Article

Thermal Comfort Assessment during Winter Season: A Case Study on Portuguese Public Social Housing

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Abstract: Many public social housing building stocks were constructed before the introduction of national thermal regulations, and, as a result, in some situations, energy poverty conditioning during severe winter seasons results in little to no heating habits involving active systems in order to improve building thermal performances. Besides rigorous summer seasons, climate change predictions also indicate rigorous winter seasons will occur that will prevail in some Iberia Peninsula locations, worsening this scenario for this Southern European region. Among others, understanding the extension of discomfort in social housing buildings during heating seasons is therefore essential so as to perceive the suitability of the building stock to deal with present and future climate scenarios. Thus, this article presents a thermal comfort assessment during a winter season period applied to two social housing dwellings located in Covilhã, Portugal, inhabited by elderly residents, under realistic heating habits. An experimental campaign was performed and the results show that discomfort was found to be extremely significant for the majority of the occupied time. Passive means alone and resident heating habits were not enough to achieve proper indoor thermal and humidity conditions, resulting in important losses of well-being to the risk group of the elderly.

Keywords: energy poverty; social housing; winter season; building thermal performance; comfort

1. Introduction

1.1. Energy Poverty

Besides the decrease in energy consumption, the eradication of energy poverty and the mitigation of climate change are currently considered the main challenges related to the building sector [1].

Among other definitions [2], energy poverty is defined as the inability of family units to pay energy bills and maintain comfortable indoor living standards. The repercussion of this phenomenon in Europe affects 50 to 125 million people, and is regarded by the European Commission as an urgent, but complex issue to solve, considering the interaction between diverse energy, social, and economic contexts [3,4]. For users who spend a significant amount of time in their dwellings—whether for personal, professional, or health issues, or due to special events such as the coronavirus pandemic—their wellbeing is directly affected once they are forced to experience several hours of thermal discomfort. This has a considerable impact on human health, especially for groups of people that present great vulnerability, like the elderly, who have already been the focus of some developed studies [5] and official guidelines [6] worldwide, especially concerning health issues that may even be associated with a risk of death [4]. Southern European countries are identified as some of the most vulnerable regions for energy poverty, where heating and cooling habits through the evolution of seasons in housing buildings are mainly intermittent or insignificant, regarding the use of active systems to correct poor building performances [7]. The European Energy Poverty Observatory established several indicators for the proper quantification and evaluation of energy poverty, considering that many Southern European
countries present concerning results related to energy poverty exposure [8]. Portugal is ranked as one of the worst countries regarding important indicators like electricity/gas prices for the residential sector and the feasibility to obtain comfortable indoor thermal conditions in summer and winter seasons [8]. This is because Portuguese family units present a median disposable income that is 39% lower than the European Union average, although its gas and electricity prices are some of the highest [7]. Although Portugal presents smoother winter seasons compared with other European countries, they are particularly challenging as users cannot afford the energy costs to maintain properly heated homes; therefore, it has the fifth worse rank among European Union countries regarding this issue, with an estimated 19% of the population being exposed to this phenomenon [9]. Some national strategies are already being implemented to deal with this problem, such as the National Energy and Climate Plan [10], which aims to properly perform a diagnosis and characterization of the existing limitations, as well as establish monitoring indicators and national, regional, and local objectives.

1.2. Climate

The climate also plays a decisive role in defining the conditions in which proper indoor thermal performances can be achieved. Current climate scenarios in Southern European countries where Mediterranean climate zones prevail indicate severe summer seasons in many regions with high mean temperatures and intense solar radiation, although winter severity is also highlighted as being rigorous in specific geographic conditions such as the site altitude [11]. Several reports of the Intergovernmental Panel on Climate Change (IPCC) highlight multiple consequences of the impact of climate change, resulting in future climate scenarios characterized by increases in temperature and sea level, with it being expected that Southern Europe will experience considerable adverse effects such as more frequent extreme events, as summer severity will increase and winter seasons are predicted to become smoother [12,13]. Within Southern European countries climate scenarios, the Iberian Peninsula is a particular region that presents different climatic zones that, depending on the altitude and latitude, can strongly differ from nearby locations, as the central and northern regions present considerable demanding heating seasons in many locations, in contrast with southern regions where winter seasons are milder [11]. In Portugal, regions such as the Beira Interior and Trás-os-Montes, located in the inner central and northern regions, respectively, present the country’s highest heating degree days (HDD) in many locations, with values mainly between 1800 HDD and 2000 HDD [14]. Thus, in contrast with other Southern European regions, predicted winter seasons for these specific Iberia Peninsula locations indicate that they will maintain a rigorous profile: for instance, Burgos (Spain), Guarda (Portugal), and Bragança (Portugal) predictions for the Representative Concentration Pathway (RCP) 8.5 scenario indicate around 5.5 °C and 7.0 °C monthly mean temperatures in heating seasons for 2050 and 2080, respectively, and monthly mean minimum temperatures of around 2.5 °C and 4.0 °C, respectively [15]. For the specific case of Portugal, which is consistently identified as the country with the highest number of excess winter mortalities in Europe [11], the fact that the energy poverty impact will remain during winter seasons for many of its locations must be considered as an urgent matter.

1.3. Public Social Housing Building Stock

Within the stock of housing buildings and considering the above-mentioned scenario, public social housing—understood as buildings with construction made or supported by national housing programs, for, among others, low and medium income residents who could not afford to buy their homes in the regular private market [16]—represent a relevant field of study in Southern European countries, considering its pivotal role in meeting the housing needs for disadvantaged sections of the population. The impact of energy poverty is considerable in these contexts regarding the use of active systems to achieve suitable indoor conditions, considering that in Southern European countries such
as Portugal and Spain, the majority of neighborhoods present no relevant heating and cooling habits [17], which is the reason proper thermal behaviors are imperative. In fact, the risk of energy poverty can also be the result of a poor thermal and energy performance of buildings [4], whose comfort requirements are expected to increase due to the mentioned climate change impact. Southern European countries currently present an aged building stock, with about 70% having been constructed prior to the implementation of national thermal regulations [4,18], resulting in poor performances regarding indoor environmental conditions. The European Union has implemented relevant legislative frameworks, such as the Energy Performance of Buildings Directive 2010/31/EU and the Energy Efficiency Directive 2012/27/EU, amended by Directive (EU) 2018/844, highlighting improvements needed for energy performance and thermal comfort; thus, several studies have been carried out in Southern European countries regarding, among others, passive measures for the design of new buildings [19,20] and constructive retrofit measures to improve the existing ones, for either actual [21,22] or future [18] climate scenarios. Regarding the specific case of Portuguese public social housing, an important part of its stock was constructed before 1990 as a result of several national housing guidelines during the 20th century [16], before the implementation of the first national thermal regulation (D.L. 40/90 of 6 February). This resulted in solutions that lacked the quality of materials and constructive processes used until then, without proper thermal criteria in the building envelope design. Thus, some projects were also designed using typologies and constructive systems so as to facilitate their quick replication across several Portuguese locations [16], some of them presenting severe climate conditions. Winter seasons must be regarded with a high importance for this issue, considering their repercussions through significant losses in the well-being of users and resulting in health issues, as economic conditioning implies little or no heating habits in the majority of cases [23].

1.4. Indoor Thermal Conditions during Winter Seasons

Several studies [24–26] regarding Southern European countries’ housing have focused on specific issues to solve or minimize residents’ vulnerability to energy poverty, such as a reduction of energy consumption and energy efficiency improvements. Nevertheless, some authors’ [7,17,23] approach towards Southern European country studies have been focused on minimizing thermal discomfort in scenarios with little to no energy consumption for heating practices, in contrast with Central or Northern Europe, where users have strong practices of heating and for whom the focus should rely on energy efficiency. Therefore, several studies in Southern European countries regarding thermal comfort assessments in social housing buildings based on experimental campaigns during rigorous winter seasons have been developed. Ramos et al. [27] performed monitoring campaigns and assessments of the thermal indoor condition quality during occupancy periods in two neighborhoods—one rehabilitated and another non-rehabilitated—located in Porto. Curado [23] performed an extensive monitoring campaign and comfort assessments in several retrofitted dwellings, also located in Porto. These procedures were also considered as part of more embracing studies. Curado and Freitas [17] studied the influence of thermal insulation of facades on the performance of retrofitted buildings, using experimental measurements in a neighborhood so as to validate a dynamic numerical simulation model for a reference dwelling in order to assess thermal comfort in eight different Iberian climates. Alonso et al. [28] proposed a methodology to characterize the existing conditions in dwellings located in Madrid, so as to identify the main factors regarding proper energy retrofit measures, with indoor measurements during winter seasons being performed and included in the proposal. Soares et al. [29] approached other useful topics related to this area, using on-site measurements taken during winter seasons to study of the perception of users about their living conditions, habits, health, and quality of life, considering retrofitted and non-retrofitted neighborhoods of Porto.
1.5. Objectives

Considering the lack of literature found for the specific Iberia Peninsula location of Beira Interior and/or similar climate scenarios regarding public social housing building thermal and comfort performances, this article aims to provide a contribution through an experimental campaign and comfort assessment applied to a case study located in the city of Covilhã during a winter season period. A precast concrete building that was replicated across some Beira Interior locations was selected, as concrete precast systems are more abundant in Eastern Europe—studies regarding Portuguese public social housing are common in buildings where stone or brick masonry systems are applied—so perceiving their performance in built environments under demanding climate conditions and realistic heating habits is considered as highly relevant. Two dwellings inhabited by elderly residents were analyzed, aiming to provide an understanding of the extension of discomfort in this region under the influence of the resident’s realistic heating habits, so as to perceive the resilience of public social housing buildings to provide acceptable indoor conditions in order to face present and future climate scenarios. This contribution provides improved and more comprehensive databases on real and measured building use under specific behaviors and lifestyles, in order to allow for developing research paths, guidelines, and programs for planners and stakeholders interested in public social housing buildings improvement applicable to similar contexts within Southern European countries.

2. Materials and Methods

The main objective of this study was to assess the comfort performance of two public social housing dwellings located in Covilhã inhabited by elderly residents, which were monitored during a winter season period. This section provides the information about the materials and methodology used.

2.1. Case Study

The Beira Interior region in Portugal was delimited in this work as the set of units “Beiras e Serra da Estrela” and “Beira Baixa”, according to national nomenclature of territorial units for statistical purposes (NUTS III), as this region is one of the Portuguese zones that presents the most severe scenarios for winter and summer seasons, according to Figure 1. In Figure 1, the climate severity is represented for winter and summer seasons according to the Portuguese national building energy performance certification system [14].

![Figure 1. Portuguese climate scenarios for winter and summer seasons.](image)

The main cities located in the northern unit, “Beiras e Serra da Estrela”, present more rigorous winters, while the ones in the southern unit, “Beira Baixa”, normally present more severe summers, and have similar climate scenarios compared to nearby Spanish northern and southern provinces, Salamanca and Cáceres, respectively [11,14]. Although
future climate scenario projections indicate a progressive increase in temperature and the occurrence of more frequent and severe heatwaves for the Beira Interior, winter seasons must also be regarded with particular caution, as they are expected to present a slightly reduced severity but still a rigorous profile [30], as the geographic and topographic specificities result in cities located at considerably reference altitudes, such as Guarda (1000 m), Manteigas (800 m), and Covilhã (650 m) [14].

Regarding the Beira Interior housing building stock, buildings constructed until 1990 represent 62% of the local social housing, with the predominant ones built between 1975 and 1990 [31] in a flourishing period of construction supported by a considerable amount of housing national policies [16]. Multifamily buildings were identified as being predominant when considering the amount of dwellings covered.

Covilhã, part of the “Beiras e Serra da Estrela” unit, was the city chosen to perform the present study. It is the Beira Interior city with the most social housing buildings constructed before 1990 [31], representing a considerable amount of diverse interventions that took place during the 20th century with the need for significant thermal improvements. Thus, studies focused on mapping energy poverty in Portugal identified this city as having a considerable vulnerability to the energy poverty phenomenon in housing contexts, with several locations ranked as the highest for winter seasons [3]. The following meteorological data of some winter season months for the 2000–2019 period, as for predicted by RCP 8.5 scenario for 2050 and 2080, are specified in Table 1 [15].

| Period and Month | GR [kWh/m²] | Tₐ [°C] | T_max [°C] | T_min [°C] | RH [%] | PP [mm] | WS [m/s] |
|------------------|-------------|---------|------------|------------|--------|--------|---------|
| 2000–2019        |             |         |            |            |        |        |         |
| December         | 57          | 7.6     | 10.9       | 4.8        | 78     | 126    | 3.7     |
| January          | 64          | 6.7     | 10.1       | 3.9        | 78     | 129    | 3.5     |
| February         | 85          | 7.5     | 11.4       | 4.1        | 71     | 87     | 3.8     |
| 2050 (RCP 8.5)   |             |         |            |            |        |        |         |
| December         | 60          | 8.9     | 12.2       | 6.1        | 79     | 116    | 3.7     |
| January          | 66          | 8.0     | 11.4       | 5.3        | 79     | 122    | 3.5     |
| February         | 89          | 8.6     | 12.4       | 5.4        | 72     | 80     | 3.8     |
| 2080 (RCP 8.5)   |             |         |            |            |        |        |         |
| December         | 61          | 10.1    | 13.4       | 7.4        | 79     | 115    | 3.7     |
| January          | 69          | 9.3     | 12.7       | 6.4        | 79     | 114    | 3.5     |
| February         | 95          | 9.5     | 13.4       | 6.0        | 72     | 86     | 3.9     |

GR: irradiation of global radiation on horizontal surface; Tₐ: average temperature; T_max: maximum average temperature; T_min: minimum average temperature; RH: average relative humidity; PP: precipitation; WS: wind speed.

The public social housing building chosen here as the case study was built in the late 1970’s, as part of a national program created in 1976 called CAR, a refugee housing commission that aimed to provide a quick answer to the housing needs Portuguese families that returned during decolonization. For this reason, the building was constructed according to the previously mentioned precast concrete constructive system in order to get fast construction times. The analyzed project has been replicated in other Beira Interior buildings in cities such as Castelo Branco and Fundão, making this case study interesting because of its representativeness. A considerable variety of construction systems and typologies were applied in Portuguese public social housing during the 20th century [16], with precast systems comprising some innovative features applied in the envelope components, such as thin thermal insulation layers, comparing with other applied systems that used granite or hollow brick masonry without any insulation applied.

The selected building has four residential floors (including the ground floor, where the entrance is located), with all four facades exposed. Each floor of the building has four dwellings, and each dwelling consists of a one- or two-bedroom typology, with a living/dining room, a bathroom, and a kitchen with an extension area for laundry. The
average area is around 50 m² for dwellings with one bedroom and 60 m² for dwellings with two bedrooms, with the ground floor having four dwellings—two dwellings with one bedroom and two dwellings with two bedrooms—while each of the upper floors have four dwellings with two bedrooms each. Regarding each of the dwelling glazed areas, they represent around 15% of the pavement area. The dwellings studied in this research are both located on the ground floor and are both inhabited by one elderly resident each: Dwelling A has only one bedroom and has two exposed facades (east and south oriented), while Dwelling B has two bedrooms and two exposed facades (north and west oriented). Figure 2 represents the building ground floor plan.

![Case study: ground floor plan with sensor positioning in Dwellings A and B.](image)

Table 2 synthetizes the building’s physical characteristics, which were obtained through on-site visits and sorting through the respective municipality archives. Conversations with residents, onsite visits, and municipality data revealed that no relevant modifications to the external envelope were made.

| Component            | Description                                      | Thickness [mm] | U-Value [W/m² °C] |
|----------------------|--------------------------------------------------|----------------|-------------------|
| External walls       | Precast concrete panel (30 mm Expanded Polystyrene within) | 150            | 0.99              |
| Internal partitions  | Precast concrete panel                           | 100            | 3.15              |
| Floors and ceilings  | Concrete beam/block slab (no thermal insulation)  | 180–250        | 1.85–2.32         |
| Glazing and windows  | Aluminum frame (no thermal break) Single clear 3 mm glazing Outside uninsulated PVC roller shutters | -              | 3.90–6.50         |

2.2. Methodology

A three-stage methodology was considered in order to assess comfort vulnerability in both dwellings: (1) the first stage consisted of obtaining qualitative data through questionnaires delivered to residents in order to provide an initial understanding about the dwelling occupancy habits; (2) the second stage consisted of obtaining quantitative data regarding the dwelling performance under occupant behaviour through monitoring the indoor temperatures and relative humidity during a specific heating season period; and (3) the third and final stage consisted of plotting the monitored indoor temperatures against the proper comfort standards so as to perceive the extent of discomfort, as well as the
conformity of the monitored relative humidity values regarding the recommended indoor ranges.

2.2.1. Qualitative Data

Qualitative data were obtained through qualitative research, which consisted of developing and providing a questionnaire to occupants regarding their occupancy and heating habits during winter seasons. The questionnaires were a mix of two types of qualitative interviews: structured and semi-structured. Structured interviews consisted of questions with a fixed choice response, while semi-structured interviews consist in questions with open-ended response, which also gathered specific details about occupancy. The residents were asked about their inhabited periods in each room, main activities during occupancy periods, window and shutter operation, heating habits using active systems, further strategies used to reduce discomfort, possible relevant sources of internal gains, and their perception about the building constructive and insulation quality. However, the residents were unavailable to record information related to clothing and specific characteristics of the activities carried out throughout the day, as well as their specific schedules. Questions about dwelling evaluation were also included in the questionnaire, regarding dwelling constructive and thermal insulation quality, and specifications or conditioning regarding the use of active systems. Qualitative data were then used to validate the findings of the quantitative data, mainly referring to occupant behavior for correcting or minimizing eventual poor building performance—a procedure that was used in other studies related to social housing contexts both on an individual and/or collective level [5].

After conversations with residents, the living rooms and the used bedrooms were identified as the areas with the longest occupancy time, and were thus the rooms analysed in this study. Although data were obtained about how and when these areas were used, allowing for the definition of occupancy profiles for winter season, residents mentioned that eventually, slight variations to this occupancy might occur in some days, mainly regarding occupied times and heating habits. Considering that no further data could be obtained to provide information for each of the monitored days, the occupied periods mentioned in the questionnaires for each division were the ones considered for the comfort assessment of the monitored indoor temperature values and relative humidity analysis.

2.2.2. Quantitative Data

Quantitative data were obtained through quantitative research, which consisted of an experimental campaign to provide real data about the dwelling performance through the monitored period under typical occupancy behavior. Once some conditioning were found regarding the installation of specific equipment in the studied rooms, only temperature and relative humidity were monitored during the 2020 heating season in the studied areas for Dwellings A and B, according to Figure 2, using bedrooms and living rooms, as well as outdoor conditions. As limitations accessing the dwellings and the outbreak of the coronavirus pandemic limited the experimental campaign during the entire heating season, the results are presented for a representative period when the residents’ heating habits enabled a consistent understanding of the occupancy impact in both dwelling performances, namely from 28 January 2020 to 10 February 2020. Five data-loggers (Lascar Electronics EL-GFX-2) were used as measuring instruments and were programmed to register the existing temperatures and relative humidity every 10 min. These loggers had ranges of \(-30\) °C to 80 °C and 0% to 100%, respectively; a typical accuracy of \(\pm 0.5\) °C and \(\pm 3\)%, respectively; and they were positioned as defined in Figure 2, 1.1 m above the floor surface, having been assured proper protection from close sources of internal gains and/or solar radiation.

2.2.3. Comfort Assessment

An extensive review of thermal comfort models based on people’s thermal sensation to several environments can be found in [32], and specifically for human thermal comfort
in the built environment in [33]. Thermal comfort, defined as “that condition of mind that expresses satisfaction with the thermal environment” [34], is generally assessed in the built environment using two different conceptual approaches: the static model and the adaptive model. The static model is mainly derived from experiments in climate chambers [35] and uses an approach based on a balance between building occupant metabolic heat production and its interaction with indoor environmental conditions, considering individuals as the only recipients of the thermal stimulus. The adaptive model uses an approach that considers the interaction between occupants’ physical and psychological conditions with the indoor environmental conditions, as well as a correlation between the perception of comfort temperature and outdoor temperature. The concept that the individual will react in order to restore or maximize their thermal comfort conditions exposed to a thermal stimulus (through the use of simple procedures, such as adding more clothes or the use of specific building components) is aligned with typical Portuguese social housing heating/cooling habits, once economic conditioning makes the occupants’ interactions with themselves and the building decisive to define specific indoor conditions [23]. The adaptive model is therefore suitable to assess thermal comfort in a Portuguese public social housing case study and was chosen as the primary model, although for comfort assessments the authors of [18] also considered it useful to compare the results obtained with the static model and the adaptive model in order to better understand the thermal comfort behaviour. This is why this procedure was selected for this study, in order to enlarge the building performance understanding regarding the likely reality of intermittent or no heating habits recurring in active systems.

Regarding the adaptive model, a review about the adaptive thermal comfort models and its integration in built environmental regulatory documents is extensively described in [34,36], as, among the several available possibilities, the ASHRAE 55–2017 and the European standard EN 16798–1:2019 are currently the two documents regarded as international standards for adaptive thermal comfort and have been used in several studies worldwide [37]. Although both documents consider that comfort temperature inside buildings depend on the variation of outdoor temperatures in the preceding days, the EN 16798–1:2019 [38] was chosen for this study as it includes the adaptive thermal comfort model developed and applicable for Europe, and it constitutes the modification of the previous standard (EN 15251:2007), for which relevant data source was collected in several locations (including Portugal) so as to define the model. The model derives a simple linear relationship between indoor comfort conditions and the outdoor temperature, considering some of Fanger’s conventional thermal comfort factors such as clothing insulation and metabolic rate, which present a significant correlation with outdoor air temperature [39]. Once relative humidity and air velocity were shown to not strongly depend on the outdoor air temperature, they were not included in the model, despite their relevance in defining thermal comfort conditions [40]. The model has an applicability for buildings without mechanical cooling systems, as well as human occupancy with mainly sedentary activities—ranging from 1.0 to 1.3 met—where occupants have easy access and the possibility of opening and closing operable windows located in the building envelope, and are also able to freely adapt their clothing to indoor and/or outdoor thermal conditions. It is structured defining the informative default choices that are considered in this study. Default values are given for a specific category of indoor environmental quality, related to the level of expectations the occupants may have, considering that for elderly occupants the standard recommends the selection of Category I, corresponding to a high level of expectation for users with less thermal adaptation. The so-called adaptive criteria consists of the definition of upper and lower temperature limits that change with the running mean outdoor temperature, considering residential buildings used mainly for human occupancy with sedentary activities, where easy access to operable windows or clothing adjustments are available. Upper 1 and Lower 1 limits for the Category I indoor environmental level (EN-C1) are defined considering 2 °C above and 3 °C below the optimal operative temperature ($T_c$),
respectively, which satisfies the greatest percentage of occupants at a given clothing and activity level in the current thermal environment, and is calculated through Equation (1):

\[ T_c = 0.33 \ T_{rm} + 18.8 \]  

(1)

Exterior conditions are considered in the form of the weighted running mean of the daily mean outdoor temperature \( T_{rm} \). \( T_{rm} \) is calculated according to Equation (2):

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

(2)

The outdoor mean air temperature of the previous days \( T_{n-i} \) is considered, specifying that the limits only apply for a \( T_{rm} \) range from 10 °C to 30 °C. If \( T_{rm} \) is outside this range, the standard assumes that mechanical cooling or heating systems have to be installed and operated according to specific setpoint conditions, and the indoor temperature would decouple from the external conditions. The work by Sánchez-García et al. [41] highlighted the possibility of horizontally extending the maximum and minimum comfort limits of the adaptive model as static setpoint temperatures, which was considered in this study so as to achieve moderate and realistic values. Regarding winter season applicability, the standard applies the adaptive criteria for summer and intermediate seasons for buildings without mechanical cooling, although it is also stated that, among others, the criteria required for its use should be defined by individual project specifications: the use of adaptive models for winter seasons, in cases where heating systems have intermittent or no usage at all, were already applied in some studies [17,23], considering their suitability for applications in low-income buildings in Southern European countries [17], which was why both Upper 1 and Lower 1 thresholds were considered in the study.

Regarding the static model, considering its importance in the definition of reference conditions for a significant number of thermal regulations in European Union member states so as to improve their building stock energy efficiency, the framework provided by EPBD 2010/31/EU and transposed for the Portuguese thermal regulation through the National Building Energy Performance Certification System—the “Sistema de Certificação Energética” (SCE)—was considered in this study [42]. The framework provides energy certificates for residential buildings, defining the nominal energy consumption needed so to achieve the predefined comfort conditions. These conditions are independent of exterior conditions and were established as fixed comfort temperature limits for energy calculation demand purposes, where indoor acceptable values are non-adjustable to individual or environmental variables—defined as air temperature values within the range from 18 °C (Lower SCE) to 25 °C (Upper SCE). Thus, among other features, the energy certificates identified proper constructive measures so as to improve the thermal conditions and energy efficiency of the existing building, and are currently a key tool to diagnose and support decision making in order to intervene in the existing building stock—which is the reason this model was also chosen.

Figure 3 shows the above-mentioned thresholds of the selected approaches to perform comfort assessment. Reference standards [38,43–46] define the operative temperature, among others, as a key variable for assessing the likely thermal comfort of the occupants of a building. In order to overcome existing limitations in obtaining the data needed to calculate operative temperatures for EN-C1, these were simplified as the monitored indoor temperatures, which are the ones required for SCE. Nevertheless, some comments must be made regarding this issue. ASHRAE 55 allows for the use of indoor air temperature as a simplified approximation of the comfort operative temperature if some conditions are fulfilled, mainly related with the inexistence of both indoor radiant heating/cooling panels and the relevant heating generating equipment, as well as the average U-factor of the building vertical envelope and the window solar heat gain coefficients. Experimental investigations regarding this subject can also be found, such as the one by Matias [47], which was performed in several building typologies such as schools, office buildings, and residential buildings—the latter including nursing homes—so as to evaluate indoor
comfort conditions. Several indoor and outdoor environmental variables were monitored, enabling the analysis of the correlation between air temperature and operative temperature, with the Pearson correlation coefficient observed between those variables being 0.99, so for those case studies air temperature was considered as an approximated value of the operative temperature. Thus, despite the fact that using indoor air temperature as the dominant factor for the adaptive approach can be pointed out as a potential limitation, this procedure in residential contexts can also be found [17,23].

Therefore, the monitored indoor temperature values corresponding to the occupied periods of each division were then plotted against the considered static and adaptive models thresholds, and when a non-compliance with those limits was verified the room was considered to be in discomfort for that time period.

Regarding relative humidity, EN 16798-1 [38] establishes the design criteria for the relative humidity in occupied spaces, where for Category I buildings a range between 30% and 50% is recommended. Therefore, in order to analyze how acceptable the indoor humidity conditions are, an analysis of the conformity of the relative humidity values obtained with that range was also taken into account.

3. Results

3.1. Qualitative Research

The information obtained from the questionnaires is synthetized in Table 3. Both dwellings presented some similar occupancy characteristics, with sedentary activities identified as being usual during the occupied period, which, according to ISO 7730 [45], are defined as 1.2 met. Once specific bedtime period schedules weren’t obtained, all occupied periods were considered with this metabolic rate, complying with the defined adaptive model range. Regarding the use of building components, possible solar gain restriction due to activated glazing protections is noticeable. Information about internal gains from sources such as lighting and equipment were considered to be aligned with typical housing internal gains at a low level [48], and window opening for air renewal was only performed for brief periods. Regarding specific heating habits, economic conditioning had a significant impact on the use of active systems—both residents only used portable fan heaters for some time periods—with an increase in clothing thermal insulation being the common strategy.
to work around this limitation, with no specific health problems demanding particular thermal conditions mentioned.

Table 3. Qualitative data obtained from questionnaires to occupants.

|                        | Dwelling A                                                                 | Dwelling B                                                                 |
|------------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| **Occupancy**          |                                                                             |                                                                             |
| Main activities        | Living room: weekday and weekend from 09:00 a.m. to 21:00 p.m.               | Living room: weekday and weekend from 18:00 p.m. to 19:00 p.m.               |
| during inhabited       | Bedroom: weekday and weekend from 21:00 p.m. to 07:00 a.m.                  | Bedroom: weekday and weekend from 19:00 p.m. to 10:00 a.m.                   |
| periods                |                                                                             |                                                                             |
| Inhabited periods      |                                                                             |                                                                             |
| schedules              | External roller shutters: Living room: partially closed during occupied     | External roller shutters: Living room: partially closed during occupied     |
|                        | periods (sometimes); totally closed during unoccupied periods                | periods (sometimes); totally closed during unoccupied periods                |
| Window protection      | Bedroom: totally closed during occupied periods; partially or totally closed| Bedroom: partially or totally closed during occupied periods; totally closed|
|                        | during unoccupied periods (sometimes)                                       | during unoccupied periods                                                   |
| Window opening         | Living room: brief periods during the morning or afternoon                  | Living room: unusual                                                       |
| for air renewal        | Bedroom: brief periods during the morning                                     | Bedford: brief periods during the morning                                   |
| Heating habits         | Living room: portable fan heater, used for brief periods in the mornings     | Bedroom: portable fan heater, mainly used from early night until bedtime    |
| using active systems   | and/or afternoons                                                           | periods during few hours, and occasionally during brief periods during the  |
|                        | Bedroom: unusual                                                            | morning and/or morning                                                      |
| Strategies to          | Clothing (usual) and hot-water bottles during night periods                  | Clothing (usual)                                                           |
| reduce discomfort      |                                                                             |                                                                             |
| Internal gains         | Typical housing lighting and equipment—low                                  | Typical housing lighting and equipment—low                                  |
| Dwelling evaluation    |                                                                             |                                                                             |
| Constructive quality   | 2                                                                            | 2                                                                            |
| (scale 1–5, 5 max.)    |                                                                             |                                                                             |
| Insulation quality     | 1                                                                            | 1                                                                            |
| (scale 1–5, 5 max.)    |                                                                             |                                                                             |
| Considerations         | When discomfort is more difficult to tolerate                               | When discomfort is more difficult to tolerate                               |
| regarding the use of   | Intermittent use (high energy costs)                                        | Intermittent use (high energy costs)                                        |
| active systems for     | No specific health problems                                                  | No specific health problems                                                 |
| heating                |                                                                             |                                                                             |

Regarding their perception about the building’s constructive characteristics, residents identified it as having a low quality, besides lacking proper thermal insulation.

Regarding specifically each of the analyzed dwellings, Dwelling A presented a predominant occupancy during daytime periods in the living room and during early night and bedtime periods in the bedroom, with active systems normally used only in the living room as during night time strategies such as clothing and hot-water bottles were used to minimize the effect of lower indoor temperatures. Dwelling B presented a predominant oc-
cupancy during late afternoon in the living room and during early night until mid-morning in the bedroom, where active systems were normally used before bedtime.

3.2. Quantitative Research

The obtained monitored values from the performed experimental campaign applied to the dwellings are specified below. These could not be compared with data from the Portuguese Institute for Sea and Atmosphere (IPMA), as the local weather station was inoperative for a significant amount of time when the monitoring campaign was performed.

In Figure 4 the resulting monitored outdoor and indoor air temperatures are shown. In Table 4, some indoor and outdoor air temperature statistical variables for the entire monitored period are defined. A one-way analysis of variance (ANOVA) was also performed so as to identify statistically significant differences for the mean achieved temperatures, followed by a post hoc Tukey’s HSD test if a statistical significance between the groups was detected. The obtained results are shown in Table 5.

![Monitored air temperatures](image)

**Figure 4.** Monitored air temperatures.

| Test  | Significance (\(\alpha\)) and Critical Value
|-------|----------------------------------|
| ANOVA | \(\alpha = 0.05\) | F\(_{crit}\) = 2.61 - F-statistic: \(F = 1269.82\) \(p\)-value: \(p = 0\) |
| Tukey HSD | \(\alpha = 0.05\) | Q\(_{crit}\) = 3.63 |

**Table 5. Significant results from one-way ANOVA tests and post hoc Tukey’s HSD test.**

| Test  | Significance (\(\alpha\)) and Critical Value
|-------|----------------------------------|
| ANOVA | \(\alpha = 0.05\) | F\(_{crit}\) = 2.61 - F-statistic: \(F = 1269.82\) \(p\)-value: \(p = 0\) |
| Tukey HSD | \(\alpha = 0.05\) | Q\(_{crit}\) = 3.63 |

This information is also presented according to the air temperature frequency (Figure 5). Outdoor temperature includes all measurements obtained from the previously mentioned monitoring period, while indoor temperatures only include measurements within the occupied periods of the respective analyzed area, according to schedules defined in Table 3. This allowed for a more clear understanding of indoor conditions during inhabited periods.

![Temperature frequency](image)

**Figure 5.** Temperature frequency.

**Table 4.** Indoor and outdoor air temperature statistical variables for the monitored period.

|                  | \(T_o\) [°C] | \(T_{max}\) [°C] | \(T_{min}\) [°C] | \(T_{maxP}\) [°C] | \(T_{minP}\) [°C] | SD [°C] | V [°C] |
|------------------|--------------|-----------------|-----------------|-----------------|-----------------|---------|-------|
| Outdoor          | 11.9         | 15.1            | 9.7             | 17.2            | 8.1             | 1.9     | 5.4   |
| Dwelling A living room | 15.4       | 17.5            | 14.7            | 18.5            | 13.3            | 0.9     | 2.8   |
| Dwelling A bedroom | 14.9        | 15.5            | 14.6            | 16.4            | 13.0            | 0.9     | 0.9   |
| Dwelling B living room | 13.9       | 14.1            | 13.7            | 14.9            | 12.2            | 0.8     | 0.4   |
| Dwelling B bedroom | 16.0        | 20.0            | 14.6            | 20.9            | 13.1            | 1.7     | 5.3   |

\(T_o\): Average temperature; \(T_{max}\): Maximum average temperature; \(T_{min}\): Minimum average temperature; \(T_{maxP}\): Maximum temperature during the entire monitored period; \(T_{minP}\): Minimum temperature during the entire monitored period; SD: Standard deviation; V: Daily average temperature variation.
Table 5. Significant results from one-way ANOVA tests and post hoc Tukey’s HSD test.

| Test       | Significance (α) and Critical Value | Honestly Significant Difference (HSD) | Results                                                                 |
|------------|-------------------------------------|--------------------------------------|-------------------------------------------------------------------------|
| ANOVA      | F = 0.05, F_{crit} = 2.61           | -                                    | F-statistic: F = 1269.82<br><br>p-value: p = 0<br><br>Mean difference, i−j：<br>DA living room/DA bedroom: +0.49<br>DB living room/DB bedroom: −2.14<br>DA living room/DB living room: +1.52<br>DA bedroom/DB bedroom: −1.10<br>DA bedroom/DB living room: +1.03 |
| Tukey HSD  | α = 0.05, Q_{crit} = 3.63           | 0.09                                 |                                                                         |

1 Room comparisons are listed in the order i/j, where i is the first subcategory in the comparison and j is the second. DA: Dwelling A; DB: Dwelling B.

This information is also presented according to the air temperature frequency (Figure 5). Outdoor temperature includes all measurements obtained from the previously mentioned monitoring period, while indoor temperatures only include measurements within the occupied periods of the respective analyzed area, according to schedules defined in Table 3. This allowed for a more clear understanding of indoor conditions during inhabited periods.

Figure 5. Air temperature frequency.
Outdoor values presented an average temperature close to 12 °C and a considerable temperature variation over several days, which resulted in an average value of 5.4 °C. It is noticeable that the range between 10 °C and 12 °C represents more than 40% of the temperature frequency, although other close ranges also represent a considerable amount of frequency as a whole.

The Dwelling A living room presented a set of days with considerable temperature increments during short morning or afternoon periods, likely related to the use of active systems, which matched the information obtain through qualitative data. The most representative period was the one from 28 January to 5 February, when these thermal peaks were registered in the majority of days and when the highest maximum temperatures from the entire monitoring period were registered, reaching values close or above 18 °C, while temperature variation reached 4 °C for some days. However, it is noticeable that from 6 to 10 February, the use of active systems was very low or even non-existent when those peaks were slight; with indoor temperatures always close to 16 °C and temperature variations mainly below 2 °C. A predominant number of occurrences in occupied periods (almost 95%) was registered in the temperature range between 14 °C and 18 °C.

The Dwelling A bedroom presented the most days without a significant temperature increase, therefore without apparent use of active systems as mentioned in the surveys. Only a few thermal additions were registered, although coincident with the use of active systems in the living room. The registered thermal oscillation was slight, with average values of around 1 °C, average minimum temperatures close to those recorded in the living room, and maximum temperatures only close when the use of active systems was scarce or non-existent in the living room. During occupied periods, the range between 14 °C and 16 °C represented a considerable amount of frequency, with more than 60% of occurrences.

The Dwelling B living room presented all analyzed days without a significant temperature increase associated with the use of active systems, as the repercussion in indoor temperatures of short occupation periods and solar gain restriction clearly matched the information obtained through qualitative data. The indoor daily temperature was near 14 °C for the majority of days, presenting a slight variability, mostly below 1 °C. A predominant number of occurrences (around 65%) was registered during occupied periods in the range of temperature between 14 °C and 16 °C, with the remaining ones within the range between 12 °C and 14 °C.

The Dwelling B bedroom presented a significant difference in thermal behavior compared with the living room considering the majority of analyzed days with temperature peaks during night and sometimes also during mid-morning periods, associated with the use of active systems, as mentioned in the qualitative data. During the remaining daytime periods, no significant temperature increments were registered for the majority of days. The use of active systems allowed for reaching temperatures above 18 °C in the majority of days, and above 20 °C in some days. However, a significant amount of registered minimum temperatures were below 16 °C, with predominance during dawn and unoccupied periods. During the occupied periods, almost 40% of occurrences were within the range of temperature between 16 °C and 18 °C, although this was the only studied room to achieve a considerable amount of occurrences (more than 20%) above 18 °C.

The results for the ANOVA tests show that the critical value was widely exceeded and had a p-value lower than 0.05, indicating strong evidence against the null hypothesis and suggesting that one or more treatments were significantly different. Thus, the results for the Tukey’s HSD test exhibited a statistically significant difference between all of the studied rooms, which matched the described thermal behavior differences. It is noticeable that lower mean differences were identified in Dwelling A—where a significant consistent occupancy occurred in both the living room and bedroom during daily periods—and between the Dwelling A living room and Dwelling B bedroom—the rooms where active systems were used with more consistency.

Figure 6 shows the resulting outdoor and indoor relative humidity values, and Table 6 shows the respective statistical variables for the monitored period.
The outdoor values presented a mean value of 84% and a variation around 51%. It should also be noted that the majority of the monitored values were above 50%, which represents a considerable severity for built environments to comply with the reference values of the EN 16798-1 standard.

The indoor, minimum, and maximum values registered during the entire monitored period were 59% (in Dwelling B bedroom) and 90% (in Dwelling B living room), with the mean and minimum values being considerably above 50% for both dwellings.

For the previously identified periods when active systems were used, the Dwelling A living room relative humidity decreased slightly, by around 10% for the period from 28 January to 1 February. It was also noticeable that when the heating systems were turned on, the indoor relative humidity decreased to values lower than 70%—although for a short period, until those systems were turned off—even when outdoor values sometimes exceeded 90%.

### Table 6. Indoor and outdoor relative humidity statistical variables for the monitored period.

|                      | RH [%] | RH\(_{\text{max}}\) [%] | RH\(_{\text{min}}\) [%] | SD [%] |
|----------------------|--------|--------------------------|--------------------------|--------|
| Outdoor              | 84     | 98                       | 47                       | 12     |
| Dwelling A living room | 73     | 83                       | 62                       | 4      |
| Dwelling A bedroom   | 76     | 86                       | 64                       | 5      |
| Dwelling B living room | 77     | 90                       | 62                       | 5      |
| Dwelling B bedroom   | 73     | 85                       | 59                       | 5      |

RH: average relative humidity, RH\(_{\text{max}}\): maximum relative humidity during the entire monitored period, RH\(_{\text{min}}\): minimum relative humidity during the entire monitored period; SD: standard deviation.
Without the use of heating systems, the Dwelling A bedroom presented a more stable relative humidity profile than the living room, with slightly higher humidity values than the latter. The Dwelling B living room presented a stable relative humidity profile, although short humidity increases were verified during morning, afternoon, or night periods, possibly related to occasional window opening or other specific indoor activity—which did not exactly match what was mentioned in the surveys—although no significant repercussion was detected in the temperature values.

The Dwelling B bedroom was the room where the use of active systems was most notorious for their impact on relative humidity values—particularly until 4 February, after which the occurrence of significant changes in external conditions made this less evident—as in occupied periods its behavior was similar to that of the Dwelling A living room, regarding some humidity decrease when the heating systems were in operation. However—and considering that it was the room where those systems were used for the longest time—the obtained values were still high, with it noticeable that only very occasionally did they decrease from 70% when the external values were higher, even when the systems were in operation.

3.3. Comfort Assessment

Figure 7 shows the comfort assessment performed for each analyzed room of the dwellings, according to the applied static (SCE) and adaptive (EN-C1) models. Each spot in the graph corresponded to an individual measurement value obtained during occupied periods. Thus, a regression analysis on the operative temperature ($T_{op}$) and $T_{rm}$ was also performed, also representing the regression line and the respective equations for the considered number of samples (n), as well as the coefficient of determination ($R^2$). The percentage of time when discomfort was experienced is synthetized in Table 7, with the criteria to estimate it relates the number of individual measurements during the occupied time outside the comfort thresholds with all individual measurements for that same period.

| [%]       | SCE  | EN-C1 |
|-----------|------|-------|
| Dwelling A living room | 98   | 100   |
| Dwelling A bedroom   | 100  | 100   |
| Dwelling B living room | 100  | 100   |
| Dwelling B bedroom   | 78   | 93    |

It can be observed that for all studied rooms, discomfort was extremely significant. The Dwelling A living room presented some insignificant portion (2%) above the Lower SCE, with some of the remaining values close to it, although most values were far from the Lower 1 threshold. The Dwelling B bedroom presented 22% of the values above the Lower SCE and a relevant amount of the remaining ones close to it, although only 7% were above Lower 1, with some of the remaining ones considerably far from it. Dwelling A bedroom and Dwelling B living room presented all temperature values in discomfort for each of the applied comfort models, with most of the values considerably far from all of the minimum thresholds.
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3.3. Comfort Assessment

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![Comfort assessment performed.](image)

Although the Dwelling B living room presented a significantly reduced number of samples compared with the remaining rooms, the obtained regression lines presented similar slopes for all rooms, except for the Dwelling A bedroom, whose slope was sharper, probably due to the inexistence of active system use during night periods.

Regarding indoor relative humidity frequencies for each of the monitored rooms, it was observed that neither of the analyzed rooms met the EN 16798-1 defined range for relative humidity during any of the occupied periods, with the indoor values always above the maximum reference value of 50%.

4. Discussion

The obtained results make clear that both dwellings do not ensure adequate indoor thermal conditions, either using static or adaptive models. As expected, the outdoor air temperature has an influence on indoor temperatures throughout the monitored period. Nevertheless, both dwellings present considerable low temperatures, considering that the building thermal behaviour is favoured by moderate external conditions—the registered values are considerably higher than the ones indicated for both present and future climate
scenario severities for heating seasons in this region, which is therefore representative of a period with a moderate severity for this season of the year. Considering the existing climate conditions during the monitored period—with a mean temperature around 12 °C—it is expected that there will be a significant building thermal and comfort demand increase for harsher winter months in Covilhã or other Beira Interior cities, with harsher present/future winter scenarios. Thus, it can be assumed that no proper response to demanding winter seasons is achieved even with the intermittent use of active systems, which is a conclusion common for other developed social housing studies in Iberian Peninsula locations; considering the use of intermittent heating, the work from Ramos et al. [27] showed improper indoor temperatures in non-retrofitted dwellings located in Porto, and regarding scenarios without the use of heating systems, the work from Curado and Freitas [17] showed that in cities such as Madrid, Bragança, and Bilbao, the use of active systems is required to obtain proper levels of thermal comfort.

The thermal fluctuations observed outside reduced the impact on dwellings’ overall thermal fluctuations, not exceeding 1 °C—for both non heated or inhabited rooms—which is partly explained by constructive and geometric features, such as the effect of the high thermal mass existing in the exterior walls with insulation and the interior walls, as well as by the moderate amount of glazed area, respectively. The benefit of similar buildings’ constructive and geometrical features to minimize adverse cold indoor conditions was also observed by Shahi et al. [49], who conducted a field survey in winter for houses located in Nepalese cold, temperate, and subtropical regions, obtaining resultant mean indoor air temperatures of 10.9 °C, 18.0 °C, and 20.0 °C, respectively—which were 6.3 °C, 2.9 °C, and 2.0 °C lower than the average estimated comfort temperature, respectively; although the results showed that a significant increase of indoor air temperature was required for the cold region, its buildings’ thermal mass combined with moderate door and window size contributed to a smaller variation in indoor air temperature than for temperate and subtropical region buildings.

Although indoor activities and internal gains have no significant relevance in differences between each dwelling’s thermal behaviour, no significant variations in indoor temperatures associated with opening windows are also identified. Both qualitative and quantitative data indicate window opening during brief or occasional periods for all rooms, which somehow matches with the findings of some works. Rijal et al. [50] monitored window opening behaviour and thermal comfort during some years in both the living rooms and bedrooms of some dwellings, and the results show that when heating systems were operating, the dwellings windows were rarely opened, while for free running mode, the winter season was the period when window opening was less, with the proportion of windows open generally being lower in bedrooms than in living rooms. Imagawa et al. [51] conducted occupant behaviour surveys in some dwellings during a four-year period, and it was noticed that the proportion of window opening in winter was very low for both living rooms and bedrooms, while heating was often used until spring, from when the proportion of heating use decreased and window opening increased. Therefore, changes in occupancy are those that have some impact in defining proper indoor conditions, mainly regarding the user’s heating habits: the registered temperature “peaks” decoupled from external temperature conditions are decisive in Dwelling A living room and Dwelling B bedroom, so as to present more pronounced maximum temperatures and therefore some daily time periods with acceptable indoor conditions, although the average minimum temperature values are close to those of the unheated rooms, inhabited or not. Therefore, although presenting some potential constructive features, conditioning using active systems results in poor indoor conditions for a large amount of time during inhabited periods, which matches similar scenarios within social housing contexts found in studies such as the ones by Alonso et al. [28], where the analyzed dwellings presented a worse constructive quality combined with the inhibition by the residents to use heating systems.

Nevertheless, the impact of individual adaptive strategies and/or activities to a proper adaptation to cold indoor conditions—besides the use of active systems—must also be
regarded: its potential is shown from works such as the one of Rajan et al. [52], who performed an experimental campaign in a condominium equipped with the same home energy management system, who noticed that in winter season periods a 4 °C difference was registered between high and low temperature groups, mainly because of individual adaptive activities of the occupants to adjust the indoor thermal environment. However, in the present study, both quantitative and qualitative data suggest that satisfactory indoor comfort conditions are not achieved through adaptive behaviour. Such an achievement can be found in the study of Rijal [53], who performed a thermal measurement and comfort survey during the winter for traditional vernacular houses exposed to extreme cold climates: indoor conditions presented rigorous cold environments—with 10.7 °C as the mean comfort temperature—but it was noticed that the residents were very satisfied with indoor thermal conditions as a result of successful adaptation behaviours to these buildings—such as proper clothing insulation, eating habits, and proximity to the fire—alongside passive heating effects that were found in some constructive features—this successful combination between adaptive habits and existing constructive features appeared not to have been achieved either in the studied dwellings. Its potential may also have considerable energy repercussions, as the effectiveness of reducing energy poverty can be considered dependent on the users’ thermal adaptation [4], and for specific conditions, the constructive quality can increase indoor temperature without necessarily increasing the use of energy for heating purposes [49]. Rijal et al. [54] performed thermal measurements and a thermal comfort survey in several dwellings, and the results showed a high level of thermal comfort mainly resulting from a successful thermal design and adaptation to indoor conditions from residents, suggesting that low energy consumption was achieved if the building behaviour provided comfortable indoor conditions over a wide range of outdoor temperatures. Regarding thermal comfort and building energy use implications, the literature review by Yang et al. [55] highlighted that adaptive comfort models present a wider comfort temperature range with a significant energy saving potential in both air-conditioned and naturally ventilated buildings. While several works regarding relevant seasonal differences in comfort temperature and related energy saving are mentioned in [54], the specific field of energy saving by adjusting the temperature setting during heating seasons can be found in studies such as the ones by Nicol et al. [56]—highlighting that a reduction of 1 °C in indoor temperature represented about 10% energy saving for heating in winter seasons—and Wang et al. [57]—stating that about a 9.6% energy saving for centralized heating system could be achieved. Regarding studies in Southern European countries, Bienvenido-Huertas et al. [4] studied the possibility of reducing the building energy consumption and minimizing energy poverty cases in Seville recurring to adaptive setpoint temperatures, and found that for Category I of EN 16798-1 a decrease in the number of energy poverty was 43%, for Category II it was around 82%, and for Category III it was up to 98.5%, although its effectiveness was higher during summer months.

Regarding variations related to different orientations, the significant temperature increases identified in the monitored rooms are mostly related with the use of heating systems. As no relevant changes to indoor thermal conditions are observed in periods when heating systems are turned off, the impact of orientation and the respective solar gains on indoor temperatures is low. This aspect is certainly reinforced by the fact that residents sometimes partially or fully activate glazing protections, as mentioned in the surveys. However, given the results obtained, a considerable reduction in discomfort is unlikely to be achieved only by resorting to passive systems, even with more favourable outdoor climate.

Once all rooms presented different occupation schedules and heating habits, analysing each one of them allowed for obtaining distinct understandings so as to consolidate the mentioned general observations regarding indoor thermal performance:

- The Dwelling A living room allows for an understanding dwelling daytime performance with and without relevant artificial heating influence. In days when active systems are perceived to have been used, its impact consists of a corrective measure...
that somehow improved indoor thermal conditions, although its use for short periods does not allow for a significantly decrease in discomfort during the relevant occupied time periods. In days when active systems use is reduced or inexistent, alongside with the insignificance of solar gains during morning periods through east-exposed glazed elements, the indoor temperature is generally low, although the impact of high thermal mass is noticeable in its stabilization, considering existent outdoor temperature variability for these periods;

- The Dwelling A bedroom allows for understanding the performance during inhabited night periods under the identified influence of high thermal mass of insulated external panels and indoor partitions, once no active systems are used nor relevant solar gains are identified during the afternoons, considering the room’s southern orientation. Although thermal variability is satisfactorily stable attending outside low temperatures, all registered values are distant from all comfort thresholds;

- The Dwelling B living room allows for understanding the building constructive characteristics’ repercussion in indoor thermal conditions with few or no occupancy impact at all, once no active systems use nor relevant solar gain are perceived. Once again, the influence of high thermal mass is essential for maintaining very stable internal conditions, but with low temperature ranges. With no relevant source of thermal gains, this is clearly the most penalized scenario regarding comfort assessment, where all registered values are considerably distant from all comfort thresholds;

- The Dwelling B bedroom is the room where active systems are used with more consistency according to the intermittent habits during inhabited night and mid-morning periods, considering that no relevant solar gains are obtained during daytime periods. Thus, it allows for an understanding of active systems as brief corrective measures to somehow improve indoor thermal conditions when outside temperatures are lower. Their impact is notorious from the moment they are turned on, with a high temperature increase, so some portion of the inhabited time is within comfort ranges. However, its restricted use until bedtime periods results in a quick drop of indoor temperatures that is unable to be prevented from the moment they are shut down, which demonstrates some insufficiencies in the existing thermal insulation. Nevertheless, it would be interesting to observe the use of active systems during longer and sequent periods to somehow obtain a better understanding of envelope thermal insulation limitations.

Regarding the comfort assessment performed using distinct comfort models, for SCE, it is noticeable that discomfort is slightly decreased in the Dwelling A living room and Dwelling B bedroom. The use of active systems clearly guarantees this decrease, besides setting an important amount of values close to those thresholds—particularly for the Dwelling B bedroom—as once in unheated rooms all registered values are in discomfort, with most of them far from minimum thresholds. As for EN-C1, similar results are obtained. Dwelling B bedroom is the only room to present at least a slight discomfort decrease, as once results are clearly insufficient considering a high level of expectation in comfort, with many of the registered values not even close to the minimum threshold, particularly for the unheated rooms: it is noticeable that only rooms with active systems could reach some discomfort decrease, which is quite concerning, particularly for situations such as the ones of Dwelling A bedroom, which presents a significant daily amount of time with occupation during night periods.

Regarding relative humidity, the obtained results show that the dwellings do not assure adequate indoor humidity conditions, considering outdoor conditions that are only slightly higher for this season of the year. For all the analysed rooms—occupied during the day/night, with long/short occupation periods, and with/without the use of active systems—there is a clear inability to comply with the EN 16798-1 Category I reference range, as well as with less demanding ranges (defined for the remaining categories) for a significant amount of monitored values. Even so, residents’ occupation habits have some impact on minimizing adverse indoor conditions: considering the repercussion of outdoor
relative humidity throughout the monitored period, the analysis of each relative humidity profile in daily periods reveals smaller variations to those abroad, with the mean values for the rooms where active systems are used resulting in slightly lower results than in the other rooms. Nevertheless, the obtained results also show that when outside humidity conditions are more demanding, indoor values are sometimes above 80% for relevant amounts of time, which can increase the risk of mould growth [58] with clear repercussions on indoor air quality.

A remark should also be made regarding constructive improvements considering the actual role of retrofitting in Portuguese national strategies for housing buildings [59], as well as the need to improve the retrofitting strategy for social housing neighborhoods [17]. Applicable constructive retrofit measures are extensively described in [60] for both inland and coastal locations regarding this CAR project, although its impact during summer seasons and indoor air quality must also be considered. Nevertheless, among several benefits provided by retrofit measures, such as adding thermal insulation or window substitution, it is possible that passive means alone may be insufficient to achieve thermal comfort during the entire winter season. This assumption matches results obtained by Curado [23], that for retrofitted social housing dwellings in Porto and in cases with both intermittent or no heating habits identified around 40% of heating season total hours as still in discomfort, although a considerable discomfort decrease was achieved. Therefore, combining constructive measures with household energy use patterns is also a potential strategy, as proposed by Pokharel et al. [61], who performed several surveys on households during the winter, and identified low indoor air temperature measurements and per-capita daily energy use from 20 to 37 MJ/(person·day) resulting in significant improvements recommended in building envelope insulation combined with small energy use strategies.

5. Conclusions

The goal of this research was to assess indoor thermohygrometric conditions in a public social housing case study located in the Beira Interior region during winter season, so as to provide an understanding of indoor performance suitability for present and predicted climate scenarios. It was observed that the analysed case study performance is not aligned with the needed proper responses, regarding high probable exposition of risk groups such as the elderly to similar insufficient indoor conditions with a serious impact on their health, and representing important losses of well-being. In many cases, this problem is even serious, regarding risk groups with specific health problems that need to stay at home for most of the day.

Therefore, the key conclusions of this study are as follows:

• Intermittent heating was used during some periods—as by several Portuguese family units—but with a reduced level of effectiveness: thermal discomfort was found to be extremely significant either for static or adaptive models applied, with the monitored rooms—heated or not—presenting 78% to 100% of time in discomfort during inhabited periods, whether during the day or night, as applicable;
• Indoor humidity conditions were inadequate during all occupied periods, outside the recommended humidity ranges. Furthermore, residents’ occupancy habits have little influence on improving these conditions, while many of the recorded values also indicate a high risk of mold growth as a consequence of improper indoor air quality;
• Passive means alone—mainly the existing envelope’s thermal insulation and thermal mass—considered individually or combined with both occupation and intermittent heating habits—were not enough to provide proper indoor thermal conditions;
• It was not possible to properly analyse the impact of solar gains on improving indoor thermal conditions, due to constant use by residents of glazing protections;
• Considering that the present case study focuses on a building with an envelope with superior thermal criteria compared with other identified constructive systems used in local public social housing, the need it to provide constructive improvements for this building stock becomes clear.
A note should also be taken regarding the static model used in this study. The described constraints during the experimental campaign—related with equipment installation as well as with clothing and activity details—restricted obtaining further relevant data throughout the days for hourly or sub-hourly periods, such as the mean radiant temperature, air speed, metabolic rate, and clothing insulation. Although the use of the SCE framework in indoor thermal comfort analysis can be found for studies that compare its results with those of adaptive model as primary models [18], potential limitations are pointed out regarding its methodology, such as establishing fixed limits of comfort temperature considering indoor permanent heating/cooling habits—which are unrealistic for some specific countries and/or contexts where those habits are mainly intermittent or insignificant, a reason alternative approaches were specifically developed to fill this gap [7]—as well as not considering the repercussion of changes to specific indoor individual and environmental variables in adjusting those limits. The use of PMV method [45] is another possibility for such studies, although the use of reference values in the absence of specific data can strongly affect the resulting comfort ranges [62]—particularly for case studies where adaptive practices are common and therefore variations of input data are frequent—besides some limitations that were found regarding its applicability in field surveys [63].

In this context, a possible evolution of this work would be by providing more complete data through the use of calibrated dynamic thermal simulation models so as to provide simulated indoor environmental variables, along with more extensive surveys applied to several public social housing dwellings that could provide precise clothing insulation and/or activity metabolic rates according to typical occupancy profiles. Additionally, proper constructive retrofit improvements—combined or alone—should be studied for building geometry and envelope, using those models to perform specific dynamic thermal simulations in order to identify how to reduce discomfort, also considering the positive influence that actions from occupants may have. These solutions should be studied alongside with other possibilities like proper ventilation and shading devices during summer seasons, in order to identify its opportunities and threats for both present and future climate scenarios [18]. Thus, specific situations regarding the elderly or users with specific health problems should be regarded in order to establish specific indoor requirements beside thermal comfort models used, such as the impact of other factors like indoor air quality. The extension of study comprehensiveness beyond building thermal and comfort performances, like the consideration of other relevant factors such as intervention costs, constructive feasibility or occupant’s acceptance, is also proposed as possible future work, considering the importance of these factors in public social housing contexts.

Author Contributions: Writing—original draft preparation and review, P.I.B.; supervision and writing review, J.C.G.L. Both authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Acknowledgments: LABSED—Housing Health Lab—UBIMedical.

Conflicts of Interest: The authors declare no conflict of interest.

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