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Assessment of vulnerability to overheating at a regional scale through parametric simulation models and cooling degree-days analysis: The case of southern Spanish social housing stock

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ABSTRACT

The urgent need to adapt urban environments to extreme weather conditions due to global warming has become a priority when allocating European funds. Current regional retrofitting plans focus on improving the well-being of the most vulnerable families by upgrading their homes. However, as there is no adequate characterization of the environmental behaviour of housing stock, local agents in charge of the management of social housing lack a procedure to identify the urban areas most urgently in need of retrofitting.

This research aims to present a protocol for evaluating the vulnerability to overheating of social housing stock at a regional scale, as a prioritization decision support system. Parametric techniques for Building Stock Modelling were used in the development of 3000 models located in four climatic zones of southern Spain to assess their thermal behaviour considering adaptive comfort equations. Moreover, an index of vulnerability to overheating has been defined by normalizing comfort assessment through cooling degree-days. The comfort assessment outcome corresponds more closely with the analysis of cooling degree-days than with the Spanish regulations' climatic zoning. According to the results, in the hottest climatic zone, occupants frequently endure discomfort up to 40% of the summertime, with hourly deviations of up to 7 °C above the indoor temperature comfort range.

Nomenclature

AVRA	Andalusian Agency for Housing and Retrofitting
BEM	Building Energy Models
BSM	Building Stock Modelling
CDD	Cooling Degree-Days [°C·day]
CDDD	Discomfort Degree-Days during cooling period due to overheating [°C·day]
CDDH	Discomfort Degree-Hours during cooling period due to overheating [°C·h]
CDH	Percentage of Discomfort Hours during cooling period [%]
DD	Degree-Days [°C·day]

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OI	Index of Vulnerability to Overheating
PBSM	Parametric Building Simulation Models
SLABE	Simulation-based Large-scale Analysis of Building Energy performance
SRRC	Standardized Rank Regression Coefficient
Tb	Base Temperature for Degree-Days calculation [°C]
Tc	Optimum Comfort Temperature [°C]
Ted	Daily mean Outdoor Temperature [°C]
Teh	Hourly Outdoor Temperature [°C]
Ter	Running Mean Outdoor Temperature [°C]
Ti	Indoor Operative Temperature [°C]

1. Introduction

The current climatic situation, with hotter summers and more intense episodes of heat waves due to global warming [1], warns of the need to adapt the existing residential stock to the extreme weather conditions that will become the norm [2]. In Europe, this progressive increase in mean temperature is expected to result in a significant increase in cooling Degree-Days and, in turn, increased cooling demand [3]. However, in southern Europe there is a high percentage of low-income population living in homes with very low energy performance [4] and which rely on natural ventilation for cooling [5]. In the near future, this population will be particularly vulnerable to these worsening climatic conditions [6].

In the specific case of southern Spain, there is a poorly constructed residential stock [7], with hardly any thermal insulation requirements and whose occupants are at serious risk of energy poverty. According to Tirado-Herrero and Jiménez-Meneses [8], 17% of the population state that they are unable to ensure their home remains at an adequate temperature. In the particular case of the social housing stock managed by the Andalusian Agency for Housing and Retrofitting [9], only 9.7% of multi-family buildings have been energy retrofitted [10].

Different studies confirm the situation of energy poverty in a large part of the existing social housing sector in Spain [11,12]. However, these studies focus primarily on energy poverty in the regions and climate of northern Spain, where heating is still a top priority [13]. In these climates, the result of the Energy Performance Certificates can be essential for evaluating the degree of vulnerability of the existing housing stock on a large scale related to building features [14], and they are available in public databases. However, in the case of social housing in southern Spain, the standardized energy certification processes estimate energy consumptions far from reality since energy poverty is not considered. These certificates assume heating and cooling devices with a standard pattern of use (according to the Spanish regulations), that occupants of this social housing stock cannot afford. Due to economic constraints these users are forced to live without comfort.

There are also some works, such as that of Guerrero-Delgado et al. [15], which evaluate the thermal discomfort associated with extremely hot climates and energy poverty in existing social housing in southern Spain, as a prior step to establish efficient and appropriate retrofitting measures for these low-income users. This work, as usual in the existing literature, is applied on a building or district scale. Therefore, there is a lack of studies on a regional scale more focused on the concept of energy vulnerability proposed by Bouzarovski and Petrova [16] and evaluating the degree of vulnerability to overheating in the existing housing stock in southern Spain.

If the goals of reducing energy consumption and efficiency are to be met there is no denying the pressing need for the extensive retrofitting of residential stocks [17]. As a necessary prior step, this requires large-scale procedures for the characterization of the constructive characteristics and environmental and energy behaviour of these building stocks [18]. This characterization must be reliable in order to keep the usual differences between the simulations and the real behaviour of the buildings to a minimum [19], as these can lead to discrepancies between the estimated and real energy savings after the retrofitting process [20]. This usually occurs when the retrofitting measures applied are generalized rather than based on calibrated simulations of energy models. In addition, as there is a tangible risk of retrofitting projects based on current standards becoming obsolete before reaching the payback period this characterization must take into consideration the new climatic outlook [21].

For large-scale characterization procedures, dynamic simulations of Building Energy Models (BEM) are a fundamental tool [22]. When focusing on Building Stock Modelling (BSM), the different approaches can be grouped into two categories: top-down and bottom-up [23]. Top-down techniques generally make use of historical aggregate data to establish relationships between energy consumption and economic and climatic variables [24]. This approach displays major limitations in the characterization of the detailed behaviour of buildings, since results are usually presented on an annual or monthly scale [25]. A finer resolution (e.g., daily or even hourly) is especially relevant in the case of overheating assessment.

For a more detailed evaluation of the building stocks performance on an hourly scale, allowing accurate assessment of the effect of thermal retrofitting measures, bottom-up engineering techniques are considered the most suitable for BSM [26]. With this method, the energy simulation results for a representative set of case studies (archetypes) can be extrapolated to large-scale levels [27]. In order to define these archetypes, large empirical databases are required to statistically determine the characteristic parameters of this category of buildings [28].

In the case of studies which make use of bottom-up techniques for BSM, most of them generate the archetypes through the information available in public databases [29], survey data [30], or scientific literature [31]. When working on privately managed residential buildings, there is a significant limitation in collecting information, since its difficulties in access [32] make this a time-consuming process. In contrast, when public housing is evaluated, the study samples can be larger due to more attainable information.

According to Ascione et al. [33], the combined use of various sources provides better information for BSM. The models cited allow the characterization at local, regional, or national level of the energy behaviour of residential stock. It is worth noting the methodology presented by Mata et al. [34], which used archetype buildings to aggregate national building stocks following the definition obtained from public databases from official housing authorities as well as from the existing literature. These archetype buildings were modelled and simulated through Simulink/Matlab environments to characterize the energy behaviour for building stocks from four EU countries with different climates: France, Germany, Spain, and the UK.

Most of the works found in the existing literature, including those cited in the paragraph above, develop bottom-up models to establish the energy consumption or demand of existing building stocks which are to be used as the basis for a future evaluation of the energy saving potential of retrofitting procedures. The study developed by Gouveia et al. [35] focuses on assessing the needs of end users through a building stock model which evaluates the energy services demand. Thus, the specific needs of the users of the housing stock analysed and the perception of the comfort conditions must determine the final objective of a study [36].

Regarding the thermal comfort assessment, most of the studies and international standards are based on Fanger's model [37], which evaluates users' thermal sensations under controlled indoor environmental conditions, activity, and clothing level. Derived from this methodology, standard EN ISO 7730 [38] is one of the most widely applied in the existing literature about thermal comfort in buildings. Nevertheless, standards considering outdoor environmental conditions and users' adaptive capacity are considered more suitable when evaluating naturally ventilated buildings [39,40]. Especially in residential buildings and temperate climates, as users frequently modify their clothing level or operate the windows to improve thermal sensation, these variables are very complex to establish. The most commonly adaptive standards applied by the scientific community are ASHRAE Standard 55 [41], EN 15251 [42] and its revision, EN 16798–1:2019 [43]. As stated above, most of the works published about models for simulating large-scale building stocks focus on energy consumption or demand assessment based on Fanger's thermal comfort approach. This model can be appropriated for tertiary buildings in temperate climates, such as assumed in the work carried out by Mauro et al. [44] for office building stock in southern Italy. However, for the residential building stocks, the adaptive comfort approach can be more reliable, such as in the study based on the standards ASHRAE 55 and EN 15251 developed by Dino et al. [45] for four Turkish cities.

In the particular case of social housing in southern Spain, the economic vulnerability of its users leads to a generalized lack of Heating, Ventilation and Air Conditioning (HVAC) systems, so that energy consumption is much lower than that estimated by the standardized energy certification processes [46]. In low-income environments, retrofitting procedures cannot be based on the active HVAC systems that occupants cannot afford to use, but on passive strategies of adaptation to the environment [47]. For this reason, in the building stock currently under study environmental assessment should focus on adaptive thermal comfort since future energy retrofitting strategies must aim to improve the well-being of its users without increasing their energy use [48]. More extensive research is therefore needed on the adaptive thermal comfort of large-scale housing stocks, also taking into consideration the adaptability of economically vulnerable users to the current climate. In contrast to similar studies, these issues will be addressed in this work.

One of the main objectives of the regional retrofitting plans is to improve the well-being of the most vulnerable families by guaranteeing the dignity of their homes and their adaptation to the challenges of climate change [49]. However, the absence of an adequate characterization of the environmental and energy performance of the existing housing stock hinders the identification of the most vulnerable urban areas from this point of view, so that local agents in charge of managing social housing have difficulty and ascertaining the cases where retrofitting interventions are most urgent. The need to establish an order of priorities for the retrofitting of the public housing stock has become even more pressing with the imminent availability of the Next Generation Funds provided by the for the process of rebuilding economies in the post-COVID-19 world [50]. In the case of Andalusia, 200 million euros will be dedicated to the retrofitting of existing housing up until the year 2026.

Faced with this, a question arises: should the climatic variable be decisive when prioritizing rehabilitation processes? In other words, is action to be taken first only in the most severe climates? Or should it be assumed that, in all locations, users have adapted to their climate and are equally affected by the worsening of the thermal behaviour of their homes due to global warming? This depends on the perspective taken. For this reason, unlike other studies carried out so far, this work aims to evaluate and contrast the different climatic severities in southern Spain, through the calculation of degree-days and the thermal comfort conditions in its social housing stock, applying adaptive methods. The main novelty of this study is the proposal of an index that normalizes this adaptive comfort assessment with degree-days, ruling out the climatic variable and focusing on the weaknesses of buildings and their users. The geometry, constructive and operation parameters that most influence thermal comfort are also evaluated through a sensitivity analysis.

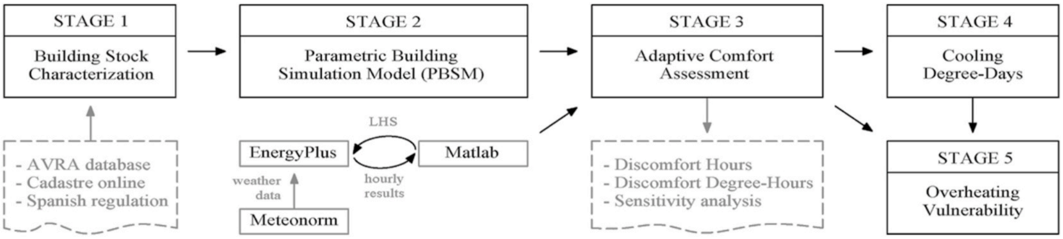


Fig. 1. Schema of work stages.

This study is part of the VULNERA regional R&D&i project, which aims to quantify the degree of environmental vulnerability of the social housing stock built in southern Spain between 1979 and 2006. This research aims to provide an innovative protocol to assess the vulnerability to overheating of this residential stock at a regional scale, intended to be transferred to the agents involved in the energy retrofitting process for residential stock as a prioritization decision support system. In this case, the analysis focused on the cooling period, given the concern for the adaptation of the urban environment to global warming.

2. Methods

The protocol presented is developed in five stages, summarized in the diagram in Fig. 1. This section, which describes the methods applied, is organized into different subsections for each stage of the protocol: case study characterization, development of the Parametric Simulation Models, adaptive comfort assessment, calculation of Cooling Degree-Days, and evaluation of the vulnerability to overheating of the case study.

2.1. Case study

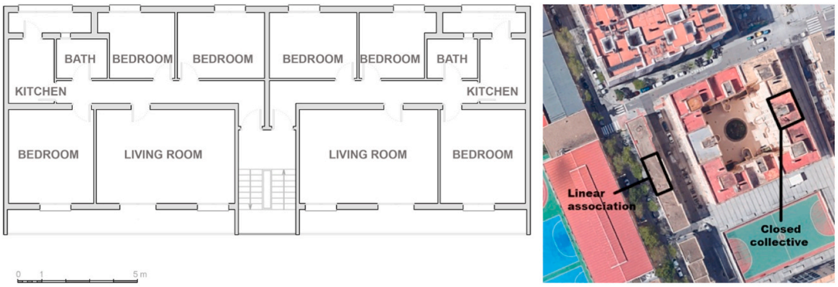
In this work, the protocol presented will be applied to the regional area of Andalusian, located in southern Spain. Particularly, the case study selected is the protected housing stock (under a social rental regime) managed by the Andalusian Agency for Housing and Retrofitting (AVRA) [9]. The information from the public AVRA database is essential to this work, since it compiles different typological, morphological, and constructive aspects for over 39400 dwellings located in the region of southern Spain and built between 1979 and 2006. The building characterization data collected in this database contrast both the original "Execution Projects" and the "Building Evaluation Report" (which describes conservation status, accessibility, and energy certification). This regional database has been restructured, checked, filtered, and completed with information obtained from the Spanish cadastre online platform [51]. In previous works, Microsoft Excel and R v.3.5.3 were used in the statistical analysis of the database to characterize this housing stock prior to the environmental analysis [52]. 77.5% of this housing stock consists of multi-family residential buildings, 27% of which are classified as linear typology blocks.

This linear block typology almost always follows the same floor plan distribution, with a central staircase which provides access to two dwellings per floor. As a result, these dwellings have two main orientations. In this case study, linear blocks connect with others forming different urban typologies (linear association, L-shaped, U-shaped, closed collective). The linear association configuration accounts for 39% of cases, while 37% of cases can be classed as closed collective. Fig. 2 shows a representative floor plan of this typology and an aerial view of the two most representative urban typologies.

This study focuses on the typology described above and on summer climatic zones 3 and 4 following the classification of the Spanish Building Technical Code [53], where 99% of the dwellings collected in the database are located. In the classification of climatic zones established in this standard a letter is used to indicate climatic severity in winter, with "A" referring to the mildest winters and "D" to the coldest ones, while climatic severity in summer is denoted by numbers, ranging from "1" (corresponding to milder summers) to "4" (hot summers). These letters and numbers are then combined to identify the different climatic zones. Fig. 3 shows the winter and summer severity which applies to the southern region of Andalusia in Spain. This study develops the analysis for climatic areas A3 (city of Cádiz), A4 (Almería), B4 (Sevilla) and C3 (Granada) (shown in Fig. 3), which offer an accurate representation of the climatic variety found in southern Spain.

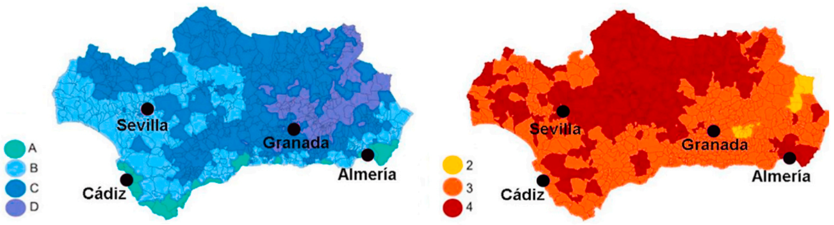
The weather data files used in this research were obtained from Meteonorm v.8.0 software [54], which includes a climate database compiled from over 8000 weather stations. In this study, the hourly weather file generated through measured data from 2010 to 2020 was applied for the energy simulations. Table 1 summarizes the main climatic conditions of the summer period in the four cities considered.

The representative ranges for the characteristic parameters of this regional stock have been statistically defined, as a result of the previous statistical analysis of the AVRA database [52], in order to characterize the social housing stock built in southern Spain between 1979 and 2006 (Table 2). These ranges have been defined for each specific climatic zone, according to the cases characterized in the database and located within each zone. These parameters are necessary for the definition of the simulation models of the building stock: orientation, floor area (the sum of all the dwellings on one floor), form ratio (major façade length divided by minor façade



(a) (b)

Fig. 2. Example of the analysed stock: floor plan (a) and urban typologies (b).



(a)

(b)

Fig. 3. Climatic zones in southern Spain: severity in winter (a) and summer (b).

Table 1
Main climatic characteristics of the summer period (June 1 – September 30).

Variable	Cádiz_A3	Almería_A4	Sevilla_B4	Granada_C3
Maximum hourly air temperature [°C]	38.0	38.4	42.8	41.7
Maximum daily average air temperature [°C]	31.3	32.2	34.1	32.5
Minimum hourly air temperature [°C]	13.4	15.5	14.4	11.0
Minimum daily average air temperature [°C]	18.0	18.2	20.2	17.2
Maximum hourly relative humidity [%]	100	100	98	100
Maximum daily average relative humidity [%]	85	82	80	79
Minimum hourly relative humidity [%]	31	36	18	13
Minimum daily average relative humidity [%]	54	52	35	30

Table 2
Characteristic parameters of the building stock evaluated.

Parameters		Distribution	A3	A4	B4	C3
Geometry	Orientation (North Axis) [°]	Uniform	0–360	0–360	0–360	0–360
	Floor Area [m^2]	Uniform	110–190	80–190	130–230	110–170
	Form ratio*	Uniform	1–5	1–5	1–5	1–5
	Floor height [m]	Uniform	2.50–3.00	2.50–3.00	2.50–3.00	2.50–3.00
	Window-to-wall ratio [%]	Uniform	10–20	10–20	10–20	10–20
	Number of floors	Uniform	2/3/4/5	3/4	3/4	2/3/4
Envelope	Roof solar absorptance	Normal	0.10–0.90	0.10–0.90	0.10–0.90	0.10–0.90
	Façade solar absorptance	Normal	0.10–0.90	0.10–0.90	0.10–0.90	0.10–0.90
	Floor U-value [W/m^2K]	–	3.00–7.00	3.00–7.00	3.00–7.00	3.00–7.00
	Floor thickness [m]	Normal	0.15–0.30	0.15–0.30	0.15–0.30	0.15–0.30
	Floor conductivity [W/m K]	Normal	0.70–1.80	0.70–1.80	0.70–1.80	0.70–1.80
	Floor density [kg/m^3]	Normal	1200–1800	1200–1800	1200–1800	1200–1800
	Floor specific heat [J/kg K]	Normal	500–1500	500–1500	500–1500	500–1500
	Roof U-value [W/m^2K]	–	0.9–2.4	0.9–2.4	0.9–2.4	0.9–2.4
	Roof thickness [m]	Normal	0.25–0.45	0.25–0.45	0.25–0.45	0.25–0.45
	Roof conductivity [W/m K]	Normal	0.30–0.60	0.30–0.60	0.30–0.60	0.30–0.60
	Roof density [kg/m^3]	Normal	1000–1800	1000–1800	1000–1800	1000–1800
	Roof specific heat [J/kg K]	Normal	500–1500	500–1500	500–1500	500–1500
	Façade U-value [W/m^2K]	–	1.30–2.75	1.30–2.75	1.30–2.75	1.30–2.75
	Façade thickness [m]	Normal	0.10–0.30	0.10–0.30	0.10–0.30	0.10–0.30
	Façade conductivity [W/m K]	Normal	0.20–0.40	0.20–0.40	0.20–0.40	0.20–0.40
	Façade density [kg/m^3]	Normal	1000–3000	1000–3000	1000–3000	1000–3000
	Façade specific heat [J/kg K]	Normal	500–1500	500–1500	500–1500	500–1500
	Window U-value [W/m^2K]	–	5.50–5.70	5.50–5.70	5.50–5.70	5.50–5.70
	Type of window glass	Uniform	Single	Single	Single	Single
	Type of window frame: aluminium (A)/steel (S)	Uniform	A	A	A/S	A
Operation	Occupancy rate [$people/m^2$]	Normal	0.01–0.15	0.01–0.15	0.01–0.15	0.01–0.15
	Infiltration rate [h^{-1}]	Normal	0.30–1.00	0.30–1.00	0.30–1.00	0.30–1.00
	Night-time ventilation rate [h^{-1}]	Uniform	0.00–4.00	0.00–4.00	0.00–4.00	0.00–4.00

length), the average height of each floor, window-to-wall ratio, number of floors, envelope constructive characteristics (solar absorptance, thickness, density, specific heat and thermal conductivity), type of window glass and frame, occupancy rate, infiltration rate and ventilation rate. In this work, natural ventilation rates vary from cases that never open the windows (for reasons relating to noise, light or privacy) to cases where windows are completely open at night-time. The Spanish Building Technical Code [53] estimates a ventilation rate of 4 h^{-1} for a common practicable window fully open during the night hours.

2.2. Parametric Building Simulation Models

The Parametric Building Simulation Models (PBSM) developed in this work follow the SLABE method (Simulation-based Large-scale uncertainty/sensitivity Analysis of Building Energy performance) originally defined by Mauro et al. [44]. This method is based on the parameterization of certain characteristic data, which define the building stock at a regional scale through their physical, constructive, geometrical, and operational characteristics (Table 2), in the EnergyPlus code of the simulation model. Latin Hypercube Sampling (LHS) is used to define a uniform and representative simulation model set within the variability range and type of distribution defined in Table 2 as a result of the statistical analysis conducted on the AVRA database described in section 2.1. Once this sample is defined, a mathematical function is generated in MATLAB environment, allowing the automatic launch of the models in EnergyPlus simulation software and the processing of the results obtained.

This method has already been applied and validated, through in-situ measurements, for the specific typology of linear social housing in southern Spain in previous works [55], which analysed the thermal behaviour of the stock built in Sevilla before 1979. For the validation of the method, a representative linear block located in Sevilla (B4 climatic zone) was selected as a reference case study. An exhaustive characterization of this case study was carried out, including a monitoring campaign of the environmental variables for a whole year. The geometrical, constructive, and operational variables of the reference case study were incorporated into the simulation model developed in EnergyPlus, and climate data measured during the monitoring campaign were used for this energy simulation for the purposes of validation. The simulated indoor air temperatures were compared with the in-situ measurements, and the model was validated according to the procedure established in ASHRAE Guideline 14–2014 [56], which sets two error indicators: the Normal Mean Bias Error (NMBE), with an hourly calibration threshold of ±10%, and the Coefficient of Variation of the Root Mean Square Error (CVRMSE), which should remain under 30%. The simulation showed high reliability, with an annual value of NMBE below 3% and of CVRMSE around 7%.

The optimal sample size for PBSM of this building category was determined to be 750 simulation models, which also allows the reliable generation of predictive models using artificial neural networks in future research. For this reason, the same sample size has been maintained in this study.

2.3. Adaptive thermal comfort assessment

The protocol described in this work provides an analysis of the environmental vulnerability of the social housing stock, using an adaptive approach to evaluate the indoor thermal comfort conditions. This study focuses specifically on the cooling period, which the current Spanish regulations [53] define as the period from June 1st to September 30th.

To do this, thermal comfort conditions are first evaluated through simulated indoor temperatures (Ti) and the percentage of discomfort hours is calculated according to the adaptive thermal comfort model proposed by Barbadilla et al. [57]. This model is based on the adaptive model established in EN 16798–1:2019 [43] for buildings with natural ventilation (in which users have a greater possibility of adaptation) but adjusted for the climatic conditions of southern Spain and for buildings with an occasional use of air conditioning systems (i.e., mixed-mode buildings). Previous research [48] concluded that a revision of the two most extensively used adaptive thermal comfort standards [41,43] was necessary to ensure their suitability for the hot summers of southern Spain given that indoor temperatures above 31 °C were considered comfortable at that point.

In this work, the optimum comfort temperature (Tc) for the summer period is calculated according to Equation (1). Assuming 80% of satisfied occupants (PPD <20%) the adaptive thermal comfort range spans a temperature interval of Tc ± 3.5 °C. This hypothesis is usually applicable to existing buildings.

$$Tc = 0.24 \times Ter + 19.3 \; [^{\circ}C] \tag{1}$$

where Ter is the running mean outdoor temperature, as defined by Equation (2).

The impact of the outdoor temperature on user comfort at a given moment decreases the more time passes. Thus, the reference outdoor temperature must be weighted over the daily mean outdoor temperature of the previous 1–7 days (Ter1 and Ter7). This equation can be applied provided outdoor running temperatures are set between 10 °C and 30 °C. In cases where Ter is below the minimum threshold or above the maximum one, it must be adjusted and set at 10 °C or 30 °C respectively.

$$Ter = \frac{Ter1 + 0.8 \times Ter2 + 0.6 \times Ter3 + 0.5 \times Ter4 + 0.4 \times Ter5 + 0.3 \times Ter6 + 0.2 \times Ter7}{3.8} \; [^{\circ}C] \tag{2}$$

The evaluation of the percentage of discomfort hours responds to the current Spanish regulations [53], which set a maximum of 4% for new buildings. However, this analysis criterion does not indicate discomfort severity, that is, how far the indoor thermal conditions are from the comfort range [46]. To further examine the comfort assessment, the study considers the overheating Discomfort Degree-Days during the cooling period (CDDD) (Equation (3)). This criterion evaluates the accumulated hourly difference between indoor temperatures (simulated in this work) and the upper comfort limit per day. It only applies when Ti exceeds the threshold, and each step h refers to 1 h. Therefore, in addition to indicating the number of hours of overheating, this value shows how far indoor thermal conditions are from comfort [58]. In other words, it is an indication of the cooling loads that must be overcome to avoid discomfort in this housing stock.

$$if\ Tc\ Upper\ limit, h < Ti, h\ CDDD = \frac{\sum_{h=1}^{n} \left(Ti, h - Tc_{Upper\ limit, h} \right)}{24} \; [^{\circ}C \cdot day] \tag{3}$$

Thanks to the results obtained from the adaptive comfort analysis for a large study sample a sensitivity analysis can be carried out to determine the most influential parameters in the thermal behaviour of the residential stock evaluated. This requires the evaluation of the Standardized Rank Regression Coefficient (SRRC) for the set of characteristic parameters. SRRC sensitivity indices range from −1 to 1, and a positive value means that the parameter and the result change with the same sign, while the opposite is true for a negative value. According to the existing literature [59], this is the most suitable method for non-linear but monotonic relations between inputs and outputs. This sensitivity analysis, which will indicate the parameters with the greatest improvement potential for this case study, is expected to be very useful for decision-making in future phases of the process of energy retrofitting the existing housing stock.

2.4. *Cooling degree-days*

In this study, the calculation of Degree-Days (DD) during the cooling period (June 1st to September 30th) is carried out to evaluate the climatic severity of the four case-study locations and normalize the comfort assessment of the housing stock. The general definition of DD is the sum of the positive differences between a base temperature (Tb) and the daily average outdoor temperature (Ted) [60]. Cooling Degree-Days (CDD) only consider the differences when the outdoor temperature exceeds the base temperature during the cooling period.

According to EN ISO 15927–6:2007 [61] there are several ways of calculating DD, depending on the data available. Accumulated hourly temperature differences are calculated when hourly outdoor temperature (Teh) measures are available, since this is the most rigorous and precise method. The accumulated hourly temperature difference may be expressed in degree-days according to Equation (4), in which each step ‘h’ refers to 1 h. This paper uses weather data files obtained from the Meteonorm database [54]. These datasets include hourly measurements of the outdoor temperature and enable the calculation of CDD using Equation (4).

$$if\ Teh,h > Tb CDD = \frac{\sum_{h=1}^{n}(Teh,h - Tb)}{24}\ [^{\circ}C\cdot day] \tag{4}$$

EN ISO 15927–6:2007 [61] defines Tb as the internal design temperature minus a decrement due to internal and solar gains. Tb values must be multiples of 2 °C. The most up-to-date air conditioning design guide for Andalusia [62] sets the Tb for calculating CDD at 20 °C. However, current Spanish regulations [53] set the design temperature for residential buildings at 25 °C during the day and 27 °C at night. For this reason, this work considers a Tb of 24 °C for the calculation of CDD (in line with [63]), after subtracting 2 °C (accounting for the extra loads considered for occupancy and solar radiation [60]) from a design temperature of 26 °C, obtained as the mean value of the design temperatures for daytime and night-time established in current regulations.

2.5. *Index of vulnerability to overheating*

Finally, this study aims to define an index of vulnerability to overheating, focusing on the building characteristics and excluding the influence of climate [64]. Equation (5) enables the normalization of CDDD via CDD, defining the overheating index (OI). The implications of this index indicate that the higher the index, the greater the vulnerability of a building to suffer from overheating, and therefore, to undergo discomfort conditions.

$$OI = \frac{CDDD}{CDD} \tag{5}$$

3. Results and discussion

3.1. *Cooling degree-days*

CDD are calculated for the period between June 1st and September 30th for the four locations contemplated in this work, following the methodology expressed in section 2.4. An additional calculation of CDD is carried out with a base temperature of 20 °C to enable a comparison with CDD included in the most up-to-date Andalusian air conditioning design guide [62]. The climatic data used in this guide, obtained from the Spanish State Meteorological Agency, cover the period 1998–2007, while the climatic files used for the environmental simulations in this work were obtained from the Meteonorm database [54], with data from 2010 to 2020.

Table 3 shows the standard CDD for the design of buildings, available in Ref. [62], in comparison with the values calculated from the Meteonorm climatic files taking both 20 °C and 24 °C as Tb. When using more recent climatic data, the results show an increase in CDD (with the same Tb) in all climatic zones. The greatest increase is observed in zone B4 (31%), followed by zones C3 and A3 (20% and 18% respectively). In zone A4, the increase in CDD is only 8%. These results confirm the need to analyse the behaviour of existing building stocks with updated climatic files for considering the current effect of climate change on the research outputs, which does not

Table 3
Cooling degree-days results [°C·day].

Climate zone	Standard [62]	Meteonorm 2020	Meteonorm 2020
	Tb = 20 °C	Tb = 20 °C	Tb = 24 °C
Cádiz - A3	448	527	213
Almería - A4	598	648	268
Sevilla - B4	692	909	515
Granada - C3	618	740	423

affect all areas of southern Spain equally.

Another aspect to highlight is the fact that CDD are not always in line with the summer climatic severity defined by Spanish regulations [53]. This can be observed in the city of Granada, classified as a summer climatic zone 3, where the CDD value is much higher than in the city of Cádiz, also in zone 3. It is also much higher than that of Almería, which is classed as zone 4 (more severe). Although the difference in standard CDD between Granada and Almería is small, it increases notably when analysing the CDD of the Meteonorm climatic files with the Tb of 24 °C. This indicates a clear need to review the official climatic zoning, which is already affected by the climatic changes of recent years and the situation is expected to worsen in the coming years. These results are in complete agreement with the conclusions obtained by Bienvenido-Huertas et al. [65], whose work presents a new climate classification methodology based on k-means.

3.2. Thermal comfort assessment

Fig. 4a and b respectively present the percentages of discomfort hours and CDDD for the summer period in the whole sample, simulated in four climatic zones representing the region of Andalusia, by means of Box plots. The central mark of the boxes indicates the median, and the lower and upper extremes the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme values that are not considered outliers, while the outliers are represented by the '+' symbol beyond these.

As expected, the social housing stock in Sevilla (B4) displays the worst indoor conditions in terms of percentage of discomfort hours in the cooling period (CDH), since it is the location with the greatest climatic severity, with values frequently ranging between 18% and 40%. The same occurs with the Discomfort Degree-Days of the cooling period (CDDD), with frequent values between 225 °C·day and 400 °C·day. In terms of poor behaviour, it is followed by Granada (C3), with frequent CDH values of 8%–24%, and CDDD values of 175 °C·day to 350 °C·day. It should also be noted that the mean CDH values for zones B4 and C3 are much farther from each other than the CDDD values. This indicates that although residential stock in Granada has more hours of comfort, when discomfort occurs it is very severe (despite being officially classified as summer climatic severity 3). These results are in keeping with other works that evaluate overheating in existing social housing in southern Spain based on in-situ measurement campaigns. In Ref. [48] similar values of discomfort hours are reported, even exceeding 60% in some cases with a similar comfort standard, and in Ref. [15] values of between 40% and 97% of discomfort hours are reported.

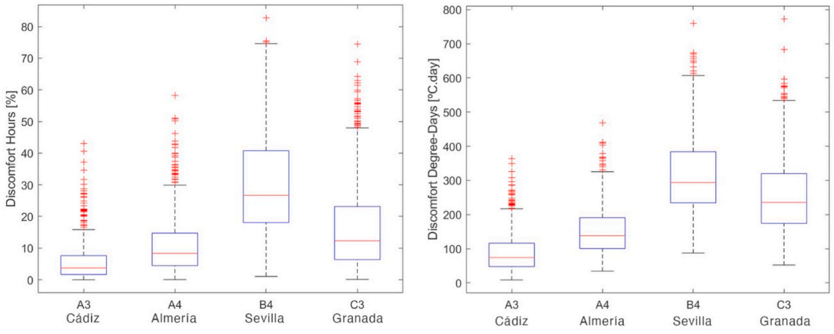
The stocks from the cities of Cádiz (A3) and Almería (A4) display the best thermal behaviour, with average CDH values of 4% and 9%, respectively, and CDDD values of 75 °C·day and 150 °C·day. The climatic severity of Almería is slightly greater than that of Cádiz, which is in keeping with the results obtained for the comfort assessment.

In the case studies with the median CDDD value for each climatic zone, the hourly difference between Ti and the upper limit of the comfort range during the discomfort hours in the summer period has been evaluated. Fig. 5 shows the results by means of histograms and the normal distribution of best fit. Thus, the median CDDD value of around 300 °C·day calculated in zone B4 translates into hourly deviations of the indoor temperature of up to 7 °C with respect to comfort conditions, with the most frequent values standing at around 3.5 °C (Fig. 5c). In the case of zone C3, the temperature deviation also reaches 7 °C, but the most frequent values are between 2 °C and 3 °C (Fig. 5d). In the two coastal locations, zones A3 and A4, the most frequent temperature difference values are below 2 °C (Fig. 5a and b).

In order to analyse the correlation between the percentage of CDH and the severity of the discomfort, Discomfort Degree-Hours during the cooling period (CDDH) have been calculated (equation (6)) instead of using CDDD (equation (3)).

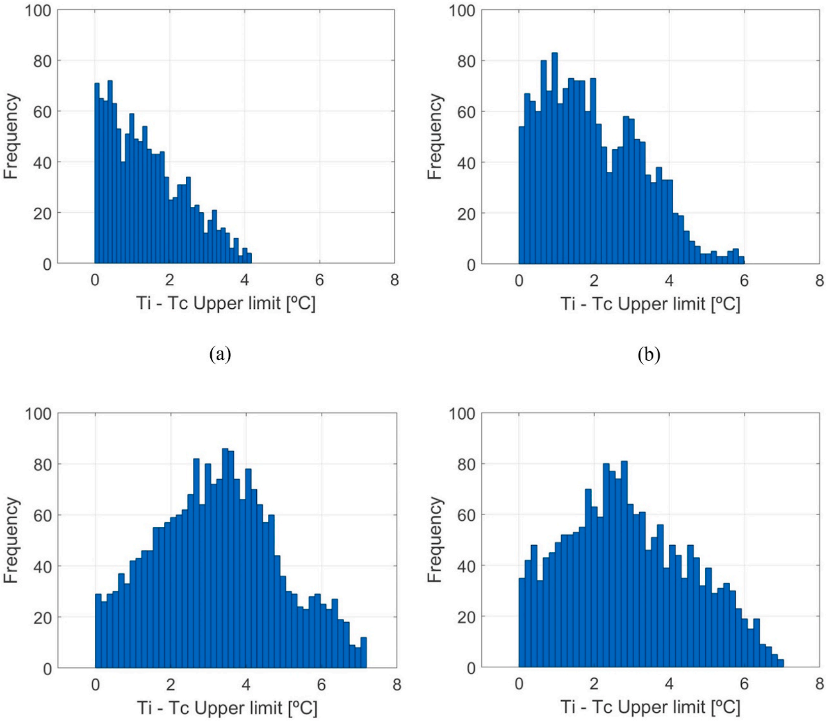
$$if\ Tc\ Upper\ limit,h < Ti,hCDDH = \sum_{h=1}^{n}\left(Ti,h - Tc_{Upper\ limit,h}\right)\ [^{\circ}C\cdot h] \tag{6}$$

Fig. 6 shows that the two coastal locations (A3 and A4) display a very similar pattern. A higher concentration of cases and a steeper slope are observed at the lowest values of the graph. In the case of climatic zone B4, the correlation is almost linear with a more homogeneous distribution, in which the cases with lower CDH have a minimum CDDH value of 2000 °C·h. The case of climatic zone C3 is the most heterogeneous, with many cases with low CDH values (below 10%) and great discomfort severity (CDDH over 4000 °C·h).



(a) (b)

Fig. 4. Comfort analysis results: Discomfort Hours in the cooling period (CDH) (a) and Discomfort Degree-Days in the cooling period (CDDD) (b).



(a) (b)

(c) (d)

Fig. 5. Distribution of the hourly difference between the indoor temperature (Ti) and the upper limit of comfort temperature (Tc) for cases with the median value of CDDD in Cádiz_A3 (a), Almería_A4 (b), Sevilla_B4 (c), and Granada_C3 (d).

This could be associated with the high daytime temperature variation in this location, with very high maximum temperatures and sharp drops in temperature at night, which significantly reduce the CDH. Moreover, unlike climatic zone B4, the housing stock in Granada has a significant percentage of 2-storey buildings, notably increasing the ratio between the roof surface and living area, which is specially detrimental to the buildings' thermal behaviour in the summer period [66].

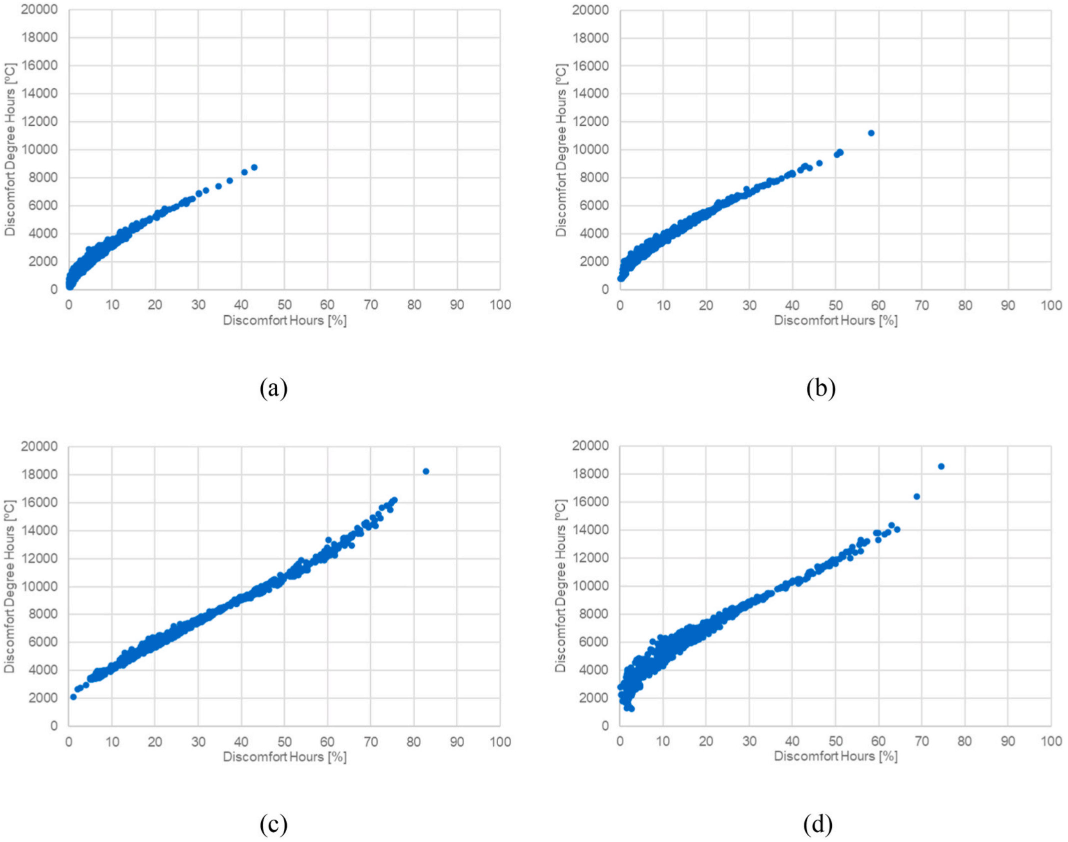
The normalization of the thermal comfort severity through the CDD by means of the overheating index (OI) minimizes the differences between zones (Fig. 7). The climatic zones B4, C3 and A4 practically have the same average OI value, varying between 0.60 in Sevilla (B4) and Granada (C3), and 0.50 in Almería (A4). Cádiz, with a mean OI of 0.35, displays the lowest values. The maximum non-atypical OI values of the four locations range from 1.00 (Cadiz, A3) to 1.30 (Granada, C3). This normalized index enables decisions on which buildings are in most urgent need of action, focusing on the degree of vulnerability to overheating of the building regardless of the climatic severity of the location.

3.3. Sensitivity analysis

The outputs of the sensitivity analysis show similar trends in all the climatic zones evaluated, with no discrepancies between the results for CDH and CDDD (Fig. 8). The parameters showing the greatest influence, both in percentage of hours of discomfort and in its severity, are.

- the night-time natural ventilation rate, the increase of which represents a significant improvement in indoor thermal conditions;
- the façade solar absorptance, the increase of which implies an increase in discomfort;
- the form ratio, since the greater the compactness, the better the indoor thermal conditions;
- the roof solar absorptance, which is the same as that of the façade, but is less relevant as it only affects top-floor dwellings;
- and the floor area of the building, also related to the compactness of the building.

It should be noted that the greater the climatic severity, the greater the influence that passive measures such as natural night-time ventilation have on thermal comfort, as observed in zones B4 and C3. These results are in line with the conclusions obtained by Calama-González et al. [67] in test cells. It is also worth highlighting that in the case of climatic zone B4 (with greater summer severity), the façade conductivity has the opposite effect to the rest of the locations, albeit not as noticeably. A reduction in façade conductivity results in a worsening of comfort conditions. This may be due to a poorly insulated façade allowing the excess of heat accumulated inside (overheating) to be dissipated during the night.



(a) (b) (c) (d)

Fig. 6. Correlation between percentage of Discomfort Hours in the cooling period (CDH) and Discomfort Degree-Hours in the cooling period (CDDH) for the building stock of Cádiz_A3 (a), Almería_A4 (b), Sevilla_B4 (c), and Granada_C3 (d).

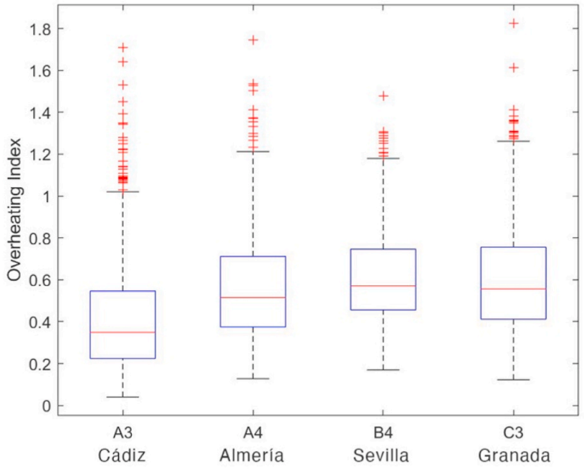
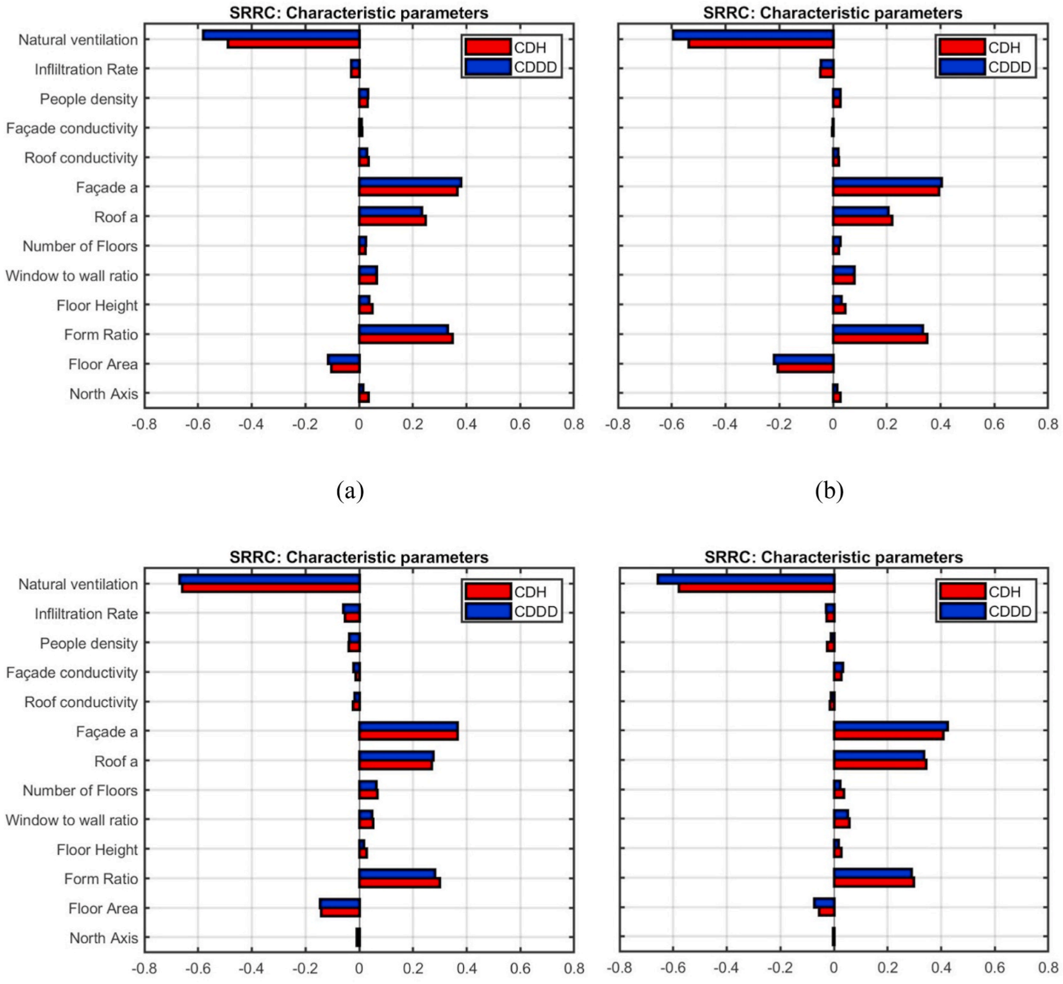


Fig. 7. Overheating Index (OI) results.

3.4. *Strengths, limitations and future research steps*

In this work, the OI is defined as a new index for the evaluation of vulnerability to overheating in buildings, normalized through degree-days. This allows future assessments to focus on the geometric, constructive, and operational weaknesses of the buildings which mainly affect their thermal behaviour in summer. In addition, this index is applied to a regional scale through the use of validated Parametric Building Simulation Models, that represent a large amount of the building stock located in four cities with different climatic conditions. Its application facilitates a direct comparison of the assessment of vulnerability to overheating of cases from different



(a)

(b)

(c)

(d)

Fig. 8. Sensitivity analysis (SRRC) for the stock of Cádiz_A3 (a), Almería_A4 (b), Sevilla_B4 (c), and Granada_C3 (d).

climatic zones. This can help organizations in charge of the renovation processes of social housing stock to identify the buildings most in need of urgent action. Otherwise, action will always be taken first in the most severe climates and not in the most vulnerable buildings.

The characterization of this building stock is based on the information compiled in a large database pooling information from a range of sources. However, developing large-scale models without exceeding acceptable computational efforts requires the simplification of certain variables involved in the simulation. An example of this is the operational parameters, such as occupation or the use of windows for natural ventilation and movable solar protections, which tend to vary, even within a single home. Large-scale models are developed for obtaining global conclusions at a regional scale, but future retrofitting processes in specific cases require a more detailed simulation model including real use and occupation patterns.

The use of a large database enables the development of a large sample size, and therefore the volume of results is considerable. This allows the future development and training of neural networks which significantly reduce computing times for predicting the thermal behaviour of any of the buildings belonging to the archetypes evaluated.

In this case, evaluations focus on summer discomfort and overheating in a specific archetype. However, the methods applied can be easily adapted in future research steps for the assessment of the winter period behaviour and of other variables such as energy demand, as well as for other building typologies. In addition, one of the main strengths of the BSM method presented in this work is that it integrates dynamic analysis techniques, since it provides advanced dynamic thermal simulation at sub-hourly timesteps. Therefore, for its prospective subsequent applicability, it is essential that this BSM can further integrate time-based scenario evaluations, such as future climate change scenarios. This aspect overcomes the limitations of most existing methods and tools for energy assessment, since it provides a comprehensive framework that accounts for the influence of time-dependent characteristics on the built environment and is able to simulate several scenarios.

This method can also incorporate a numerical optimization of retrofitting scenarios through genetic algorithms to determine the best cost-effective solutions according to multi-criteria decision-making (MCDM). The MCDM methods are of great potential to facilitate easier decisions at the initial steps of the retrofitting procedures [68], urgently required in these social housing stocks, by quantitatively assessing the interdependencies between social, economic, and environmental indicators, which is essential for realistic prediction of the future impacts. Therefore, the future scope of this work should focus on the implementation of dynamic analysis techniques considering future climate scenarios, coupled with MCDM methods to improve and optimize the energy retrofitting policies by taking into consideration the complex nature of the built environment and its users.

4. Conclusions

This study has presented an innovative protocol for the evaluation of the vulnerability to overheating of social housing stock at a regional scale, based on an adaptive thermal comfort assessment for the cooling period. This represents a new contribution to the existing literature, given the need for more extensive research on the adaptive thermal comfort of large-scale housing stocks considering the adaptability of economically vulnerable users to the current climate. In addition, as the main novelty of this study, an index of vulnerability to overheating is proposed, that normalizes the adaptive comfort assessment through the degree-days calculated for the outdoor conditions of each location, primarily considering the weaknesses of buildings and their users rather than being so influenced by climatic variables.

This protocol has been applied to the region of southern Spain, by means of validated parametric models and carrying out over 3000 simulations representing the social housing stock built between 1979 and 2006 in four climatic zones of southern Spain. The definition of the residential stock under study relies on public datasets with geometric and constructive information for more than 39400 dwellings.

CDD have been calculated for the four case study locations selected, but the results are not always in line with the summer climatic severity determined by the current Spanish regulation, since Granada (severity 3) has the second highest CDD value, behind Sevilla (severity 4). However, Almería (severity 4) and Cádiz (severity 3) display the lowest values with a difference of only 55 °C·day between them.

The results of the thermal comfort evaluation led to the global conclusion that social housing stock in the region of Andalusia presents a low level of comfort in inland locations (such as Sevilla and Granada), with frequent values of between 5 and 40% of discomfort hours, and a better behaviour in coastal locations (such as Cádiz and Almería), with frequent values of between 0 and 15% of discomfort hours. The case of Sevilla (B4) displays the poorest thermal behaviour, with a median value of more than 25% of hours in discomfort, followed – in order – by Granada (C3), Almería (A4) and Cádiz (A3), with median values of 12%, 10% and 5% respectively. Despite there being fewer hours of discomfort in Granada than in Sevilla, discomfort severity in the social housing stock is equally high in both locations.

In general, these thermal comfort results have a greater correspondence with the calculated CDD than with the analytical climatic zoning approach found in the Spanish regulations. A clear example of this is the fact that results for Granada and Cádiz (both in zone 3) are very far apart, despite sharing the same regulatory thermal requirements as they are both within in the same climatic zone. As the geometric, constructive, and operational conditions are quite homogeneous in the four locations, the main differences in thermal behaviour are attributed to climate severity.

Thus, in Spain, the current climatic zones defined by regulations, on which the thermal requirements, and in turn the official energy rating procedures, are based, should be reviewed as they do not accurately reflect the current situation of this social housing stock. An update of climatic databases and zoning is necessary to adapt to the current situation and anticipate future projections affected by global warming. However, this is a very complex issue that should not be based solely on CDD but also on additional parameters such as solar radiation, humidity, night-time temperatures (for passive cooling potential), etc.

Thanks to the proposed index of vulnerability to overheating, a novel intervention prioritization decision support system is provided. The results obtained show a very similar distribution of the index across the four climatic zones, since the four social housing stocks show similar features, with slightly lower values in Cádiz (A3). Consequently, the use of this widely applicable index of vulnerability to overheating facilitates a direct comparison between two specific cases from different climatic zones, helping the organizations involved in the energy retrofitting processes of the social housing stock to decide the order in which buildings should be intervened taking into consideration their main weaknesses. The well-being improvement of vulnerable families requires urgent action from the Regional Government, so that the retrofitting of the social housing urban areas in the coming years is becoming essential.

CRediT authorship contribution statement

Rocío Escandón: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Simone Ferrari:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Teresa Blázquez:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Rafael Suárez:** Methodology, Writing – review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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