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# Mitigation of climate change in Mediterranean existing social dwellings through numerical optimization of building stock models

Carmen María Calama-González *, Rafael Suárez, Ángel Luis León-Rodríguez

*Instituto Universitario de Arquitectura y Ciencias de la Construcción, Escuela Técnica Superior de Arquitectura, Universidad de Sevilla, Av. Reina Mercedes 2, Seville 41012, Spain*

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ABSTRACT

Retrofitting the existing building stock is widely accepted as a crucial factor to reaching 2030 and 2050 climate and energy targets, given that the building sector is among the top three most dominant energy consumers. This paper presents a bottom-up study which uses calibrated and parameterized energy stock models (building archetypes), while also incorporating building stock information from a large database. The thermal performance of the existing social housing stock of southern Spain is assessed through dynamic simulation under present and future climate change scenarios. Subsequently, several passive and low-cost operation-related strategies are numerically optimized through genetic algorithms to determine the best retrofit solutions, taking into consideration global warming scenarios. A multi-objective decision analysis is carried out by optimizing annual overheating hours (%), annual undercooling hours (%), and investment costs (€/m$^2$). Among the conclusions reported, it is important to note the feasibility of implementing low-cost retrofit strategies considering investment costs of up to around 200 €/m$^2$, which would lead to average annual overheating and undercooling hours below 55 % and 45 %, respectively. However, retrofit solutions exclusively based on passive and low-cost operation measures were proven to be significantly limited to improve thermal comfort results in the social stock.

## 1. Introduction

### 1.1. The European building sector under future energy targets

According to a recent study conducted by NASA, the global surface temperature of the planet increased by 1.02 °C in 2020 compared to the pre-industrial period [1]. Climate change will cause more frequent and extreme weather phenomena [4], with severe repercussions for the low adaptive capacity and resilience of populations [5] and adverse health effects [6]. To tackle climate change, political leaders and public administrations are promoting building decarbonization through the development of sustainable energy approaches, contributing to the reduction of the anthropogenic carbon footprint. In the last climate change conference, the COP26 presented a highly ambitious 2030 energy framework to reach net zero carbon emissions by the middle of the century while setting a limit of 1.5 °C to the global warming temperature [7]. Since in 2019 the building sector was identified as the most dominant energy consumer [8], a key objective in the European low-carbon economy plan is to increase the energy efficiency of the existing stock, promoting its durability and adaptability [9]. Given that almost half of the total buildings' energy-related carbon dioxide emissions were derived from the housing stock and that existing buildings are expected to become a significant extension of the future stock due to the low new-built construction rate [10], retrofitting the existing housing stock becomes key.

### 1.2. Building energy performance and retrofit optimization towards climate change

The impact of climate change on the building sector has been extensively analysed in dominant heating regions of northern and central Europe. Nevertheless, <20% of studies have focused on warmer climates [11], such as the Mediterranean, which will be more sensitive to global warming [12]. Global warming is expected to increase cooling energy consumption in southern Europe [13] and lead to a noticeable reduction in indoor air quality and thermal comfort [14], deriving in indoor overheating issues, which could be worsened by excessively high-insulated envelopes [15] or fuel poverty in social dwellings [16]. In the case of residential building retrofit optimization in the Mediterranean area, Dervishi et al. [17] conducted an energy performance optimization on three traditional single-family houses in Albania, after performing a calibration process through on-site measurements. Even

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* Corresponding author.
*E-mail address:* ccalama@us.es (C. María Calama-González).

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though several retrofit strategies (window replacement, thermal insulation in envelope, etc.) were assessed, manual optimisation was conducted, selecting the best solutions in terms of indoor temperatures and energy demand. Rosso et al. [18] proposed the implementation of a genetic algorithm in a multi-objective problem to optimize building retrofit strategies applied to a single residential building in Rome (Italy). Dynamic energy performance simulation was used for the optimization of investment and energy costs, energy demand and carbon dioxide emissions. Penna et al. [19] analysed 12 residential buildings by using a genetic algorithm and dynamic energy simulation to modify different characteristics of a reference case in Milan (Italy). The best building retrofit strategies were obtained by optimizing energy savings, costs and thermal comfort. Panagiotidou et al. [20] defined the best strategies for retrofitting a single-family residential building in Greece, considering passive and active measures (thermal improvement of envelope, window replacement and implementation of several Heating, Ventilation and Air Conditioning – HVAC systems). Greenhouse gas emissions and life cycle costs were minimized applying a generic algorithm. Ascione et al. [21] considered energy consumption and global costs in order to obtain optimal solutions for the retrofit of an Italian neighbourhood, applying photovoltaic production at district level. Several studies have also been conducted in order to optimize existing residential buildings towards nearly zero energy buildings [22,23].

Nonetheless, none of the previous retrofit optimization studies include different global warming scenarios and over time the effectiveness of energy retrofit strategies can be greatly affected by climate change. Therefore, the energy retrofit of buildings must consider present energy and thermal performance, while also taking into account future climate change scenarios. In this field, Makantasi and Mavrogianni [24] manually defined optimized retrofit packages to combine the reduction of energy consumption and carbon emissions with future climate resilience in social housing buildings in central London (U.K.). Streicher el al. [25] presented optimal building retrofit pathways to the Swiss residential stock, considering a bottom-up approach for dynamic building stock modelling. The reduction of greenhouse gas emissions from the energy consumption of buildings is analysed under 2020, 2040, 2060 and 2080 weather scenarios. However, none of the authors mentioned earlier include indicators for numerical optimization decision analysis.

In the specific case of residential Mediterranean stock, Lassandro and Di Turi [26] focused on the proposal of optimized retrofit facade solutions based on the addition of thermal insulation, using the case study of a multi-storey residential building in Bari (Italy) to determine its future climate change resilience. Baglivo et al. [27] predicted the energy performance of a multi-family residential building in Lecce (Italy) under 2020, 2050 and 2080 weather scenarios. Although the aim of this study was to reduce thermal energy for air conditioning in this building, no retrofit strategies were proposed. Similarly, Dascalaki et al. [28] provided a simple assessment of possible passive and active retrofit scenarios applied to the Greek residential stock for 2020 and 2030, in order to enhance energy savings, but with no optimization approach. A residential single-family case study in Benevento (Italy) was analysed by De Masi et al. [29] under 2050 and 2080 future climate scenarios. Although several passive retrofit strategies were implemented into the case study for an energy demand comparison, no optimization method was considered. Dino and Akgül [30] assessed the impact of future weather data on a typical existing residential building in Turkey. While this study takes into consideration the impact on energy requirements, carbon dioxide emissions and thermal comfort, it does not address the proposal of optimized retrofit strategies. No retrofit solutions are considered by Escandón et al. [31] when comparing energy performance of the social housing stock of southern Spain under present and 2050 weather scenarios. Ascione et. al [32] presented a multi-objective approach to ascertain robust cost-optimal solutions for retrofitting a residential building in Naples (Italy). Passive (thermal insulation, modification of emissivity and solar absorption in external envelope layers, window replacement) and active (different HVAC systems) measures are optimized according to potential cooling energy consumption savings and global cost savings to provide the highest building resilience under global warming scenarios. However, this study examined a single-case building method.

### 1.3. Objective and relevance of the study

In southern Spain (Mediterranean climate), around 60% of the existing housing stock were built prior to any energy regulations and with low economical and technical resources [33], given the impending necessity of residential buildings in 1950–80. Moreover, almost 90% of the existing social public multi-family dwellings were built prior to the Spanish Building Technical Code [34], which in 2006 established relevant energy demand and consumption requirements. Given the low-income resources of social householders, considering fuel and energy poverty issues when implementing retrofit measures is of the utmost importance. Nowadays, only 15 % of the intervention packages in the Spanish stock consider the incorporation of both passive and active energy-related systems [35], since funds are mainly focused on structural retrofits and accessibility adaptations due to the poor conservation conditions of the social households. Besides, social housing providers respond to the ubiquity of low consumption practices in social dwellings and place energy poverty at the core of retrofit programmes, focusing on passive measures to provide thermal comfort with no heating nor cooling systems [36]. This is also related to the fact that social householders cannot afford to pay for HVAC costs due to their low economic incomes, leading to a general lack of use of these systems in the social stock. In this context, the challenge in the social housing stock is the improvement of indoor comfort conditions, rather than the reduction of energy demand, as energy waste is generally lower than expected [37]. Thus, improving the building's thermal envelope through passive and low cost operational solutions may lead to a reduction in energy demand and, hence, to the achievement of energy saving goals [35].

Considering all the previous aspects. the main aim of the research presented is to propose optimal retrofit strategies applied to social housing buildings in southern Spain in order to mitigate future global warming scenarios. The novelty aspects of this paper are:

- The social housing buildings of southern Spain are assessed through energy stock modelling and a bottom-up method which incorporates statistical data from an extensive building database, as opposed to the most commonly used single-case building modelling approach.
- Building performance of the existing stock in southern Spain is analysed under current and future climate change scenarios through parameterized dynamic energy simulation, addressing the scientific gap on climate change studies applied to Mediterranean climates.
- Several retrofit strategies are proposed in accordance to Public Retrofit Programmes and social householders' economic resources.
- Retrofit strategies are numerically optimized through genetic algorithms in a multi-objective decision analysis, rather than through manual and brute force assessments.

- In comparison to the most commonly energy-related optimization, this paper explores low-cost strategies applied to social households to mitigate climate change taking into consideration investment costs and indoor thermal comfort optimization.

## 2. Methods

This work was conducted in several stages through the combination of an extensive database statistical analysis with on-site monitoring, energy building simulation modelling and numerical optimization (Fig. 1). Tasks carried out are described in the following subsections.

### *2.1. Task 1: Southern Spain social housing stock characterisation*

Statistical analysis of an extensive database provided by AVRA (Andalusian Agency of House and Retrofitting) [38] was used to carry out the typological, construction, and energy characterization of the public social housing stock of southern Spain. Following the addition of new variables, this database contains information on 39,486 dwellings built between 1970 and 2005. This includes general data (cadastral reference, address information, construction year, climatic area), geometrical and morphological data (orientation, total built area, average dwelling built area, number of dwellings, building storeys, building height, architectural and urban typologies, percentage of window-to-wall ratio), construction data (type of window glass and frame, envelope details), and energy data (cooling and heating demand, building systems).

The climatic areas of southern Spain are identified in the Spanish Building Technical Code [39], through two indices: climatic severity in winter and climatic severity in summer, both of which depend on the degree-day and solar radiation. The first index is represented by a letter (A to E), whereby A defines areas with milder winters and E corresponds to colder winters. Meanwhile, climatic severity in summer is identified with a number (1 to 4), with 1 referring to regions with milder summers and 4 corresponding to warmer summers (Fig. 2).

In southern Spain, the combination of these parameters results in a total of 8 climatic areas: A3, A4, B3, B4, C3, C4, D2 and D3, all of which are included in the database. However, this paper only addresses areas A3, A4, B4 and C3, where the highest percentage of multi-family dwellings is found. This statement was determined in previous research [34], where specific results on the statistical analysis of the building stock in southern Spain may be found. Furthermore, the focus of this paper is the top building typology in southern Spain, the H-block.

### *2.2. Task 2: Calibration and validation of a case study BEM*

This task consisted in the construction of a building energy model of a representative case study. The building selected for this was a 4-storey residential block built in 1973 and located in climatic area B4 (Fig. 3). After importing geometrical, construction and physical data of the case study into the EnergyPlus v. 9.0.1 [40] open accessed simulation tool, the model was calibrated and validated through hourly on-site measurements. Following the requirements of ASHRAE Guideline 14:2002 [41], the BEM of the case study was considered to be adequately validated. Further information on tasks 1 and 2 can be found in previous works [42].

### *2.3. Task 3: Construction of building archetypes through parameterized building stock modelling*

A bottom-up approach was used to construct parameterized building archetypes representative of residential stock in southern Spain. Variability ranges (general information, geometrical characteristics, building envelope details and operation aspects) of the social building stock obtained from the statistical analysis of the database conducted in Task 1 [34] were incorporated into the parameterization as variable modelling inputs, using the calibrated and validated case study BEM as baseline. Specifically, the simulation variables related to the parameters in Table 1 were parameterized in the BEM, modifying the code in the simulation file to create variables instead of fixed values (i.e. the partition thickness variable was named as @@PARTITION@@ and assigned a normal distribution with possible values of 0.07–0.12 m, considering a mean of 0.1 and a standard deviation of 0.01, following the procedure explained in [43]).

This bottom-up approach, allows the definition of building archetypes, which are representative of the existing housing buildings, to assess the performance at the stock level. Thus, instead of analysing a single-building case study, thousands of building models may be constructed based on the variability ranges of the parameterized variables and, later, simulated to assess the thermal and energy performance of the existing stock.

### *2.4. Task 4: Generation of future weather data projections*

Future climate scenarios were selected taking into consideration the Special Report on Emissions Scenarios [44] by the Intergovernmental Panel on Climate Change (IPCC). This report presents four possible future scenarios, to which different demographic, social, economic, technological, and environmental developments are assigned: A1 refers to a future with rapid economic growth, in line with the rapid introduction of efficient technologies

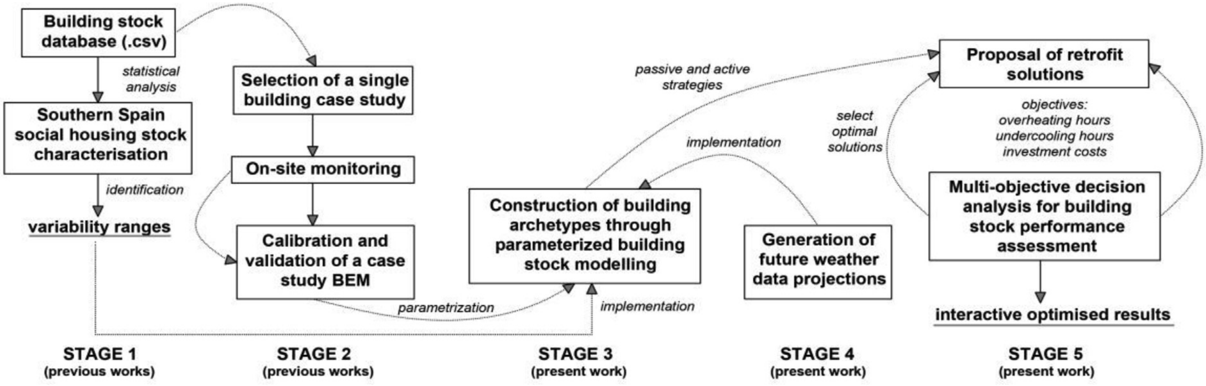
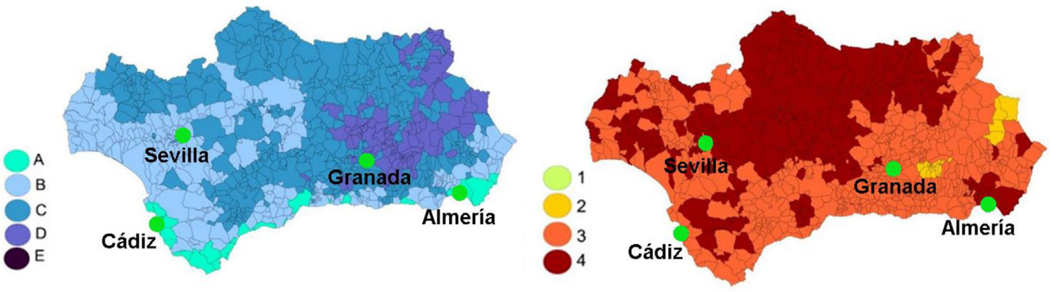


**Fig. 1.** Work plan.



(a) (b)

**Fig. 2.** Climatic areas in southern Spain [45]: Climatic severity (a) in winter; (b) in summer. The green dots refer to the climatic areas analysed: Sevilla (B4), Cádiz (A3), Granada (C3), Almería (A4). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(a) (b)

**Fig. 3.** Case study: (a) Floor plan, (b) General view.

and a global population that will continue to increase up to mid-century; A2 corresponds to a heterogeneous world with a continuously increasing global population and slow technology changes, where local identities are preserved, leading to regional economic growth; B1 presents a convergent world, with rapid economic changes and the introduction of efficient technologies, while maintaining a global population similar to that of A1; and, finally, the future in B2 is more diverse in terms of technology, with local and regional economic approaches and a global population similar to that of A2. These storylines are classified into six future emission scenarios, all of which are equally valid and possible and depend on the climatic modelling approach: A2, B1, B2, and three possible emission scenarios for A1 which consider different energy technologies (A1F1, A1T and A1B: from an intensive fossil fuel approach to a predominantly non-fossil fuel approach).

According to Riblaygua et al. [45], A2 corresponds to the most negative emission scenario. Thus, in this research emission scenario A2, which includes 2030, 2050 and 2080 future periods, has been considered. This scenario predicts an increase in global average surface temperature of around 3–4 °C and average global

**Table 1**
Building characterization of H-typology social housing stock in southern Spain [34].

| Variables | | | BEM (case study) | BSM (stock database) | | | | Distr. |
|---|---|---|---|---|---|---|---|---|
| **General** | – | Construction year | 1973 | 1970–2005 | | | | – |
| | – | Building typology | H | | | | | – |
| | – | Spanish climatic area | B4 | | A3 | C3 | A4 | – |
| | – | Number of dwellings | 26 | 5,935 | 3,185 | 1,624 | 349 | – |
| | – | Urban typology | Terraced | | | | Freestanding | – |
| **Geometry** | P1 | Orientation (°) | 53 | 0 (N-S), 90 (E-W) | | | | U |
| | P2 | Floor area ($m^2$) | 78 | 60–122.50 | 50–95 | 60–85 | 70–90 | U |
| | P3 | Floor height (m) | 2.70 | 2.50–3.00 | | | | U |
| | P4 | Window-to-wall ratio (%) | 14.5 | 10–30 | 10–25 | 10–20 | 10–20 | U |
| | P5 | Number of storeys | 4 | 4–5 | 3–5 | 4–5 | 4 | U |
| **Building envelope** | P6 | Roof solar absorptance | 0.55 | 0.1–0.9 | | | | N (0.5,0.1) |
| | – | Roof U-value ($W/m^2K$) | 2.29 | 1.2–2.4 | | | | – |
| | P7 | Roof thickness (m) | 0.3 | 0.25–0.40 | | | | N (0.30,0.02) |
| | P8 | Roof thermal conductivity (W/mK) | 0.56 | 0.3–0.6 | | | | N (0.45,0.04) |
| | P9 | Roof density ($kg/m^3$) | 1220 | 1000–1800 | | | | N (1400, 125) |
| | P10 | Roof specific heat (J/kgK) | 1000 | 500–1500 | | | | N (1000, 150) |
| | – | Floor U-value ($W/m^2K$) | 3.60 | 3.0–7.00 | | | | – |
| | P11 | Floor thickness (m) | 0.25 | 0.15–0.30 | | | | N (0.20,0.03) |
| | P12 | Floor thermal conductivity (W/mK) | 0.73 | 0.7–1.8 | | | | N (1.2,0.2) |
| | P13 | Floor density ($kg/m^3$) | 1220 | 1200–1800 | | | | N (1500, 100) |
| | P14 | Floor specific heat (J/kgK) | 1000 | 500–1500 | | | | N (1000, 150) |
| | P15 | Facade solar absorptance | 0.70 | 0.1–0.9 | | | | N (0.5,0.1 |
| | – | Facade U-value ($W/m^2K$) | 1.52 | 1.2–2.5 | | | | – |
| | P16 | Facade thickness (m) | 0.25 | 0.10–0.35 | | | | N (0.25,0.05) |
| | P17 | Facade conductivity (W/mK) | 0.20 | 0.2–0.4 | | | | N (0.3,0.03) |
| | P18 | Facade density ($kg/m^3$) | 2170 | 1000–3000 | | | | N (2000,250) |
| | P19 | Facade specific heat (J/kgK) | 1000 | 500–1500 | | | | N (1000, 150) |
| | P20 | Partition thickness (m) | 0.08 | 0.07–0.12 | | | | N (0.1,0.01) |
| | P21 | Type of window glass | Single | | | | | C |
| | P22 | Type of window frame | Aluminium | | | | | C |
| | – | Window U-value ($W/m^2K$) | 5.70 | 5.50–5.70 | | | | – |
| | P23 | Infiltration rate (ACH) | 0.53 | 0.30–1.00 | | | | U |
| **Oper.** | P24 | People density ($people/m^2$) | 0.05 | 0.01–0.15 | | | | N (0.08,0.02) |
| | P25 | Natural ventilation rate (ACH) | 4 | 0–4 | | | | U |
| | P26 | Night-time natural ventilation | 22:00–8:00 | | | | | U |

*Note: Oper.: operation; Distr.: distribution; U: uniform; N(mean, standard deviation): normal; C: categorical.*

carbon dioxide emissions somewhere in the region of 30 GtC/year. The future weather files (.epw) for each climatic area were generated through Meteonorm 7.2 software [46] and later incorporated into the EnergyPlus simulation tool. This software provides access to over 8,000 weather stations and features three IPCC climate change projections, including the A2 scenario presented.

### *2.5. Task 5: Multi-objective decision analysis for building stock performance assessment*

This section presents the multi-objective decision analysis process. The first step was an initial thermal performance assessment of the social housing stock of southern Spain, comparing the climatic areas selected under both present and future climate change scenarios. Following this the optimization objectives of the multi-objective analysis were defined. A sensitivity analysis was then performed in order to identify the most influential variables in the thermal performance of the stock aiming to drive climate change. Subsequently, retrofit solutions were proposed based on the results from the sensitivity analysis and the implementation opportunities for public retrofit programmes and the limited financial resources of social householders. Finally, retrofit solutions were numerically optimized under future climate change scenarios, reporting interactive results for each of the climatic areas studied in southern Spain.

#### *2.5.1. Thermal performance assessment and optimization objectives*

The adaptive thermal comfort model included in EN 16798–1:2019 [47] was considered for the assessment of the thermal performance of the social housing stock. This model determines the adaptive temperature comfort ($T_{co}$) from the running mean dry bulb outdoor temperature ($T_{ext,ref}$), as seen in Equations 1 and 2.

$$T_{co} = 0.33 \times T_{ext,ref} + 18.8 \tag{1}$$

$$T_{ext,ref} = (T_{ext,ref1} + 0.8\,T_{ext,ref2} + 0.6\,T_{ext,ref3} + 0.5\,T_{ext,ref4} + 0.4\,T_{ext,ref5} + 0.3\,T_{ext,ref6} + 0.2\,T_{ext,ref7})/3.8 \tag{2}$$

where:

$T_{ext,ref}$: running mean dry bulb outdoor temperature for today.

$T_{ext,ref1}$ to $T_{ext,ref7}$: daily mean dry bulb outdoor temperature for previous 1 to 7 days.

The comfort band was obtained establishing a temperature interval between + 3 °C and – 4 °C (upper and lower limits, respectively). This means that a predicted percentage of dissatisfied lower than 10 % is considered, corresponding to building category II and a predicted mean vote (PMV) of $-0.5 < PMV < 0.5$. Specifically, the annual percentage of discomfort hours was calculated, taking into account the percentage of hours which do not meet the adaptive comfort band.

In the case of optimization, three objectives were defined:

- Overheating hours (%). The annual percentage of hours when indoor air temperatures were above the adaptive comfort upper limit was established.
- Undercooling hours (%). The annual percentage of hours when indoor air temperatures were below the adaptive comfort lower limit was established.
- Investment costs of retrofit strategies (€/$m^2$). Economic information was obtained from the public Spanish Price Construction Generator [48], which includes both direct and indirect

costs (materials, installation, replacement…). The costs of construction elements such as walls and roofs were compiled from the database in €/m$^2$ and later multiplied by the surface area of the element (m$^2$) in the energy models. The costs of individual elements, such as windows, were obtained from the database in €/element and later multiplied by the number of elements in the energy models. After this, investment costs were presented in €/m$^2$, dividing total costs (€) by the total built area of the dwellings (m$^2$). As costs related to the MV system only include installation costs, operational costs were not included in this research. Equally, life cycle costing and any coefficients relating to possible future variations in investment costs were not taken into account.

### 2.5.2. Sensitivity analysis of the building stock performance towards climate change

A Standard Rank Regression Coefficients (SRRC or Std) sensitivity analysis was implemented to determine the most influential model variables (included in Table 1) towards thermal overheating and undercooling. This meant that the retrofit solutions proposed focused on the variables which enabled the most significant changes in comfort. This method is based on the rank transformation of outputs and inputs considering a multiple linear regression model with a standardized input–output matrix [49]. The variables ranged between −1 and + 1, and represent a direct and indirect variable-output relationship, respectively.

### 2.5.3. Proposal of retrofit solutions

Taking into consideration the results of the sensitivity analysis (see section 3), different strategies were proposed for the retrofitting of the social housing stock under future weather scenarios. Passive solutions foster the improvement of envelope characteristics (walls, roof, window), the implementation of natural ventilation and the optimization of blind aperture schedule. 20 roof solutions and 18 wall solutions were considered, analysing different types of thermal insulation (MW: mineral wool, XPS: extruded polystyrene, PUR: polyurethane, EPS: expanded polystyrene), thermal insulation positions (In: Internal, Ex: External), thermal insulation thickness and floor coverage (pavement or green roof). 16 window solutions were proposed by combining different glazing and frame types (Table 2). Only double glazing windows with and without low-emissivity (LE) surfaces were assessed, since it would be difficult for social users to access better windows. All the construction elements proposed meet the energy requirements of the Spanish Building Technical Code [39], in other words, retrofit solutions meet the maximum U-values establish per each building element.

Another passive strategy considered is natural ventilation. Four ventilation schedules were established, based on use schedules and annual solar radiation gains, distinguishing between summer and winter periods. Natural ventilation occurs through the window openings of the buildings. Likewise, the operation of blinds, the most commonly used solar shading system in southern Spain, was included. Three different aperture schedules were incorporated into the analysis, based on previous studies in the Mediterranean area, optimizing the schedules according to the seasonal period. Finally, another operation-related strategy focused on the addition of mechanical ventilation systems, considered low-cost strategies. In this case, mechanical ventilation fans were defined in the simulation models. Two schedules were analysed: OFF and ON (continuous), meeting the Spanish Building Technical Code indoor air requirements [39]. The mechanical ventilation rates were also determined according to these regulations (Table 3). The addition of other heating / cooling systems and solar or photovoltaic panels were ruled out due to the low incomes of the social householders and the priority objectives of Spanish public retrofit programmes.

### 2.5.4. Optimization analysis under future weather scenarios

In order to tackle the optimization problem, parametric analysis techniques were used with the jEPlus + EA open access tool [43]. For the multi-objective optimization this software used the JEA online engine (ENSIMS Web Services Platform) to carry out the multi-objective optimisation. Specifically, the non-dominated sorting genetic algorithm (NSGA-II), developed by Deb et al. [50], was used. The reason for this is its major advantages related to buildings' optimisation, as stated by Carlucci et al. [51] after reviewing slightly under 70 papers.

The population size (solutions to be evaluated per iteration) in the optimization problem was established considering the Latin Hypercube Sampling (LHS) technique and the generally accepted rule of 10 LHS per parameterized variable [50]. The optimization settings selected were based on the computation power available and the recommendations included in this optimization tool [50]: the maximum number of iterations or generations in the runs was set at 100; the crossover rate (frequency related to the creation of new solutions merging features of existing ones) and the mutation rate (frequency of randomly changing new solutions) were set at 100 % and 20 %, respectively; and, finally, the tournament selection size was considered to be 2 (the algorithm employs the best solution out of two).

## 3. Results and discussion

### 3.1. Sensitivity analysis. Influential simulation variables on thermal discomfort

Fig. 4 shows the results of the sensitivity analysis, conducted for the optimization objectives of both overheating (red bars) and undercooling (blue bars) discomfort hours. Up to 37 variables related to general aspects, envelope characteristics and operational parameters were assessed, including the ones described in Table 1, as well as other variables which were incorporated into the analysis, such as future scenario (weather file climate change projections) or urban typology.

In terms of overheating discomfort (red bars), the top 5 most influential variables are: future weather scenario, climatic area, floor conductivity, roof thickness and blind schedule. However, mechanical ventilation, wall type and roof insulation conductivity are also of the utmost importance. In the case of undercooling hours (blue bars), the top 5 is held by: blind schedule, future weather scenario, urban typology, natural ventilation rate and roof conductivity. It is also worth highlighting the significance of people density, roof type, floor conductivity, facade conductivity, glazing and frame types, climatic area and roof density on undercooling hours. These results were taken into account for the proposal of retrofit solutions, as already described.

### 3.2. Thermal performance assessment prior to retrofit strategies

Fig. 5 shows the percentage of annual discomfort hours of social housing stock in southern Spain, classifying the results per climatic area (A3, A4, B4 and C3) and climatic scenario (present, 2030, 2050 and 2080). The red and blue dots correspond to the percentages of annual overheating and undercooling hours, respectively. The values in each boxplot refer to the results of 260 simulations (10 LHS).

can be observed that the percentage of undercooling hours in all climatic areas is generally reduced as the future climatic scenario is changed. Worrying results are obtained in the C3 climatic scenarios compared to other areas, with higher percentages of undercool-

**Table 2**
Envelope retrofit solutions considered. Passive strategies.

| Element | Label | TI position | TI type | TI thickness (m) | Pavement | Green coverage | Rendering | Ex. Glass (mm) | Gap (mm) | In. glass (mm) | Frame | U-value (W/m2·K) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Roof | Unretrofitted | – | – | – | X | – | – | – | – | – | – | 1.2–2.4 |
| | InMW_0.05 | In | MW | 0.05 | X | – | – | – | – | – | – | 0.38–0.48 |
| | InMW_0.06 | | | 0.06 | X | – | – | – | – | – | – | 0.35–0.42 |
| | InMW_0.08 | | | 0.08 | X | – | – | – | – | – | – | 0.29–0.33 |
| | InMW_0.09 | | | 0.09 | X | – | – | – | – | – | – | 0.27–0.3 |
| | InMW_0.10 | | | 0.10 | X | – | – | – | – | – | – | 0.25–0.28 |
| | InMW_0.12 | | | 0.12 | X | – | – | – | – | – | – | 0.22–0.25 |
| | OutXPS_0.05 | Ex | XPS | 0.05 | X | – | – | – | – | – | – | 0.38–0.52 |
| | OutXPS_0.06 | | | 0.06 | X | – | – | – | – | – | – | 0.34–0.45 |
| | OutXPS_0.08 | | | 0.08 | X | – | – | – | – | – | – | 0.29–0.36 |
| | OutXPS_0.09 | | | 0.09 | X | – | – | – | – | – | – | 0.26–0.32 |
| | OutXPS_0.10 | | | 0.10 | X | – | – | – | – | – | – | 0.24–0.30 |
| | OutXPS_0.12 | | | 0.12 | X | – | – | – | – | – | – | 0.21–0.25 |
| | Green | – | – | – | – | X | – | – | – | – | – | 0.5–0.7 |
| | Green_OutXPS_0.05 | Ex | XPS | 0.05 | – | X | – | – | – | – | – | 0.28–0.35 |
| | Green_OutXPS_0.06 | | | 0.06 | – | X | – | – | – | – | – | 0.26–0.31 |
| | Green_OutXPS_0.08 | | | 0.08 | – | X | – | – | – | – | – | 0.23–0.27 |
| | Green_OutXPS_0.09 | | | 0.09 | – | X | – | – | – | – | – | 0.21–0.25 |
| | Green_OutXPS_0.10 | | | 0.10 | – | X | – | – | – | – | – | 0.2–0.23 |
| | Green_OutXPS_0.12 | | | 0.12 | – | X | – | – | – | – | – | 0.18–0.20 |
| Wall | Unretrofitted | – | – | – | – | – | X | – | – | – | – | 1.2–2.5 |
| | InMW_0.04 | In | MW | 0.04 | – | – | X | – | – | – | – | 0.46–0.68 |
| | InMW_0.05 | | | 0.05 | – | – | X | – | – | – | – | 0.41–0.51 |
| | InMW_0.06 | | | 0.06 | – | – | X | – | – | – | – | 0.36–0.44 |
| | OutMW_0.04 | Ex | | 0.04 | – | – | X | – | – | – | – | 0.46–0.61 |
| | OutMW_0.05 | | | 0.05 | – | – | X | – | – | – | – | 0.41–0.51 |
| | OutMW_0.06 | | | 0.06 | – | – | X | – | – | – | – | 0.36–0.43 |
| | OutMW_0.08 | | | 0.08 | – | – | X | – | – | – | – | 0.29–0.34 |
| | OutMW_0.09 | | | 0.09 | – | – | X | – | – | – | – | 0.27–0.3 |
| | OutMW_0.10 | | | 0.10 | – | – | X | – | – | – | – | 0.25–0.28 |
| | OutPUR_0.04 | | PUR | 0.04 | – | – | X | – | – | – | – | 0.42–0.56 |
| | OutPUR_0.05 | | | 0.05 | – | – | X | – | – | – | – | 0.37–0.47 |
| | OutEPS_0.04 | | EPS | 0.04 | – | – | X | – | – | – | – | 0.47–0.58 |
| | OutEPS_0.05 | | | 0.05 | – | – | X | – | – | – | – | 0.42–0.48 |
| | OutEPS_0.06 | | | 0.06 | – | – | X | – | – | – | – | 0.37–0.41 |
| | OutEPS_0.08 | | | 0.08 | – | – | X | – | – | – | – | 0.26–0.32 |
| | OutEPS_0.09 | | | 0.09 | – | – | X | – | – | – | – | 0.25–0.29 |
| | OutEPS_0.10 | | | 0.10 | – | – | X | – | – | – | – | 0.24–0.27 |
| Window | Unretrofitted | – | – | – | – | – | – | 4 | – | – | Al. | 5.5–5.7 |
| | 4LE-Air8-6 | – | – | – | – | – | – | 4LE | Air8 | 6 | Wood PVC | 2.0–2.3 |
| | 4LE-Air10-6 | – | – | – | – | – | – | 4LE | Air10 | 6 | AlTBB | 1.8–2.0 |
| | 4LE-Air12-6 | – | – | – | – | – | – | 4LE | Air12 | 6 | | 1.7–1.9 |
| | 6-Air12-8 | – | – | – | – | – | – | 6 | Air12 | 8 | | 2.4–2.6 |
| | 4LE-Xe6-6 | – | – | – | – | – | – | 4LE | Xe6 | 6 | | 1.4–1.5 |

*TI refers to thermal insulation. In refers to internal. Ex refers to external. LE refers to low emissivity. Xe refers to xenon. Al. refers to aluminium. TBB refers to thermal bridge break. All roof and wall solutions maintain the existing base solution. Roof solutions offer the possibility of modifying the external coverage (pavement or green coverage). 6-Air12-8 was only considered in climatic area B4 due to Building Technical Code requirements.*

**Table 3**
Building operation retrofit solutions considered.

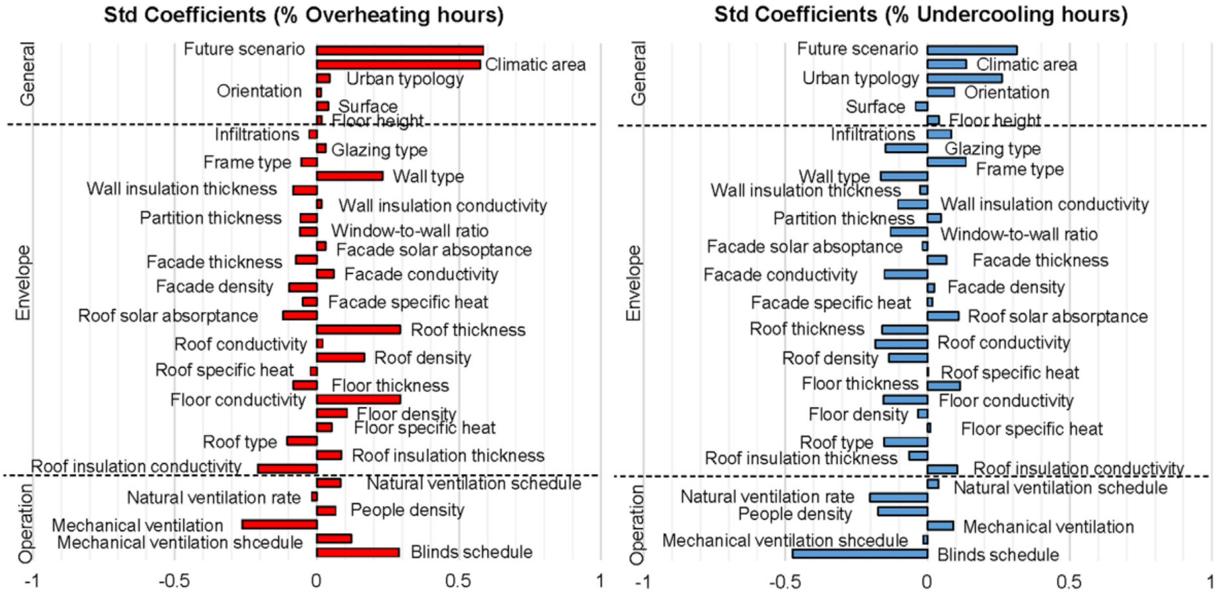
| **Building operation retrofit solutions** | | |
|---|---|---|
| **Natural Ventilation Schedule** | | |
| Label | Summer | Winter |
| Nat Vent 1 | 8:00–9:00 | 8:00–9:00 |
| Nat Vent 2 | 8:00–9:00 | 14:00–15:00 |
| Nat Vent 3 | 22:00–8:00 | 8:00–9:00 |
| Nat Vent 4 | 22:00–8:00 | 14:00–15:00 |
| **Blinds aperture Schedule** | | |
| Label | Summer | Winter |
| Blinds 1\|1 | 50 % opened | |
| Blinds 2\|2 | 0 % from 8:00–16:00<br>50 % from 16:00–21:00<br>100 % 21:00–7:00 | 100 % from 9:00–19:00<br>0 % from 19:00–9:00 |
| Blinds 3\|3 | 0 % from 7:00–21:00<br>100 % from 21:00–7:00 | 100 % from 9:00–19:00<br>0 % from 19:00–9:00 |
| Mechanical Ventilation Schedule | | |
| Label | Summer | Winter |
| MechVent | On (continuous) | |
| Off | Off | |

*0 % blind aperture level means totally closed.*

ing hours. As regards overheating hours, these are noticeably increased in all climate areas when the different climatic scenarios are considered. The rise in overheating hours in climatic area C3 is slightly lower. In contrast, climatic areas A3 and A4 experience the highest increase in overheating. In A4, the percentages of overheating and undercooling hours are practically equal. Meanwhile, in the remaining areas undercooling is more severe than overheating.

Focusing on 2050, Fig. 6 compares present and future hourly indoor air temperatures in the social housing stock of southern Spain during the year and by climatic area, showing average results from 260 simulations (10 LHS) for each scenario analysed. Differences between 2050 and present periods are of the utmost significance: indoor air temperatures are drastically increased, especially in climatic areas A3, A4 and C3 compared to the present period.

The specific average percentages of discomfort, undercooling and overheating hours of the social housing stock in both present and 2050 scenarios (grey lines) can be seen in Table 4, distinguishing between winter, summer, and annual results. Values are shown per climatic area and correspond to average results of 260 simula-



(a) (b)

**Fig. 4.** SRRC sensitivity analysis: (a) overheating hours (%); (b) undercooling hours (%).

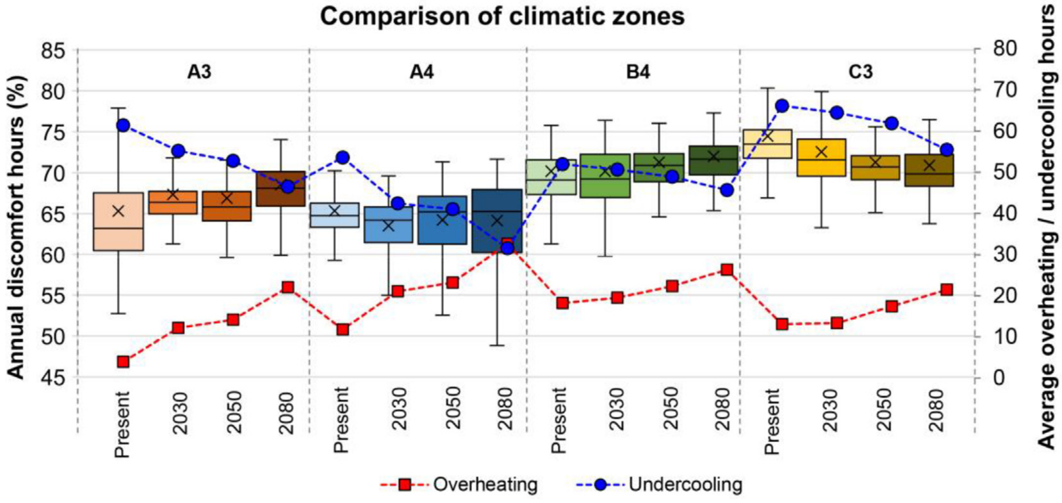


**Fig. 5.** Comparison of present and future percentage of annual discomfort hours in the social housing stock per climatic area. The box plots represent results from 260 simulations per analysed case.

tions per analysed case (10 LHS). As already stated, overheating hours significantly increase in A3 and A4, with smaller differences in climate areas C3 and B4. Undercooling hours are noticeably reduced in A3 and A4, and to a lesser extent in C3 and B4. As regards annual discomfort hours, changes between the present and 2050 are not of great importance: values are slightly increased in areas A3 and B4, while they are slightly reduced in A4 and C3. This is due to the fact that the summer season is longer than the winter season, so that the reduction in undercooling hours outweighs the increase in overheating hours in terms of comfort.

### *3.3. Optimization results after retrofit strategies*

Results for the retrofit optimization of the social housing stock towards the 2050 climate scenario in terms of annual undercooling hours (%), annual overheating hours (%) and investment costs (€/m$^2$) of the retrofit solutions for each climatic area can be seen in Fig. 7. Optimal solutions (Pareto's front) are indicated in red.

Even though the simulation sampling was set at 10 LHS, considering the variability ranges of the social housing stock established per climatic area (Table 1), the total number of simulations was: 986 in A3, 993 in A4, 989 in B4, and 976 in C3. The number of optimal solutions obtained was: 108 in A3, 169 in A4, 144 in B4, and 92 in C3, corresponding to 10.9 %, 17.1 %, 14.6 %, and 9.4 % of the total simulations, respectively. The multi-objective analysis carried out with a computation power equal to a 12-core i7-8700 CPU 3.20 GHz with 32 GB RAM, reported optimized solutions per climatic area in a 6-hour period.

Fig. 8 presents the parameter combination of the retrofit solutions analysed per climatic area, under the 2050 weather scenario.

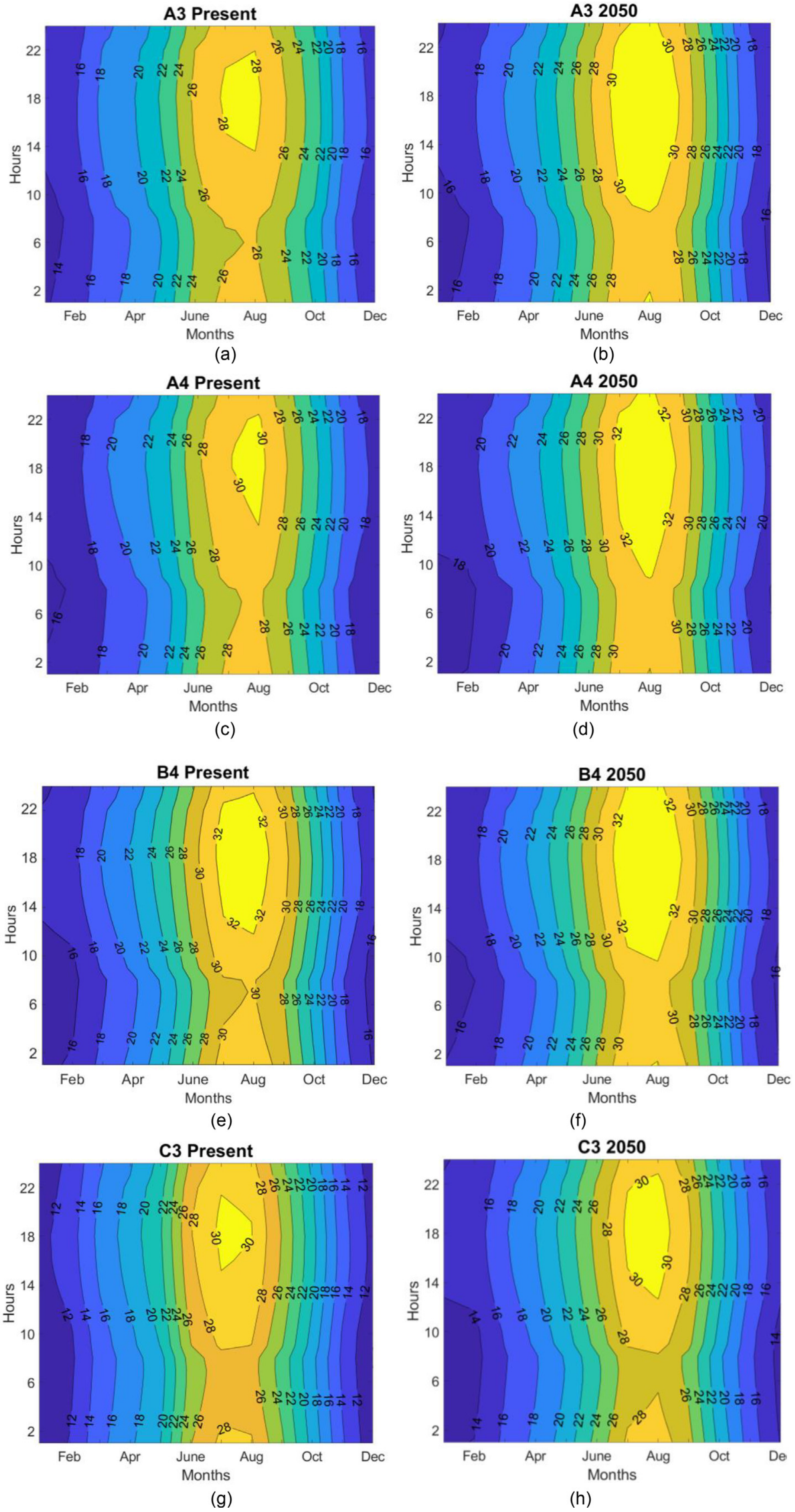
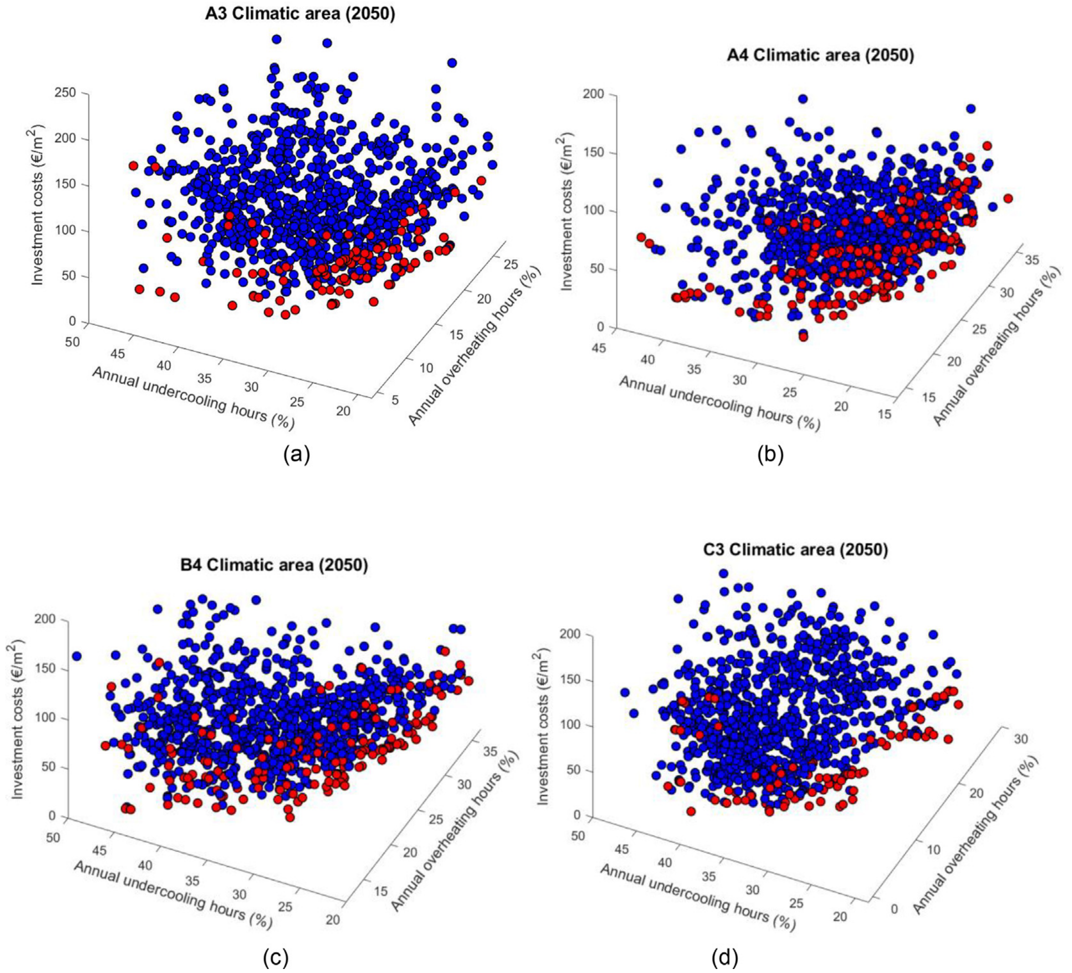


**Fig. 6.** Comparison of present and 2050 hourly indoor air temperatures in the social housing stock during the whole year per climatic area. Average values from 260 simulations per analysed case.

**Table 4**
Comparison of present and 2050 percentage of discomfort hours, undercooling hours and overheating hours in the social housing stock per climatic area. Results are shown per seasonal period and year. Average values from 260 simulations per analysed case.

| Scenario | Discomfort hours (%) | | | Undercooling hours (%) | | | Overheating hours (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Winter | Summer | Annual | Winter | Summer | Annual | Winter | Summer | Annual |
| A3 present | 91.2 | 29.5 | 65.3 | 91.2 | 20.1 | 61.4 | 0.0 | 9.4 | 3.9 |
| A3 2050 | 83.1 | 44.4 | 66.9 | 82.8 | 11.1 | 54.7 | 0.3 | 33.3 | 14.1 |
| A4 Present | 82.8 | 41.1 | 65.3 | 82.8 | 13.1 | 53.6 | 0.0 | 28.1 | 11.8 |
| A4 2050 | 67.0 | 60.3 | 64.2 | 65.4 | 7.4 | 41.1 | 1.7 | 52.9 | 23.2 |
| B4 Present | 80.7 | 55.6 | 70.2 | 80.4 | 12.5 | 52.0 | 0.3 | 43.1 | 18.2 |
| B4 2050 | 78.1 | 61.9 | 71.3 | 77.5 | 9.4 | 48.9 | 0.6 | 52.5 | 22.3 |
| C3 Present | 96.3 | 44.4 | 74.5 | 96.2 | 24.4 | 66.1 | 0.0 | 19.9 | 8.3 |
| C3 2050 | 91.6 | 43.1 | 71.3 | 91.6 | 20.7 | 61.8 | 0.3 | 41.4 | 17.4 |



(a) (b)

(c) (d)

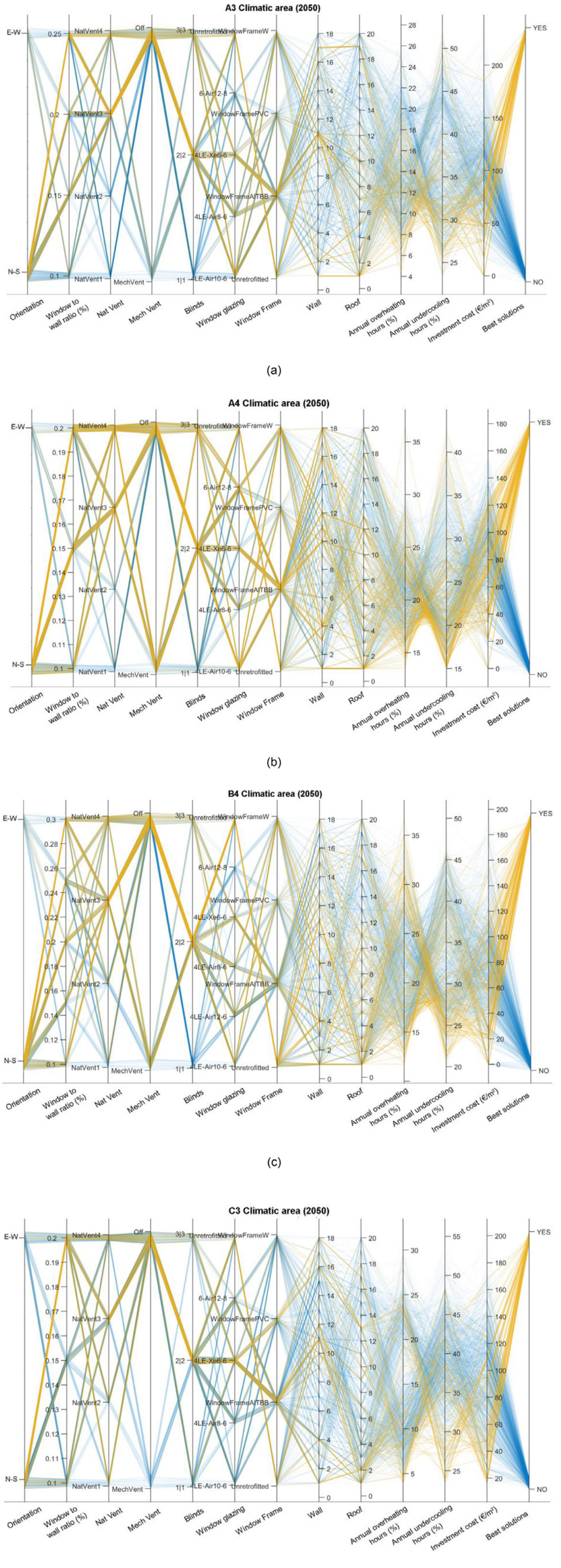
**Fig. 7.** Retrofit optimization results obtained for the social housing stock in the 2050 period, shown per climatic area: (a) A3; (b) A4; (c) B4 and (d) C3. Red dots represent the best solutions (Pareto's front). This figure can be interactively accessed through the.html files included in the Supplementary Data Section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The variables included are: orientation, window-to-wall-ratio, natural ventilation schedule, mechanical ventilation schedule, blind aperture schedule, window glazing and frame types, wall solution, roof solutions, annual overheating hours, annual undercooling hours, investment costs and the classification into best or worst solutions. It should be noted that in practically all the climatic areas of southern Spain most of the optimal retrofit solutions consider the use of night-time natural ventilation in summer and day-time natural ventilation in winter (morning or afternoon), a blind aperture schedule optimized by seasonal period, and the mechanical ventilation OFF.

In climatic area A3 (Fig. 8a), the best solutions are normally those with investment costs below 190 €/m$^2$, reporting annual overheating and undercooling hours of up to around 26% and 50 %. In order to obtain optimal results, windows must be replaced when considering non-retrofitted walls and roofs. If existing windows and non-retrofitted roofs were maintained, best results would require walls to be retrofitted, mainly through the addition of external insulation. Specifically, when the incorporation of low-thickness external thermal insulation in the facades (0.04–0.06 m) is combined with low-thickness internal thermal insulation in the roof (0.05–0.08 m), also maintaining existing windows, comfort results are quite similar to the case with high-thickness external thermal insulation in the roof (0.09–0.12 m) and high-performance windows (double glazing 4LE-Air12-6 or 4LE-Xe6-6 with PVC frame). However, the first case results in higher annual overheating hours in 2050. One of the best solutions is the use of medium-thickness external insulation in facades (0.08–0.10 m) with high-performance windows (double glazing 4LE-Air12-6 or 4LE-Xe6-6 with PVC frame) and a green roof with low-thickness external insulation (0.05–0.08 m). Furthermore, similar comfort results are obtained if in the previous case windows are replaced by medium-performance ones (double glazing 4LE-Air8-6 or 4LE-Air10-6 with wood or PVC frames) and high-thickness external insulation in facades (0.09–0.12 m) is added.

In climatic area A4 (Fig. 8b), the best results were usually under 135 €/m$^2$, with up to 37 % and 42 % of annual overheating and undercooling hours respectively. The consideration of a non-retrofitted envelope in this area is of great interest, since optimal results were obtained by simply maintaining mechanical ventilation OFF, natural ventilation schedule 3 (night-time ventilation in summer and morning ventilation in winter), and blind schedule 3 (optimized per hour and seasonal period). This scenario would lead to annual overheating and undercooling hours under 20 and 28 %, respectively. Maintaining existing windows and considering low-thickness internal insulation in the facades (0.04–0.06 m) and the roof (0.05–0.08 m) report similar indoor overheating hours in 2050 as in non-retrofitted present scenario. However, annual overheating and undercooling hours are drastically reduced in 2050 compared to a non-retrofitted future case. One of the best retrofit solutions is the inclusion of high-performance windows (double glazing 4LE-Air12-6 or 4LE-Xe6-6 with PVC frame) in combination with medium-thickness external insulation in the facades (0.08–0.10 m) and low-thickness external insulation in the roof (0.05–0.08 m). However, the thermal effect is similar when considering low-thickness external insulation in the facades (0.04–0.06 m) and high-thickness external insulation in the roof (0.09–0.12 m) in the previous case. Despite the incorporation of a green roof in this last case, no significant improvements in discomfort were reported.

In climatic area B4 (Fig. 8c), the best solutions refer to investment costs under 180 €/m$^2$, with annual overheating and undercooling hours around 37 % and 46 %, respectively. Non-retrofitted envelopes would lead to annual overheating hours between 15 and 28 % and undercooling hours of 28–45 %. The use of low-thickness internal insulation in facades (0.04–0.06 m) is beneficial when combined with medium-performance windows (double glazing 4LE-Air8-6 or 4LE-Air10-6 with wood or PVC frames), as well as with high-thickness interior insulation in the roof (0.09–0.12 m) or low-thickness external insulation in the roof (0.05–0.08 m). When low-thickness external insulation is implemented in facades (0.04–0.06 m), best solutions normally also consider high-performance windows (double glazing 4LE-Air12-6 or 4LE-Xe6-6 with PVC frame) and external low-thickness insulation in



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

**Fig. 8.** Parameter combination of the retrofit solutions for each climatic area: (a) A3; (b) A4; (c) B4 and (d) C3. Optimal solutions (Pareto's front) are indicated in blue. This figure can be interactively accessed through the.html files included in the Supplementary Data Section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

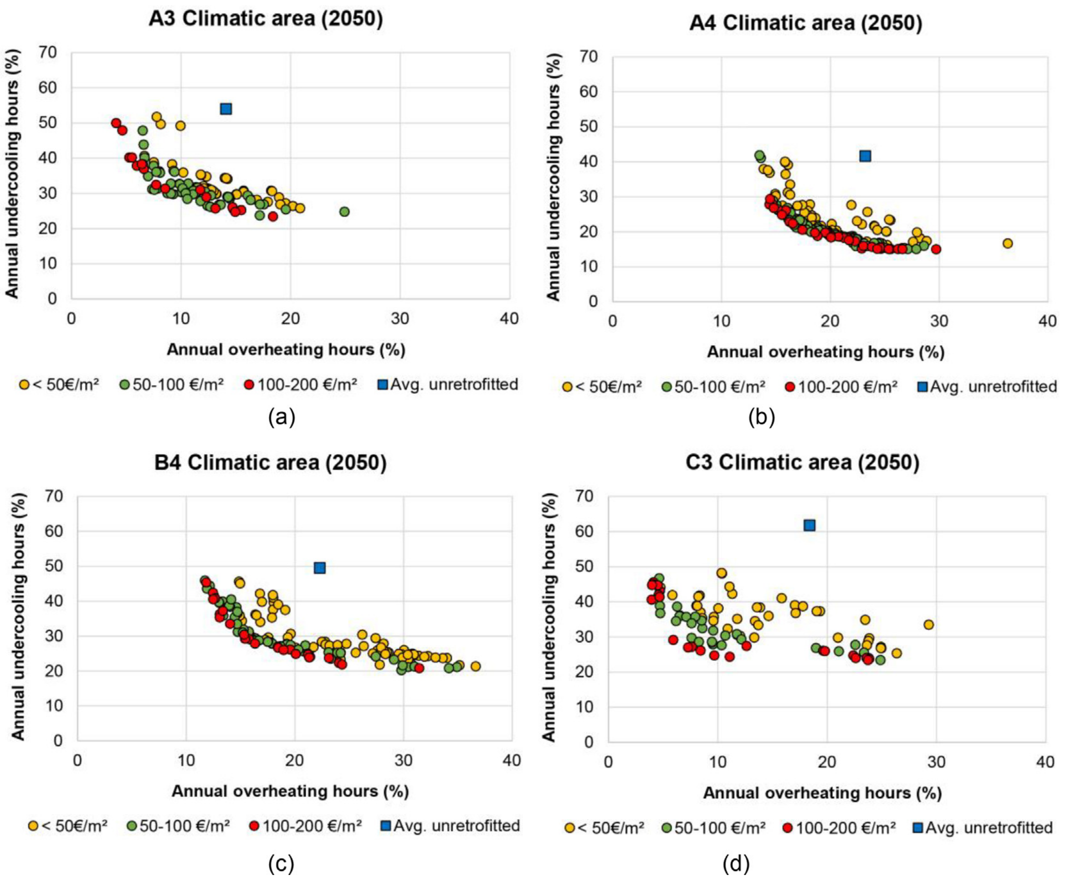
the roof (0.05–0.08 m) or a green roof externally insulated with a high-thickness insulation layer (0.09–0.12 m). Similar results are obtained if higher external insulation thicknesses are used in the facades (0.08–0.10 m) with medium-performance windows (double glazing 4LE-Air8-6 or 4LE-Air10-6 with wood or PVC frames).

Finally, the best solutions in the C3 climatic area (Fig. 8d) reported investment costs of up to 170 €/m$^2$, annual overheating hours below 30% and undercooling hours up to 48%. When compared to the other climatic areas, in this one annual undercooling hours are of the utmost importance. In cases where existing windows were maintained, retrofitting the walls would lead to a reduction in annual overheating hours, while retrofitting the roof would decrease annual undercooling hours. Specifically, combining low-thickness external insulation in walls (0.04–0.0.6 m) with low-thickness internal insulation in the roof (0.05–0.08 m) and medium performance windows (double glazing 4LE-Air8-6 or 4LE-Air10-6 with wood or PVC frames) would provide similar results to low-thickness external insulation in the roof and non-retrofitted windows in terms of thermal discomfort. Even though these two scenarios have similar undercooling results at present, non-retrofitted windows report better results in present overheating and future undercooling hours, but worse future discomfort due to overheating. When medium-thickness external insulation in the facades (0.08–0.10 m) was considered, the best results were obtained with high-thickness external insulation in the roof (0.09–0.12 m) and high-performance windows (double glazing 4LE-Air12-6 or 4LE-Xe6-6 with PVC frame). In this last case, considering a natural ventilation schedule other than 3 or 4 (night-time in summer and day-time in winter - morning or afternoon) drastically worsens overheating discomfort.

Fig. 9 presents a comparison of the percentage of annual overheating and undercooling hours (%) reported by the optimal retrofit solutions towards 2050 scenario per each climatic area. Results have been classified into low-cost (<50 €/m$^2$), medium-cost (50–100 €/m$^2$) and high-cost (100–200 €/m$^2$) interventions. The average percentage of overheating and undercooling hours simulated for the un-retrofitted future case (results shown in Fig. 5) have been indicated in blue.

Generally, it can be seen that high-cost interventions (red) normally report the best comfort results. Yet, the thermal improvement of medium-cost interventions (green) is normally more significant than that of high-cost solutions, when compared to the low-cost cases (yellow). This is particularly important in A4 and B4 areas, as well as in A3, where several optimal retrofit packages referred to medium-cost solutions. The results in C3 show greater dispersion values in terms of thermal overheating and undercooling, in comparison with the remaining areas. It has to be highlighted that, retrofit solutions always improve the percentage of undercooling hours when compared to the un-retrofitted case. Nonetheless, retrofit actions which report the lowest percentage of undercooling hours may also worsen indoor annual overheating in contrast with the un-retrofitted scenario. This may be due to over-insulated and highly airtightness envelopes, which may reduce the buildings' capacity for thermal dissipation.

These results have been compared to other existing studies in the Mediterranean region. Lassandro and Di Turi [32] and Dascalaki et al. [34] highlight the benefits of incorporating thermal insulation to the facades, to improve indoor temperatures. De Masi et al. [35] conclude that thermal insulation and double glazed



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

**Fig. 9.** Comparison of thermal comfort results obtained in the optimal retrofit solutions under 2050 climate scenario per each climatic area in contrast with the average value obtained for the un-retrofitted case: (a) A3; (b) A4; (c) B4 and (d) C3.

low-emissivity windows should be implemented in conjunction with cool roofs and external shading solutions to reduce energy demand. In the presented analysis, these retrofit solutions have been assessed and were proven to have a substantial impact on thermal comfort. Ortiz et al. [51] establish that external insulation performs better than internal insulation and that window replacement and thermal insulation in the roof have a significant influence of thermal comfort, facts that were also reported in the presented research. Penna el et al. [25] point out that mechanical ventilation systems provide better thermal comfort results with the advantage of lower energy consumption. Nonetheless, in the presented study, mechanical ventilation was not always among the optimal retrofit packages. Finally, Ascione et al. [38] establish that the best energy, environmental and economic approach to retrofit the existing stock should not only incorporate the addition of thermal insulation to walls and roofs and double glazing low-emissivity windows, but also the replacement of the existing systems by more efficient ones. In this study, retrofit solutions exclusively based on passive strategies and low cost ventilation systems are insufficient to guarantee future thermal comfort in the social housing stock during the whole year. Thus, for the improvement of the thermal comfort results reported, active systems should also be incorporated.

## 4. Strengths and limitations. Future research

Among the several strengths of this research, it is worth highlighting the retrofit results of the building stock obtained through optimization algorithms, as opposed to the manual optimization method that is normally used. Furthermore, dynamic building stock simulation was implemented following a bottom-up approach, incorporating statistical building stock data into parameterized energy models (archetypes), rather than the more commonly used single building case-study method. Since parameterized building variability ranges were defined during the building stock characterization, building stock data from other cities and different weather files can be incorporated with ease. It is worth mentioning that the research gap identified on thermal comfort assessment has been addressed, complementing the energy-related approach generally followed in similar studies. Additionally, interactive results have been provided on the optimal retrofit solutions of the social housing stock of southern Spain under future weather scenarios, using open-access files (.html) included in the Supplementary Data. Fig. 7 can be freely accessed and downloaded and the image can be zoomed or rotated through interactive actions. Data value points of the optimization results can also be accessed by placing the mouse on the dots. Fig. 8 can also be freely accessed and downloaded. In this case, as the values of the individual variables analysed can be filtered by clicking and dragging the mouse, the results can be easily accessed by stakeholders, administrations and the general public. Similarly, Fig. 9 may be also interactively accessed, so that data values may be obtained by placing the mouse on the dots.

A drawback of this research is that results reported refer only to the H-block building typology. Thus, new archetypes must be defined and parameterized in order to assess different building typologies. Another downside is the lack of available data for calibrating and validating the building stock models after applying retrofit strategies. Furthermore, neither operational costs related to the mechanical ventilation systems nor indices referring to the variations and fluctuations in future investment costs were included. Likewise, simulations were run under the IPCCs future scenarios. Hence, conducting a comparison between those scenarios and the Representative Concentration Pathway scenarios (RCPs) may provide interesting results.

Future research should explore the inclusion of active retrofit strategies as a second level of intervention, such as the addition of HVAC systems, solar panels or photovoltaic panels. Hence, incorporating new optimization objectives, for instance in order to conduct a primary energy consumption assessment or a life cost analysis, could also report interesting conclusions.

## 5. Conclusions

This paper presents the thermal comfort performance of the existing social housing stock in southern Spain in both present and future climatic scenarios. Building information from an extensive database has been incorporated into building stock models through a bottom-up method. Sensitivity analysis was used to obtain the most influential variables on thermal comfort and propose retrofit solutions, considering their implementation opportunities regarding public retrofit programmes and low incomes of social householders. Later, optimal retrofit solutions have been determined for 2050 scenario, applying numerical optimization algorithms with multi-objective decision analysis, through the assessment of thermal comfort and investment costs.

Specific results are included in the interactive.html files in the Supplementary Data. Generally, optimal retrofit solutions for all climatic areas in southern Spain consider investment costs of up to 200 €/m$^2$, with future percentages of overheating and undercooling hours of around 4–37 % and 15–50 %, respectively. For instance, among the optimal solutions, in climatic area A3, adding 0.04–0.06 m external insulation in facades combined with 0.05–0.08 m internal insulation in the roof reports similar comfort results to 0.08–0.10 m external insulation in facades, double low-emissivity glazing with PVC frame windows and a green roof with 0.05–0.08 m external insulation. In A4 area, 0.08–0.10 m external insulation in façades and 0.05–0.08 m in the roof derive in similar comfort conditions in comparison with 0.04–0.06 m and 0.09–0.12 m external insulation in façades and roof, respectively, both considering double low-emissivity glazing with PVC frame windows. In B4, 0.08–0.10 m external insulation in facades and medium performance double glazing with wood or PVC frames windows would lead to similar comfort hours compared with double low-emissivity glazing with PVC frame windows, 0.04–0.06 m external insulation in facades and 0.05–0.08 m in roof. Finally, in C3 area, combining 0.04–0.06 m external insulation in facades with 0.05–0.08 m internal insulation in the roof and medium performance double glazing with wood or PVC frames windows provides similar thermal conditions to 0.05–0.08 external insulation in the roof.

Results obtained prove that a thermal comfort improvement based exclusively on passive strategies and low-cost operation-related measures is significantly limited. Hence, active retrofit strategies with higher investment costs should be implemented to improve thermal comfort in future climate change scenarios. Furthermore, it is clear that 2050 optimal retrofit solutions do not foster a thermal comfort improvement compared to the present scenario, but generally mitigate discomfort when compared to a possible non-retrofitted future scenario. Yet, over-insulating the building's envelope without implementing adequate operational retrofit aspects may lead to worse future thermal results than the un-retrofitted case, especially in terms of overheating.

This research has demonstrated that it is possible to conduct a multi-objective decision analysis through the implementation of a bottom-up approach in building stock modelling in order to optimize retrofit solutions, considering the case study of H-typology social housing stock in southern Spain under future global warming scenarios.

## 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.

## Acknowledgments

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## Author Contributions

All authors have conceived and designed the experiments, performed the experiments, analysed the data and written, reviewed and approved the final manuscript.

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