conditioning, except during winter season [5,6,17–19]. The results presented in these studies support the arguments that passive strategies can be feasible for contemporary buildings and that they could contribute towards reducing buildings' energy demands for heating and cooling. In addition, there is still a vernacular built heritage that needs conservation/renovation, where the advantages of climatic-responsive features must be understand in order to be preserved and improved.

Taking into consideration that thermal comfort governs energy consumption in buildings [19], in order to properly design a building to be comfortable and low energy-intensive, there is the need to comprehend which is the most appropriate thermal comfort model to assess each case. It is well-known that environmental conditions required for comfort are not the same for everyone and there are variations from person to person [20]. Vernacular buildings are naturally ventilated spaces where occupants regulate thermal conditions primarily by opening and closing the windows, changing the clothing, *etc.* Thus, thermal comfort standards for air-conditioned buildings are not suitable to be used in the design of this type of building. Thus, the most adequate model to assess and predict thermal comfort conditions in vernacular buildings is the adaptive model of thermal comfort, part of the standards ASHRAE Standard 55 [20] and EN 15251 [21].

Although some studies have been focusing on the passive strategies used in Portuguese vernacular buildings, there is a lack of results from *in situ* measurements that might demonstrate the influence of these different strategies in the indoor thermal environment. This paper attempts to provide a contribution in this field by presenting the results on the thermal performance assessment of two case studies located in different climate zones. This study is based on the Portuguese adaptive model of thermal comfort [22], which is an adaptation to the Portuguese context of the model specified in the ASHRAE Standard 55 [20] and EN 15251 [21], and includes both *in situ* measurements of hygrothermal parameters and a survey on the occupants' thermal comfort perception. The results obtained show that it is possible to achieve thermal comfort conditions with no need for air-conditioning and that the adaptive model of comfort is the most adequate to predict thermal comfort conditions in Portuguese vernacular buildings.

1.2. Climate-Responsive Strategies in Vernacular Architecture from Northern and Southern Portugal

Vernacular architecture is strongly influenced by its geographical location. Due to the close relation with local conditions, vernacular buildings have different characteristics from region to region. From all the geographical constraints, one of the most relevant is undoubtedly the climate. In addition to latitude, the most relevant characteristics affecting the climate of continental Portugal are the orography and the influence of the Atlantic Ocean [23]. Although Portugal is a relatively small country, it has a territory full of contrasts. Even though the variation in climatic factors is rather small, it is sufficient to justify significant variations in air temperature and rainfall [23].

In Figure 1, it is possible to verify the contrast in mean air temperature for continental Portugal during winter and summer. In general, it can be stated that the northern part has harsher winter conditions and milder summers, while the southern part is the opposite, with mild winter and harsh summer conditions. To suit these climatic conditions, Portuguese vernacular architecture developed specific mitigation strategies, that in a general form are: (i) in the northern part of the country, the adopted strategies aim to increase heat gains and to reduce indoor heat losses during winter; (ii) in the southern part, the strategies are more focused on passive cooling during summer.
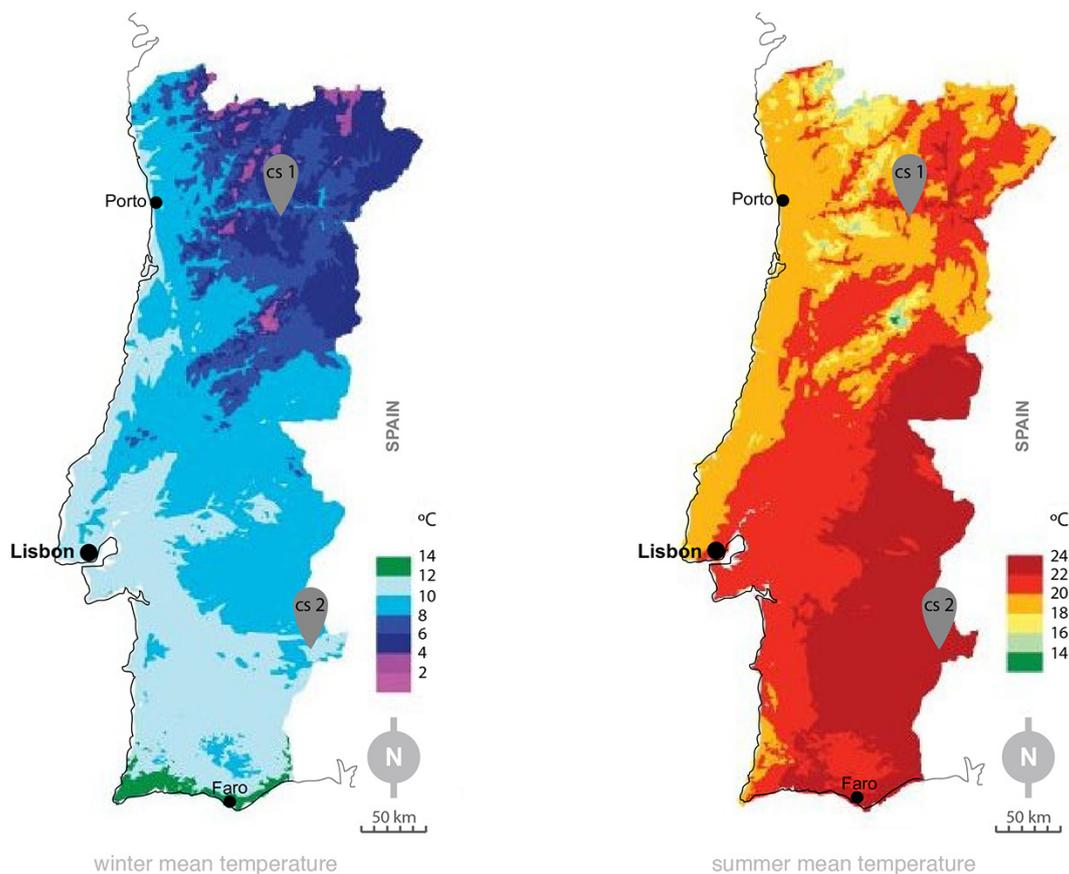

Figure 1. Winter/summer mean air temperature maps [24] and location of the case studies.

In order to mitigate winter cold conditions, vernacular buildings from the north were designed to reduce heat losses and to increase solar gains. For that, they often used a thatched roof—because of its insulating properties—and use south-facing balconies to take advantage of solar radiation. The glazed-balconies are a feature of the architectonic identity of the northern interior part of the country (Figure 2a). Due to the advantages they bring, many are still in use today. The balconies are usually facing between south and west so that they can receive in winter a high level of radiation during the higher number of hours of sunshine, while affording the best shelter from the prevailing winds [25]. Although this strategy presupposes a functioning aimed for the heating season, the cantilevered volume of the balcony and the possibility to open windows allow also proper operation during the cooling season, by shading the walls and promoting natural ventilation. The contemporary use of these kind of structures is feasible and has considerable benefits on energy savings, especially if facing south, as demonstrated in the study

developed by Ware and Pitts [26] and by Küess *et al.* [27] in a refurbishment project with energy efficiency purposes of a residential complex in Dornbirn, Austria.

Figure 2. (**a**) Northern building with glazed-balcony; (**b**) Southern rammed-earth building.

In the south of the country, the focus is to minimise heat gains during summer. With this purpose, several techniques were developed, such as (Figure 2b): reducing the size of windows and doors; the use of high thermal inertia building systems; the use of *patios* (courtyards); and the use of light colours in order to reflect solar radiation.

The abovementioned strategies are relevant in the discussions around energy efficiency in buildings because they are aimed at reducing energy consumption and increasing the comfort level of occupants by passive means. Despite the advantages of the presented passive strategies, for the Portuguese context, there is a lack of quantitative data on the effectiveness of these approaches on the thermal performance of vernacular buildings in different climate zones. Nevertheless, the interpretation of the results of studies that have been conducted in Portugal and in other European countries highlighted some techniques as being effective and having the potential for use in contemporary buildings [5,6,17]. The effect of these strategies on the thermal performance of buildings is described in the following section.

2. Methodology and Case Studies

2.1. Methodology and Equipment

The main aim of this study was to measure hygrothermal parameters that characterise the indoor thermal environment and that affect the body/environment heat exchange (air temperature, relative humidity, mean radiant temperature and air velocity). To assess indoor thermal performance, *in situ* assessments were divided into short and long term monitoring. The first were carried out at least one time (usually one day) per season of the year and consisted of objective and subjective measurements. The objective measurements were performed with the purpose of quantitatively assess the thermal conditions within a specific room using a thermal microclimate station (model DeltaOHM 32.1) (Figure 3a) equipped with the probes required, namely, globe temperature probe Ø150 mm; two-sensor probe for measuring natural wet bulb temperature and dry bulb temperature; combined temperature and relative

humidity probe; and omnidirectional hot-wire probe for wind speed measurement, in compliance with the following standards: ISO 7726 [28] and ISO 7730 [29]. The location of the equipment is chosen according to occupants' distribution in the room. The readings recorded were downloaded to a PC. This data is used in the analysis of the thermal comfort conditions to determine the operative temperature, namely in the adaptive model of thermal comfort, as explained below. The measurements were performed at the center of gravity, approximately 0.6 m for seated occupants, as recommended in ASHRAE Standard 55 [20]. These measurements were carried out simultaneously with the subjective measurements, *i.e.*, evaluating the environment conditions by surveying the occupants. The survey used was based in the "Thermal Environment Survey" from ASHRAE Standard 55 [20] and was used to determine occupants' satisfaction according ASHRAE thermal sensation scale. In case study 1, two occupants were surveyed during summer and winter monitoring. In both seasons, the two occupants were surveyed in two different rooms (kitchen/living room and bedroom with glazed balcony). In winter, monitoring an additional survey was carried in the kitchen/living room with the heating system on in order to compare thermal enviroment results. In case study 2, three occupants were surveyed during summer monitoring and four occupants during winter monitoring. In both seasons, the occupants were surveyed in the living room. The two types of measurements were conducted for the room that occupants considered more comfortable and/or where they spend more time. The results of these two procedures were then compared to conclude if they converged or diverged.

The long-term monitoring was aimed at understanding the fluctuations of air temperature and relative humidity profiles, indoors and outdoors, throughout the various seasons. For this purpose, thermo-hygrometer sensors were installed outdoors and indoors (in the most relevant rooms for the assessment of the thermal performance of each case study) (Figure 3b,c). The equipment has an internal sensor for measuring the air temperature and relative humidity. They have a measuring range between −40 and 70 °C and an accuracy of ± 0.5–1 °C. The readings recorded were downloaded to a PC. The measurements were carried out during different monitoring campaigns for all seasons of the year, in compliance with specified procedures and standards (ISO 7726 [28], ISO 7730 [29], ASHRAE Standard 55 [20]). The monitoring campaigns were carried out for periods of at least 25 days and with the various thermo-hygrometer sensors recording data at 30 min intervals. Results on indoor environmental climate parameters were correlated with the outdoor parameters. During these measurements, occupants fulfilled an occupancy table where they recorded how they used the building, *i.e.*, if they used heating or cooling systems, promoted ventilation, *etc.* These occupancy records were useful to understand sudden changes in air temperature and relative humidity profiles. Local weather data was collected from the nearest weather stations.

In the analysis of the thermal comfort conditions, the relation between indoor comfort temperature and the outdoor temperature was evaluated using an adaptive model of thermal comfort, since this is the most adequate model for naturally conditioned areas. In order to be more representative of the Portuguese reality, the chosen model was the Portuguese adaptive model of thermal comfort developed in the National Laboratory of Civil Engineering (Laboratório Nacional de Engenharia Civil—LNEC) by Matias [22], which is an adaptation to the Portuguese context of the model specified in the ASHRAE standard 55 [20] and EN 15251 [21]. Briefly, the LNEC model [22] is an adaptive approach aimed at defining the indoor thermal comfort requirements applicable to Portuguese buildings, considering the typical Portuguese (Mediterranean) climate, ways of living, designing and operating buildings [22,30]. The author carried out field tests all over the country in buildings with different uses (office, residential,

educational and elderly homes), assessing and measuring *in situ* the main indoor environmental parameters during all seasons and evaluating occupant's thermal perception and expectation through surveys. The results obtained in this study show that: occupants may tolerate (under wider comfort conditions) broader temperature ranges than those indicated in current standards, in particular in the heating season; the outside temperature has strong influence on the occupants' thermal perception/ sensation [22,30].

Figure 3. (**a**) Thermal microclimate station; (**b**) thermo-hygrometer + datalogger; (**c**) thermo-hygrometer sensor.

This adaptive model includes the vast majority of the factors that influence thermal comfort, such as: clothes; the use, or not, of air conditioning systems to change the existing indoor environmental conditions; thermal expectation and behaviour adopted by the occupants in the face of certain thermal conditions (factors which depend on the outside temperature) [22,30]. In this model, it is also stated that thermal comfort is only verified when a person feels neutral and simultaneously shows preference to keep that neutrality [22,30].

In the application of the proposed model to the case studies, the following conditions were assumed: (i) the occupants have activity levels that result in metabolic rates (met) ranging from 1.0 to 1.3 met (sedentary activity levels); (ii) occupants are free to adapt their clothing's thermal insulation; (iii) air velocity bellow 0.6 m/s; (iv) indoor operative temperature between 10 °C and 35 °C; (v) outdoor running mean temperature between 5 °C and 30 °C. The buildings have no air-conditioning systems, or its use is sporadic, and, therefore, in the analysis of the case studies, the adaptive model for buildings without mechanical systems was applied.

Considering that an individual takes approximately one week to be fully adjusted to the changes in outdoor climate, the thermal comfort temperature (operative temperature, Θ_o) is obtained from the exponentially weighted running mean of the outdoor temperature during the last seven days (outdoor running mean temperature, Θ_{rm}) [22]. The calculation of the exponentially weighted running mean of the outdoor temperature during the last seven days is done using Equation (1) [21].

$$\Theta_{rm} = (T_{n-1} + 0.8T_{n-2} + 0.6T_{n-3} + 0.5T_{n-4} + 0.4T_{n-5} + 0.3T_{n-6} + 0.2T_{n-7})/3.8 \tag{1}$$

where Θ_{rm} (°C)—exponentially weighted running mean of the outdoor air temperature; T_{n-i} (°C)—outdoor mean air temperature of the previous day (*i*).

In this model, two comfort temperatures ranges are defined, one to be applied in spaces with active air-conditioning systems and other in non air-conditioned spaces (do not have air conditioning systems or these are turned off). The operative temperature limits defined in this model are for 90% of acceptability, these limits are up to 3 °C above or below the estimated comfort temperature both for non-air-conditioned spaces ($\Theta_o = 0.43\Theta_{rm} + 15.6$) and air-conditioned spaces ($\Theta_o = 0.30\Theta_{rm} + 17.9$).

The operative temperature was calculated based on the results obtained in the measurements from the Thermal Micro-climate Station. With the operative temperature (Θ_o) and the outdoor running mean temperature (Θ_{rm}) is possible to represent in the adaptive chart the point that characterises the thermal environment condition in the moment of measurement.

2.2. Case Studies Description

2.2.1. Case Study 1—Northern Portugal Glazed-Balcony Building

Case study 1 is located in an old village center, in Tabuaço's municipality, northern of Portugal (see Figure 1). The region has a Mediterranean climate, sub-type Csb according to Köppen climate classification, characterised by rainy winters and hot and dry summers [31]. The building, with two storeys, less than 50 m^2, is southwest oriented (Figure 4). Additionally, as other constructions in regions with cold winters, it has very few and small openings to avoid heat losses, with the exception of the balcony that has the goal to capture solar gains. In this type of climate, it was also common to store the cattle on the ground floor of the dwelling (in order to take advantage of the animals' body heat), while the upper floor was for human occupancy. In this case study, after the refurbishment, the ground floor was converted into kitchen and living areas. On the upper floor, two bedrooms and a bathroom are now located (Figure 5). The building envelope consists of: external walls in granite with about 50–55 cm thick (heat transfer coefficient (*U*-value) around 2.87 W/(m^2·°C) [32]); pitched roof; upper storey in timber structure; insulated ceiling in timber structure with 4 cm of extruded polystyrene (XPS) (*U*-value = 0.84 W/(m^2·°C)); wooden doors and single glazed sash windows (Uwdn—mean day–night heat transfer coefficient, including the contribution of shading systems = 4.3 W/(m^2·°C) [33]).; balcony with timber frame, 10 cm thick (*U*-value = 1.70 W/(m^2·°C)).

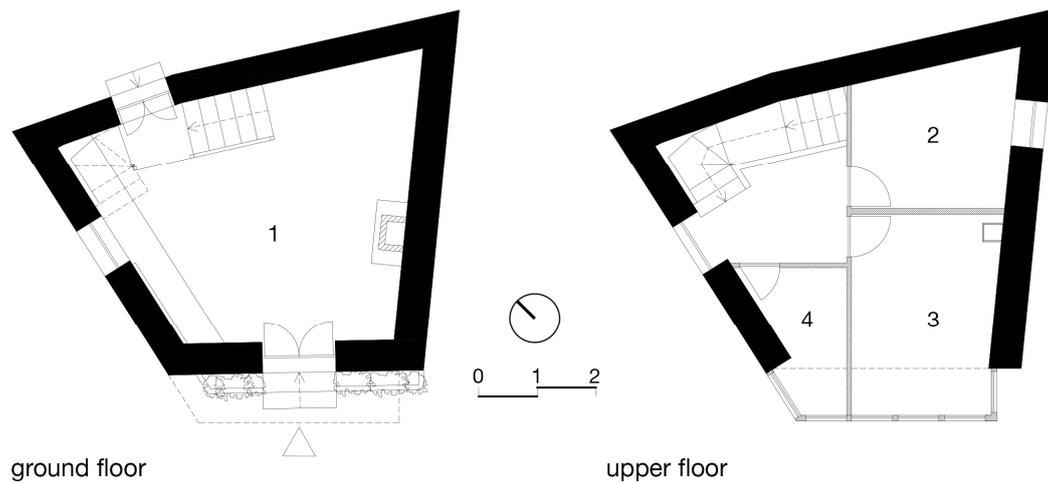**Figure 4.** (**a**) Case study 1—External view; (**b**) Inside view of the balcony.

Figure 5. Floor plans (1—living room / kitchen; 2—bedroom; 3—bedroom with balcony; 4—bathroom).

2.2.2. Case Study 2—Southern Portugal Rammed-Earth Building

Case study 2 is located in an old village center, in Moura's municipality, southern Portugal (see Figure 1). The region has a Mediterranean climate, sub-type Csa according to Köppen climate classification, hot and dry during summer [31]. In summer, the mean values for maximum air temperature vary between 32 and 35 °C, reaching sometimes maximum temperatures of 40 °C or 45 °C, July and August being the hottest months [31]. The annual average rainfall is below 500 mm, July being the driest month (below 5 mm) [31]. To respond to these constraints, vernacular buildings from this region have a range of strategies to minimize heat gains and to promote passive cooling. This case study has several passive cooling strategies (Figure 6a–c), such as: small and few windows and doors; the use of high thermal inertia building systems; the use of *patios* (courtyards); and the use of light colours in order to reflect solar radiation. From these strategies, the heavy walls made of rammed earth—the most widespread vernacular construction technique in the Alentejo region—should be highlighted. The heavy mass that characterizes earthen constructions allows them to respond appropriately to the hot summer of Alentejo, since the strong thermal inertia delays the heat flow into the interior. The building has main and rear facades oriented southeast and northwest, respectively. The building has an approximate gross floor area of 200 m^2 divided in two storeys, although the upper storey is just a small attic area. On the ground floor, at the southeast are the living areas and the bedrooms, and in the northern part are the kitchen and the bathroom (Figure 7). The building envelope consists of: white-washed external walls in rammed earth with an average thickness of 60cm (*U*-value = 1.30 W/(m^2·°C) [32]); pitched roof with ceramic tiles, a small insulation layer of sprayed polyurethane foam (SPF) and reeds on timber structure (*U*-value = 0.49 W/(m^2·°C)); wooden doors; and single glazed windows (Uwdn = 3.4 W/(m^2·°C) [33]). Several of the indoor spaces are vaulted and the floor is in *baldosa*—a sun-dried clay tile. Regarding the windows, it is relevant to highlight the existence of small openings above the window to promote controlled natural ventilation, which are particularly useful for the purpose of overnight cooling without compromising the security level (Figure 6c).

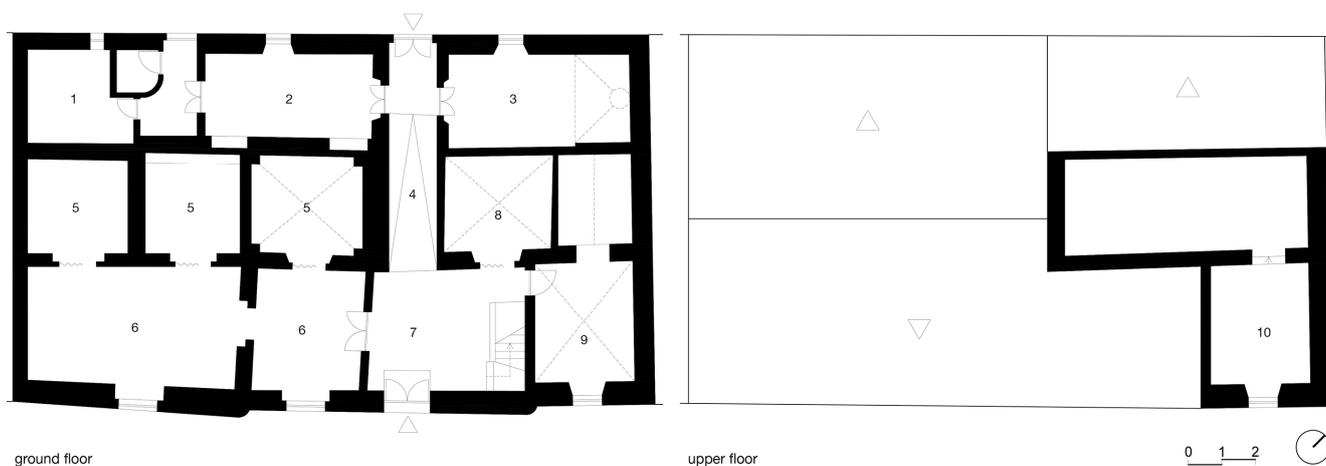**Figure 6.** (**a**) External view; (**b**) indoor corridor; (**c**) ventilation window.

Figure 7. Floor plans (1—bathroom; 2—kitchen; 3—old kitchen (living room); 4—corridor; 5—alcove; 6—living room; 7—entrance; 8—library; 9—bedroom; 10—attic).

3. Results and Discussion

Although the thermal performance monitoring was carried out for all seasons of the year; in this paper, the results obtained for the two most demanding seasons in what thermal comfort is concerned, *i.e.*, winter and summer, are addressed and discussed.

3.1. Case Study 1—Northern Building with a Glazed-Balcony

3.1.1. Summer Monitoring

The summer monitoring was conducted over the period from 6 August 2014 to 10 September 2014. From the analysis of the results, it is possible to verify that during summer, outdoor mean air temperature was about 23 °C (Table 1). However, maximum air temperature surpassed 35 °C in most of the monitored days and daily temperature variation was of about 17 °C.

Table 1. Comparison of outdoors and indoors air temperature and relative humidity values in case study 1 during summer season.

Season Place/Room	Summer Outdoor	Kitchen/Living Room	Bedroom/Balcony	Bedroom	Bathroom
Temperature (°C)					
Mean	23.2	23.9	25.8	26.0	26.0
Maximum	40.8	27.3	33.8	30.0	35.2
Minimum	11.7	20.9	17.8	22.5	20.4
Relative Humidity (%)					
Mean	59	53	50	50	51
Maximum	100	66	69	61	79
Minimum	14	28	26	29	26

Indoors, the kitchen/living room showed a very stable and uniform air temperature profile, only affected by the opening of doors and windows (Figure 8a). During all of the monitoring period, the mean air temperature in this space was around 24 °C and daily temperature variation was less than 5 °C. This temperature profile reveals the influence of the high thermal inertia of the thick granite walls, which give to the space a good capacity to stabilize indoor temperature.
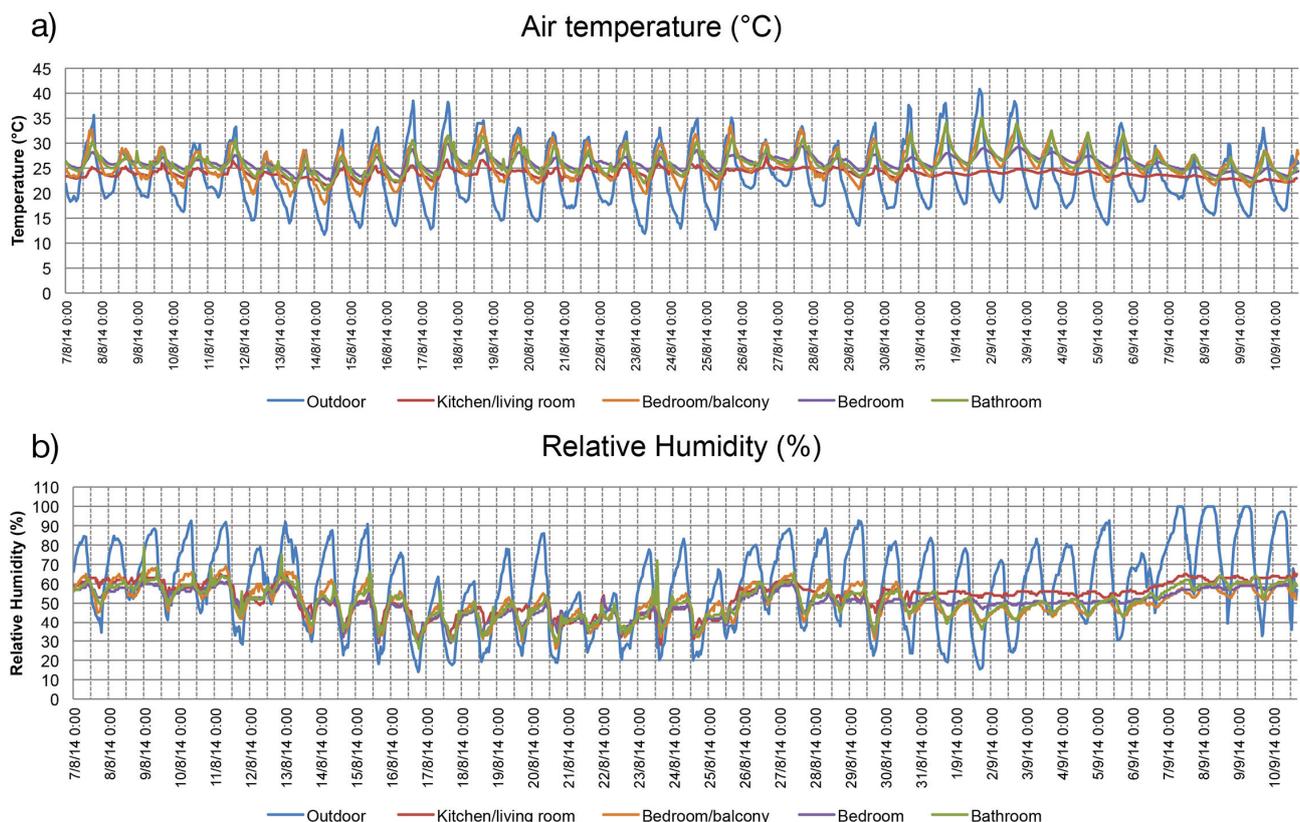

Figure 8. Case study 1 performance during summer season. (**a**) Indoor and outdoor air temperature profile; (**b**) Indoor and outdoor relative humidity profile.

The upper storey rooms, namely the bedrooms and the bathroom, when compared with the living room, showed higher mean air temperature of about 26 °C (Table 1). Daily thermal variation was also

slightly higher, 6–8 °C. The large glazed balcony area of these spaces, facing southwest, is the reason why these spaces have higher solar gains. The high heat transfer coefficient of the single-glass windows and the lack of external shading devices are the reason for the relative susceptibility to outdoor temperature variations.

The other bedroom has an intermediate behaviour with lower daily thermal variations, of about 3 °C. The fact that this room's envelope is facing north and east, having only a window, is probably the reason for the milder temperature profile, when compared with the remaining upper floor rooms (Figure 8a).

Regarding the relative humidity (Figure 8b), it was found that the actions of the inhabitants, particularly the opening of doors and windows affected indoor relative humidity. However, relative humidity values remained lower and more stable than outdoors. Indoor average relative humidity was around 50% (Table 1).

The assessment of the summer season comfort conditions was done for two rooms, namely the kitchen/living room (Figure 9a) and the bedroom/balcony (Figure 9b). From the analysis of the charts in Figure 9a,b, it was found that both spaces had a comfortable thermal environment. Although both rooms had a thermal environment within the comfort range, the operative temperature in the kitchen/living room is close to the lower limit, influenced by the heavy thermal inertia of the granite envelope. In the subjective assessment carried out in both spaces, all the occupants indicated in the survey being "neutral" (comfortable) in the thermal sensation scale, confirming the objective measurements. Although the results from the short-term measurements showed in this paper represent one day, the conditions of thermal comfort can be extrapolated to almost all seasons. According to the work developed by Matias [22], there is a strong relation of dependency between the air temperature and the operative temperature, thus confirming that, for the common cases, the air temperature can be used as an approximation to the operative temperature.
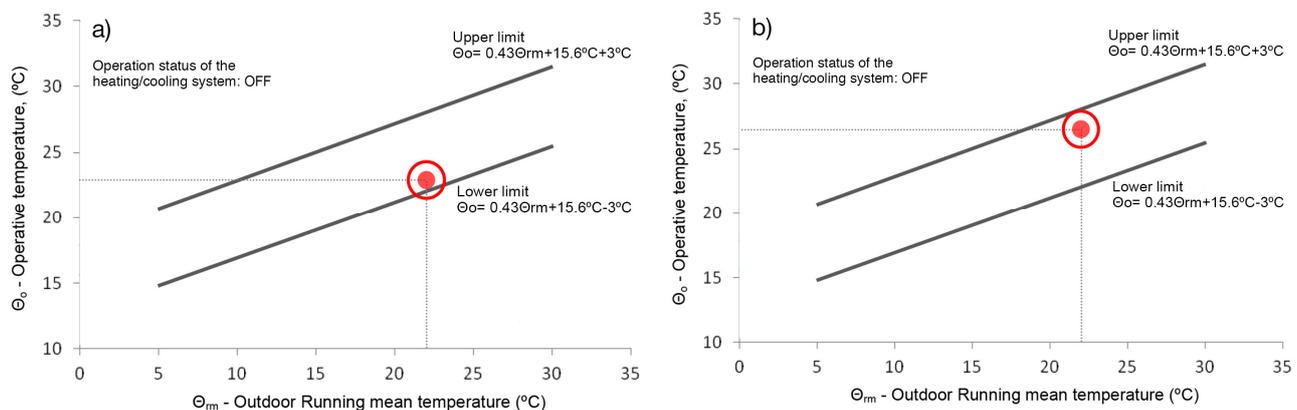

Figure 9. (**a**) Thermal comfort temperature (operative temperature) in the kitchen and living room during summer monitoring; (**b**) Thermal comfort temperature (operative temperature) in the bedroom/balcony during summer monitoring. Based on the relation between the limits of the indoor operative temperature (Θ_o) for buildings without mechanical air-conditioning systems as a function of the exponentially-weighted running mean of the outdoor temperature (Θ_{rm}) (adapted from [22]).

3.1.2. Winter Monitoring

The winter monitoring was conducted over the period from 22 December 2014 to 4 February 2015.

In winter monitoring outdoor mean air temperature was of about 5 °C, with an average daily temperature variation near 12 °C (see Figure 10a). The maximum air temperature surpassed 15 °C just in a few days and the minimum air temperature was around or below 0 °C most of the days (Table 2).
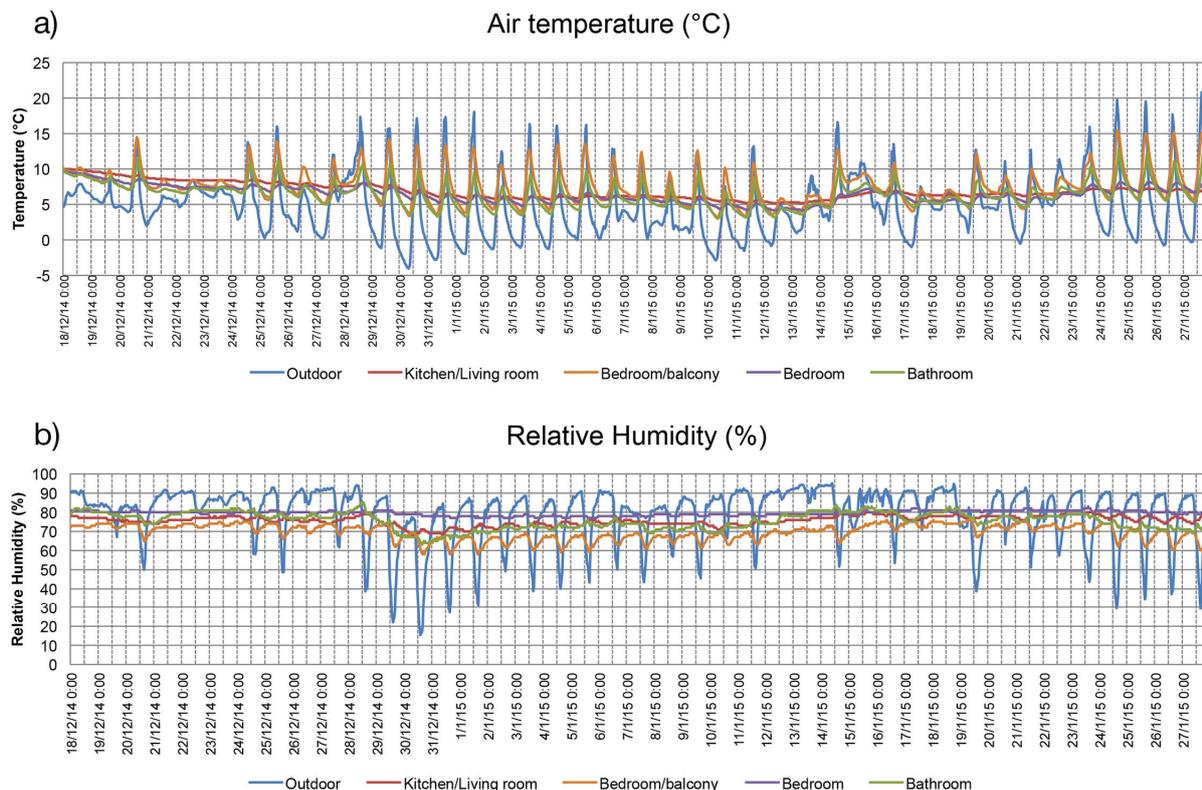

Figure 10. Case study 1 performance during winter season. (**a**) Indoor and outdoor air temperature profile; (**b**) Indoor and outdoor relative humidity profile.

Table 2. Comparison of outdoors and indoors air temperature and relative humidity values in case study 1 during the winter season.

Season	Winter	Kitchen/Living Room	Bedroom/Balcony	Bedroom	Bathroom
Place/Room	Outdoor				
Temperature (°C)					
Mean	4.9	6.9	7.6	6.4	6.4
Maximum	20.9	10.0	15.7	9.8	12.8
Minimum	−4.0	5.2	3.0	4.2	3.1
Relative Humidity (%)					
Mean	79	76	70	80	76
Maximum	95	80	76	83	85
Minimum	15	68	58	77	63

The air temperature profiles of the kitchen/living room and bedroom (north) were generally stable and uniform during the entire monitoring period with low daily temperature variations (on average less than 1 °C). The bedroom/balcony and the bathroom had a more pronounced daily temperature variation than the other rooms but lower than outdoor, 4–6 °C, once again influenced by the large glazed balcony area. Taking in consideration that the glazed-balcony is a strategy to capture solar gains, its influence during the monitoring period is not clearly noticed because the internal shading devices were activated most of the time. This is due to the fact that, during this monitoring period, the building was unoccupied most of the time, so no changes were made in the operation of the building to regulate indoor thermal environment. Although this allowed for verifying the true passive thermal performance of the building during the winter season, the glazed-balcony did not perform as it should if the building was occupied. Thus, there was the need to evaluate the effect of the glazed-balcony during the days when the building was occupied. In a day with no shading devices activated, temperature inside the bedroom/balcony reached 17.3 °C when, at the same time, outdoor temperature was about 9 °C. In this case, the difference between indoor and outdoor and the results of the thermal comfort assessment reveal the effectiveness of this strategy to achieve comfort conditions by passive means.

In what relative humidity is concerned, outdoor relative humidity was high with daily peaks near 90% (see Figure 10b; Table 2). Indoor relative humidity, for all spaces, followed the outdoor trend, being, however, more stable and lower (an average of about 70% in the bedroom/balcony and 77% in the bedroom (north) (Table 2)).

The assessment of comfort conditions in the winter season for the kitchen/living room (see Figure 11a,b) was carried out in two stages: without and with the heating equipment on (wood-burning stove), in order to determine its effect. In the analysis of Figure 11a, it is found that without the wood-burning stove on, the thermal sensation was of discomfort (cold). All of the occupants in the thermal comfort surveys corroborated this condition reporting being "very cold". Since this room was originally intended for the storage of agricultural products, it has the adequate thermal performance for that purpose. For the present use, it is not possible to satisfy occupants' comfort conditions without a heating system. In the second stage, it was found that the wood-burning stove allowed improving thermal comfort needs of the occupants (Figure 11b). In the surveys, one occupant qualified its thermal sensation as being "neutral" (comfortable) while the other considered being "slightly cool". According to the objective measurements, the operative temperature in the kitchen/living room (Figure 11b) is of thermal comfort for 90% acceptability. Thus, the thermal sensation of the latter occupant could have been influenced by the proximity to a cool building element such as a wall, or is in the 10% of people predicted to be dissatisfied.

From the analysis of Figure 11c, it is possible to conclude that the thermal environment in the bedroom/balcony was uncomfortable. In the survey, one occupant answered as being "slightly cool" while the other, possibly due to solar exposure during the measurement, answered as being "neutral" (comfortable). Although the results show that this room was uncomfortable, its operative temperature was considerably higher than in the ground floor and in days with good solar gains, occupants can be comfortable with less use of heating systems.
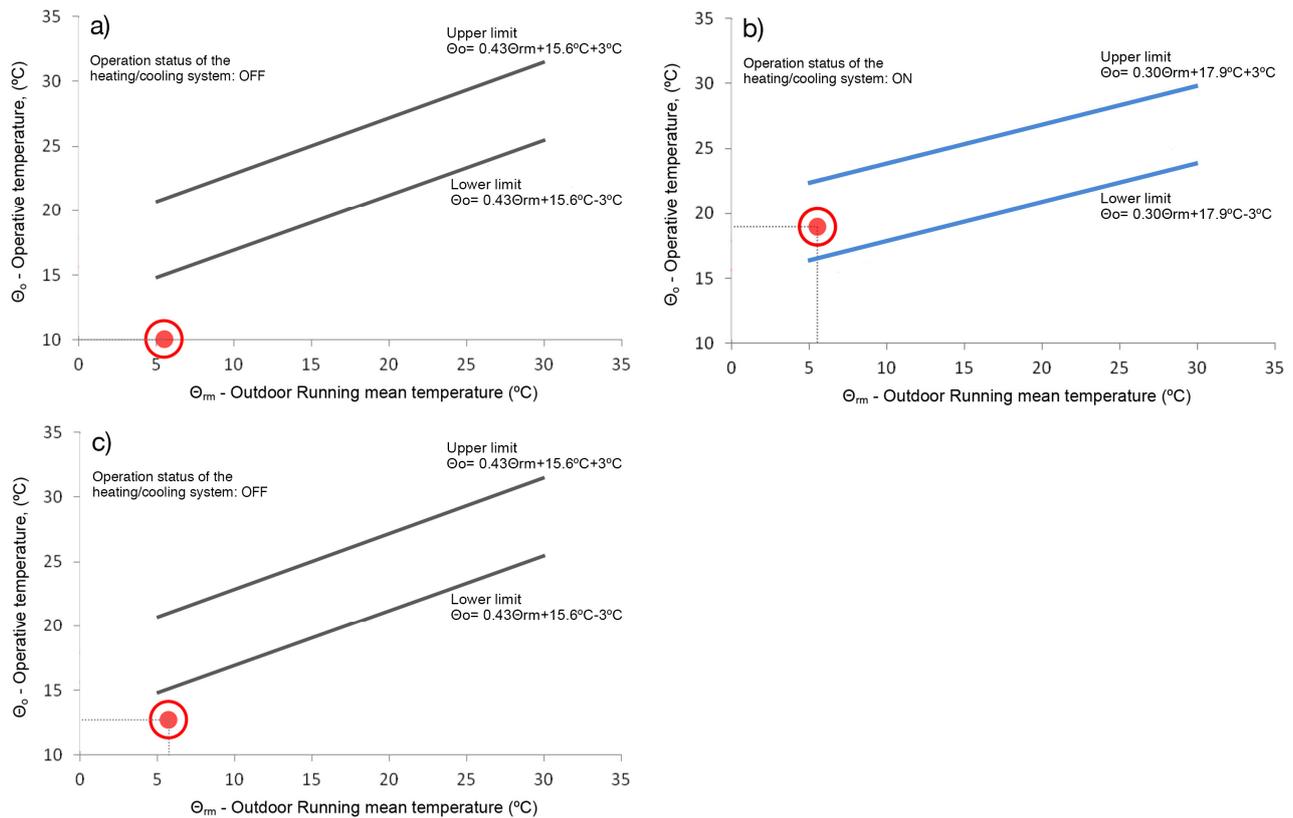
Figure 11. (**a**) Thermal comfort temperature (operative temperature) in the kitchen and living room during winter monitoring without heating system; (**b**) Thermal comfort temperature (operative temperature) in the kitchen and living room during winter monitoring with the heating system on; (**c**) Thermal comfort temperature (operative temperature) in the bedroom/balcony during winter monitoring without heating system. Based on the relation between the limits of the indoor operative temperature (Θ_o) as a function of the exponentially-weighted running mean of the outdoor temperature (Θ_{rm}) (adapted from [22]).

3.2. Case Study 2—Southern Rammed-Earth Building

3.2.1. Summer Monitoring

The summer monitoring was conducted over the period from 2 August 2014 to 13 September 2014. From the analysis of the results, shown in Figure 12a, it is possible to verify that during summer outdoor mean air temperature was of about 26 °C (Table 3). During the day the maximum air temperature was often higher than 35 °C, reaching on some days nearly 40 °C (Figure 12a; Table 3). Minimum air temperature was usually above 20 °C. Although the daily outdoor temperature variation is high (differences of 15 °C between night and day), it is found that indoor temperature remained very stable over the monitoring period, with temperature values around 25 °C (Figure 12a). The indoor space that recorded the highest temperature was the attic with a slightly higher temperature of 27 °C, while outdoor peak temperature was around 40 °C, due to its location near the roof (Table 3). The indoor temperature profile shows that the high thermal inertia of the building envelope (e.g., thick walls of rammed earth

and vaulted ceilings) provides a high capacity to delay the progress of the heat flux and to stabilize indoor temperature.
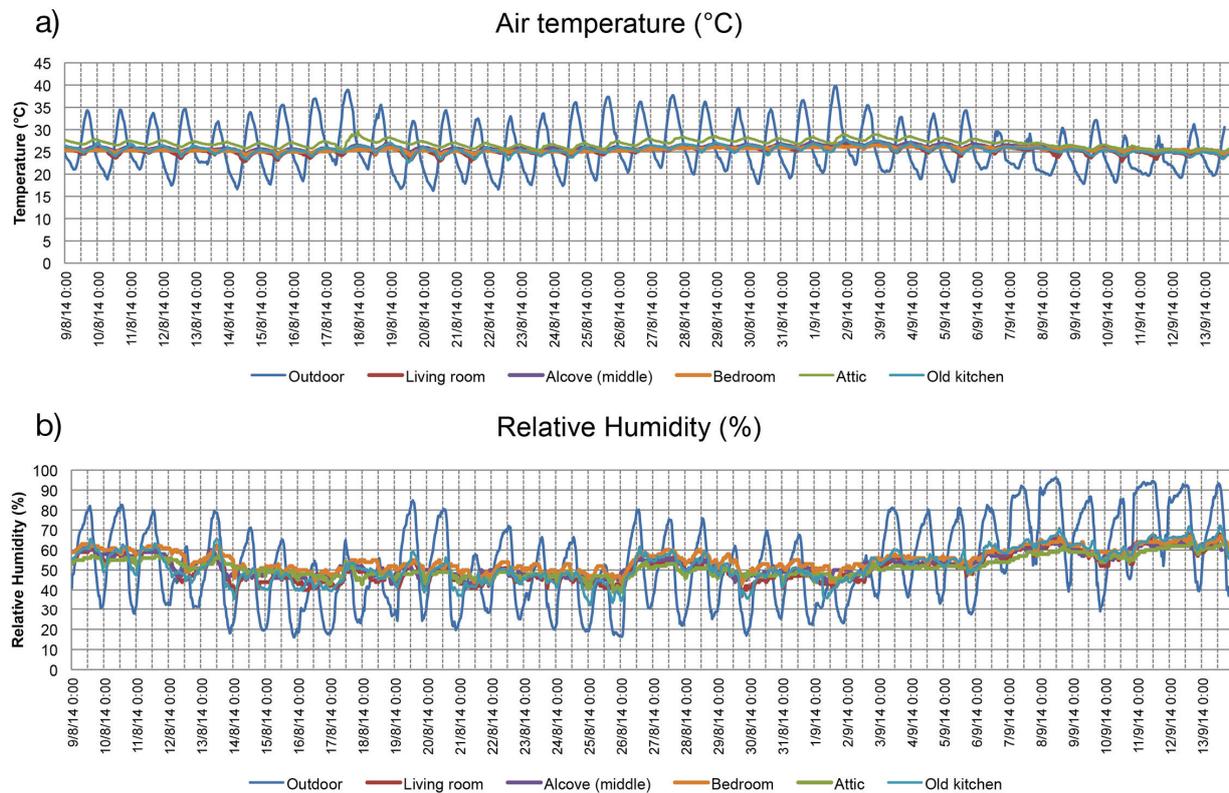

Figure 12. Case study 2 performance during summer season. (**a**) Indoor and outdoor air temperature profile; (**b**) Indoor and outdoor relative humidity profile.

Table 3. Comparison of outdoors and indoors air temperature and relative humidity values in Case Study 2 during summer season.

Season	Summer	Living Room	Alcove (Middle)	Bedroom	Attic	Old Kitchen
Place/Room	Outdoor					
Temperature (°C)						
Mean	25.7	25.3	25.9	25.5	26.9	25.5
Maximum	39.8	27.0	27.4	26.8	29.8	27.9
Minimum	16.3	22.9	24.6	24.2	25.0	22.6
Relative Humidity (%)						
Mean	53	51	53	55	51	52
Maximum	96	68	66	67	64	72
Minimum	16	37	42	43	39	32

In the profile of relative humidity, it is also verified that there is a high outdoor day/night variation, with maximum values of 80%–95% and minimum lower than 20% (Figure 12b). When compared to the outdoor profile (Figure 12b; Table 3), indoor spaces have relative humidity profiles more stable with fluctuations between 40% and 60%—the most appropriate range for human health and comfort [34]. The difference between indoor and outdoor relative humidity values is due to the hygroscopic inertia of

the building systems, namely the rammed-earth walls, the lime plaster, *etc.*, that have the capacity to regulate air humidity [35], *i.e.*, absorbing when moisture is excessive and releasing it when the air is too dry.

Regarding the assessment of the thermal comfort, Figure 13 shows the results of the measurements conducted in the living room during the summer. The living room is the compartment where the occupants remain longer during the day (as the bedroom during night time) and the results show that it has thermal comfort conditions within the defined limits. In the "thermal environment survey," two occupants answered as being "neutral" (comfortable) and one answered as being "slightly cool". These results confirm the objective measurements that show an operative temperature in the centre of the comfort range (Figure 13). The active behaviour of the occupants in order to improve their comfort conditions, *i.e.*, promoting passive cooling by natural ventilation of the indoor spaces during the night and early morning should also be noted.
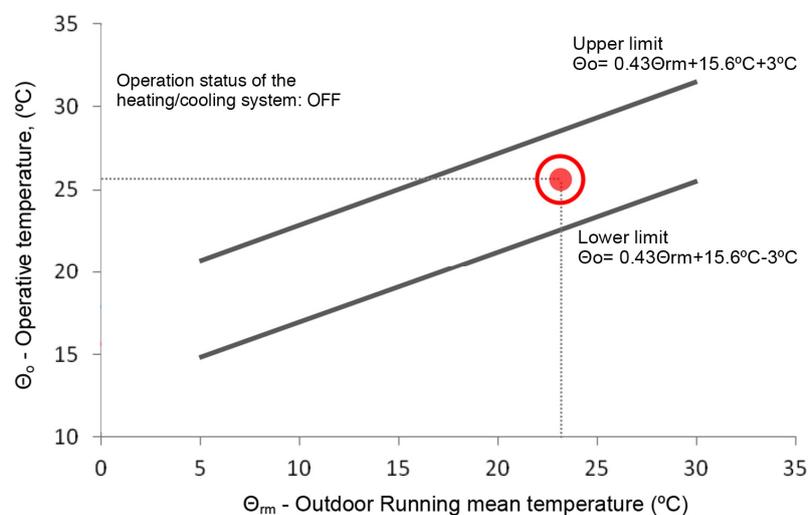

Figure 13. Thermal comfort temperature (operative temperature) in the living room during summer monitoring, based in the relation between the limits of the indoor operative temperature (Θ_o) for buildings without mechanical air-conditioning systems as a function of the exponentially-weighted running mean of the outdoor temperature (Θ_{rm}) (adapted from [22]).

3.2.2. Winter Monitoring

The winter monitoring was conducted over the period from 22 December 2014 to 7 February 2015. From the analysis of the results, it is possible to verify that during winter outdoor mean air temperature was of 7.5 °C (Table 4). During the day, the outdoor maximum air temperature rarely reached 15 °C while the minimum air temperature was frequently lower than 5 °C (Table 4).

As in the summer monitoring, despite the oscillation of outdoor temperature, it is found that indoor temperature remained very stable over the monitoring period, with air temperature values around 15 °C (Figure 14a). The spaces in the southern part of the house recorded slightly higher temperatures than the spaces in the northern part. The indoor spaces with higher temperature variation are the ones where the occupants regularly use heating equipment, namely a wood-burning stove (located in the living room) and an electric heating vent in the kitchen. In Figure 14a, it is possible to verify that, with simple heating

equipment, occupants can quickly warm the rooms up to 25 °C. After using the heating equipment, temperature falls slowly during several hours (more than 8 h in the living room) until the stabilization point.

Table 4. Comparison of outdoor and indoor air temperature and relative humidity values in case study 2 during the winter season.

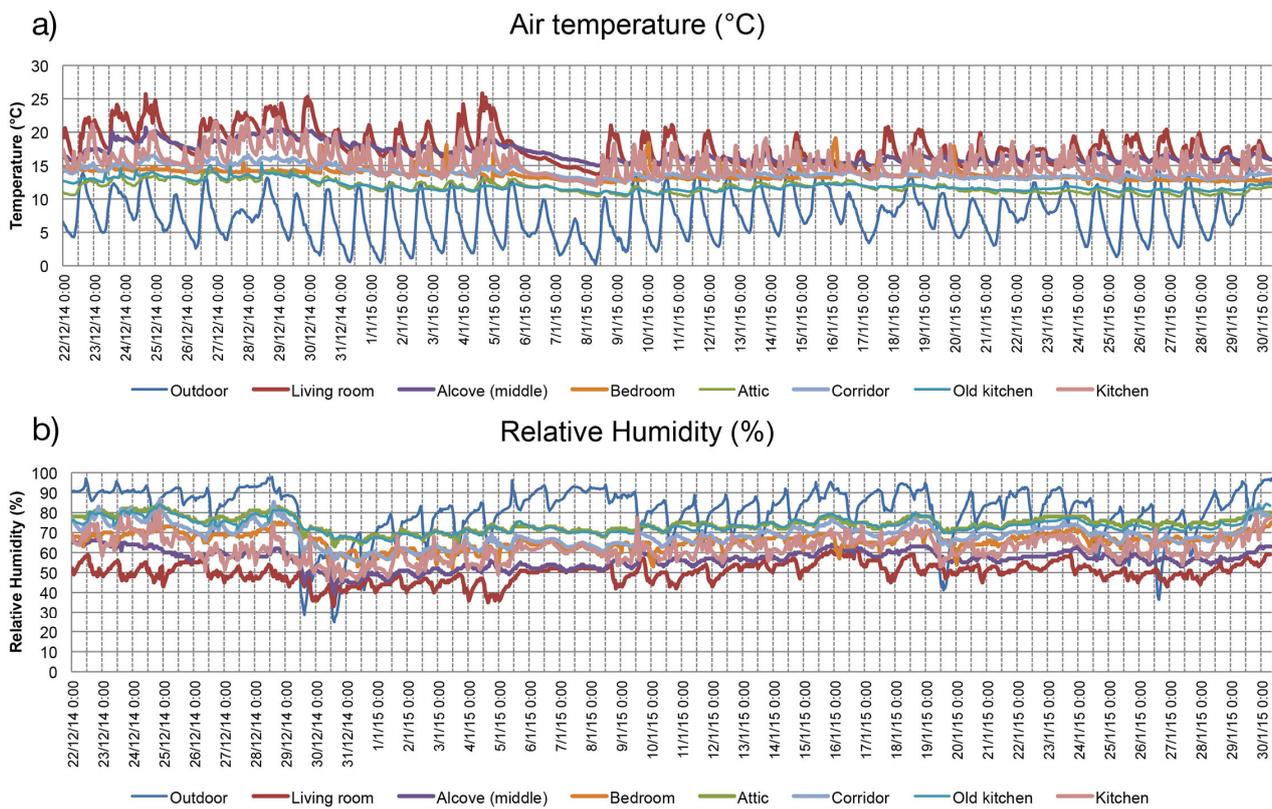| Season	Winter	Living	Alcove	Bedroom	Attic	Corridor	Old Kitchen	Kitchen
Place/Room	Outdoor	Room	(Middle)					
Temperature (°C)								
Mean	7.5	17.7	16.8	13.6	11.8	13.9	12.0	15.2
Maximum	14.8	25.8	20.7	19.3	14.4	16.6	15.4	22.2
Minimum	0.2	13.6	14.9	12.3	10.2	12.6	10.7	12.0
Relative Humidity (%)								
Mean	81	50	57	66	75	69	74	62
Maximum	98	65	69	79	86	87	84	82
Minimum	25	33	39	52	63	55	65	46

Figure 14. Case study 2 performance during winter season. (**a**) Indoor and outdoor air temperature profile; (**b**) Indoor and outdoor relative humidity profile.

In the profile of the relative humidity, it is observed that the values for the indoor spaces are very stable, though with values above 60%, except in the living room and alcove (about 50%). The periodic use of the stove in this space may be the reason for the recorded values to be lower than those recorded for other rooms (Figure 14b; Table 4).

Regarding the assessment of the thermal comfort, Figure 15 shows the results of a measurement conducted in the living room during the winter. This measurement was conducted with the wood-burning stove in operation. From the air temperature and relative humidity recorded in zones that were not influenced by the heating system, it can be deduced that the thermal sensation in the other rooms was considerably below the thermal comfort condition; while in the living room, with the stove on, it was possible to reach comfort conditions. Although the indoor temperature is considerably higher and more stable than outdoor temperatures, a heating system is required to achieve thermal comfort conditions. However, from the temperature profiles, it can be seen that, with a simple heating system, it is possible to quickly reach comfort temperatures. In the "thermal environment survey," three occupants answered as being "neutral" (comfortable) and one as being "slightly cool". Once again, the results from subjective measurements corroborated the objective measurements that show an operative temperature in the centre of the comfort range (Figure 15).
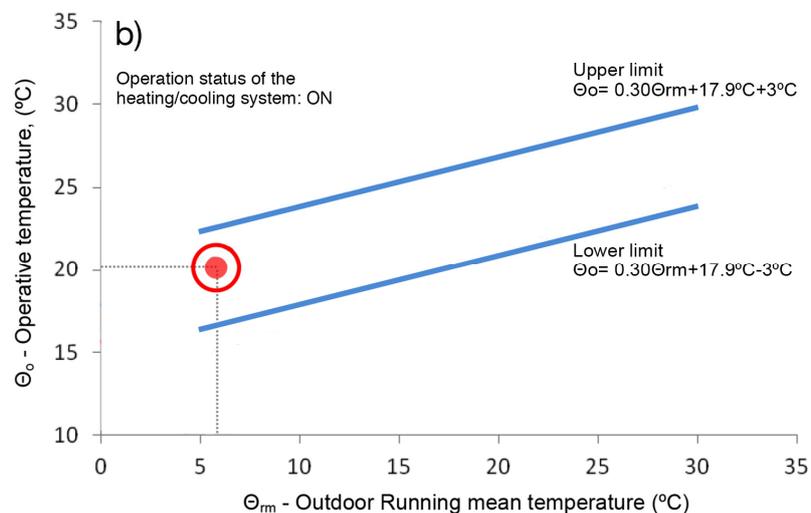

Figure 15. Thermal comfort temperature (operative temperature) in the living room during winter monitoring when the heating system was on, based in the relation between the limits of the indoor operative temperature (Θ_o) as a function of the exponentially-weighted running mean of the outdoor temperature (Θ_{rm}) (adapted from [22]).

4. Conclusions

The results of the thermal environment monitoring carried out in the two case studies during summer and winter, the two most demanding seasons in which thermal comfort is concerned, support the conclusion that it is possible to achieve indoor thermal comfort by passive means alone. During winter, in both case studies, there were periods of thermal discomfort that were overcome by using simple heating systems such as wood-burning stoves. The subjective assessment of occupants' comfort was carried out using a Thermal Environment Survey and corroborated the objective assessments, showing that the adaptive model of comfort is adequate to predict thermal comfort conditions in Portuguese vernacular buildings.

In both case studies, it was observed that the heavy thermal inertia of the envelope, a correct solar orientation, shading devices and the adequate organization of the internal spaces are fundamental aspects

to control the indoor air temperature within the thermal comfort range. It should also be noted that the action of the occupants could also positively influence the indoor temperature and humidity profiles. This demonstrates the importance of occupants in the regulation of their comfort conditions (e.g., promotion of night ventilation during the summer period, activation of shading devices, *etc.*).

Regarding the glazed-balconies, the solar orientation to the south quadrant allows them to be a privileged and effective element to capture solar gains. Considering the results obtained in this study, the balconies are architectural elements that can have a positive impact on the optimization of the passive behaviour of buildings by reducing their energy needs for air conditioning, especially for heating. If properly designed, it can be a well-integrated element in the building with all the inherent functional advantages.

From the analysis of the rammed-earth case study located in the south, in the Alentejo region, it is possible to conclude that the use of a combined set of passive strategies has an adequate response to the intense heat during the summer period. The combination of passive cooling strategies allowed ensuring thermal comfort conditions just by passive means, without the use of any mechanical cooling system. The adoption of such strategies in buildings from this region can greatly contribute to reduce energy needs for cooling and therefore to reduce energy use and potential environmental impacts during the operation phase.

Taking into consideration the results presented in this study, it can be stated that solar passive strategies used in vernacular architecture for generations to mitigate the effects of climate, due to their simplicity and pragmatism, have significant potential to be improved and adapted to contemporary construction. Thus, if properly considered in the design stage, vernacular passive strategies can be an asset for buildings that are intended to concomitantly reach thermal comfort conditions while reducing energy consumption. Therefore, this is an on-going research work that intends to collect more detailed and comprehensive data on the contribution of vernacular passive solar strategies, in order to be useful for architects and engineers involved in the development of climate-responsive and energy-efficient buildings.

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Author Contributions

Jorge Fernandes undertook the main body of the research to develop this paper and performed the fieldwork with the help of Carlos Pimenta. The paper was written with the contribution of all authors. Ricardo Mateus, Sandra M. Silva and Luís Bragança helped to shape the discussion sections of the paper and provided critical judgment on the research being undertaken.

Conflicts of Interest

The authors declare no conflict of interest.

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