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Optimal retrofit solutions considering thermal comfort and intervention costs for the Mediterranean social housing stock

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ABSTRACT

There is an impending need to retrofit the existing social housing stock to improve thermal comfort and to reduce energy demand. This research proposes calibrated building stock models to assess thermal comfort of the social housing stock of southern Spain (Mediterranean area). Several retrofit strategies are optimised using a genetic algorithm to obtain the best retrofit solutions, considering three objectives: annual overheating hours (%), annual undercooling hours (%) and investment costs (€/m^2). Results are shown for four different climatic areas in southern Spain. This study finds that it is possible to retrofit the aforementioned stock considering investment costs from approximately 20–200 €/m^2. The percentage of improvements for each climatic area are as follows: in Sevilla (B4 climatic area), investments costs up to 50 €/m^2 led to 40% and 20% annual overheating and undercooling hours. In Cádiz, (A3 climatic area), 15% and 22% overheating and undercooling hours were achieved with medium-cost solutions (50–100 €/m^2). In Almería (A4 climatic area), also medium-cost strategies reported approximately 15% and 30% overheating and undercooling hours. In Granada (C3 climatic area), 15% and 38% overheating and undercooling hours were obtained with medium-cost measures. Yet, applying high-cost solutions (100–200 €/m^2) only significantly improved thermal comfort in Almería and Sevilla.

1. Introduction

1.1. The building sector in the European Union

In the European Union (EU), the top three dominant energy consumers in 2019 were buildings, industry and transport [1]. Specifically, the building sector accounted for almost 40 % of the total global energy-related carbon dioxide emissions (CO_2), among which 17 % were caused by the existing residential stock, also responsible for around a quarter of the final energy consumed. Existing residential buildings were mostly built prior to energy performance regulations. Moreover, current building renovation rates are low and the replacement rate of existing buildings by new ones is less than 3% per annum [2]. Thus, existing residential buildings are expected to remain a large proportion of the future stock. For this reason, energy retrofit strategies play a crucial role in meeting 2030 and 2050 climate and energy targets, included in the European Green Deal [3].

When retrofitting the existing residential stock, considering social issues such as fuel poverty is of great importance. Health risks triggered by exposure to cold or heat is one of the most severe consequences of fuel poverty, resulting in excess mortality due to cardiorespiratory, heat stroke and other diseases [4]. In southern Spain (Mediterranean area), low income households cannot afford to pay heating and cooling costs due to fuel poverty, and there is also a general lack of Heating, Ventilation and Air Conditioning (HVAC) systems installed in the social housing stock [5].

Although the energy efficiency of existing buildings may be evaluated though on-site monitoring and survey techniques [6], large-scale intervention instead of single-building approaches must be prioritized to adequately improve the energy efficiency of the existing stock [7]. Dynamic simulation through Building Energy Modelling (BEM) has commonly been used in the assessment of building energy performance and retrofit strategies. Hence, Building Stock Modelling (BSM) has proven to be a useful tool for decision-making in the design, operation and retrofit stages at the district level [8]. Likewise, a clear analysis of current energy efficiency and thermal comfort status for existing residential buildings at the stock level is essential in order to propose effective local retrofit strategies [9].

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1.2. State of the art on building performance and retrofit assessment

Assessing building performance and retrofit strategies through energy performance optimisation has been extensively analysed, as may be concluded from the work of Hashempour et al. [10], who conducted a review of up to 153 papers. When considering social housing buildings in the Mediterranean area referenced in the aforementioned paper, it can be deduced that passive and active retrofit strategies are both assessed. Passive strategies are 31.5 % more commonly implemented than active solutions, due to the low economical cost to users. The most typical passive retrofit solutions in the Mediterranean area consist of window replacement (i.e. double instead of single glazing) (25.3 %), addition of thermal insulation to walls (24.7 %), roof (22.6 %) and floors (10.3 %) or using solar shading blinds (4.1 %). In relation to active strategies, papers often analyse the addition of thermal and photovoltaic panels (43.4 %), replacement of domestic hot water systems (15.2 %) and cooling or heating systems (13.0 %) with more energy efficient systems (i.e. low emission boilers or heat pumps). The addition of mechanical ventilation (4.3 %) is assessed in fewer studies. Likewise, most of these studies are focused on a single building case (85.7 %) that is representative of a specific building typology, normally considering isolated (61.9 %) multi-family (65.9 %) dwellings. Fewer studies (14.3 %) present results on retrofit strategies at the stock level through the use of large information contained in databases. Around 55.0 % of these publications apply numerical optimisation methods, while the remaining studies consider an approach based on the analytical comparison of different possible scenarios. Furthermore, 72.1 % of these studies applied dynamic simulations, 25.6 % use static simulations and only 2.3 % consider both dynamic simulations and on-site measurements for energy model calibration prior to the analysis of retrofit actions.

Somewhere in the region of 80 % of the 153 studies involve multi-criteria decision analysis, while the remaining 20 % revolve around single-variable optimisation. The top-four retrofit objectives in the Mediterranean area are normally investment costs or economicaspects (29 %), primary energy consumption (26 %), energy demand (16 %) and carbon dioxide emissions (10 %), with less than 10 % of papers considering thermal comfort as a retrofit target. Thermal comfort is an important parameter since it impacts on both the health and wellbeing of occupants and the potential energy consumption of buildings [11]. Among the few studies that analyse the existing residential stock in the Mediterranean area, Ballarini et al. [12] assess through scenario analysis how the addition of thermal insulation in walls and roof, window replacement, improvement of heating, cooling and domestic hot water systems affect primary energy consumption and CO_2 emissions when retrofitting Italian single-family dwellings. To do so, information from a public database is implemented into static simulations. Ascione et al. [13] generated urban-energy maps of Benevento city (Italy) through Geographic Information System (GIS) to study energy demand and CO_2 emissions of the existing multi-family stock, taking into account the implementation of district heating and cooling technologies. Corrado and Ballarini [14] modelled passive and active refurbishment of the existing residential stock in Piedmont (Italy), optimising primary energy use and CO_2 emissions. Manjarres et al. [15] implemented optimisation algorithms to report conclusions on how window replacement, addition of thermal insulation in walls, roof and floor, addition of PV and thermal panels or replacement of heating and cooling systems may impact environmentally and economically on retrofit strategies for multi-family buildings in San Sebastian (Spain). In this case, dynamic energy simulations are considered based on fixed model parameters statistically obtained from large databases. Escandón et al. [16] use a surrogate modelling approach implementing an artificial neural network to predict thermal comfort in the linear-block stock of southern Spain, yet these authors do not propose any retrofit strategies. Ascione et al. [17] find optimal solutions to retrofit the Italian multi-family housing stock through parameterized dynamic simulations, analysing passive (window replacement and addition of thermal insulation in walls and roof) and active strategies (improving heating and cooling systems). These authors optimised the results based on global cost savings, CO_2 emissions and primary energy consumption.

1.3. Objective and relevance of the study

This paper aims to find optimal social housing retrofit strategies, addressing the literature gap on H-block typologies and thermal comfort assessment. Although previous work has considered linear blocks, this research models H-blocks which are the predominant building typology of southern Spain (45.3 % compared to 35.0 % of linear blocks) [18]. Compared to previous work, the novelty of this research lays on the use of a bottom-up multi-objective method for the assessment and retrofit of the building energy stock performance of southern Spain (Mediterranean area), considering adaptive thermal comfort. This parameter is of greater importance in the aforementioned stock than energy demand reduction given that energy consumption is lower than expected in the social housing buildings [19]. Open access interactive tools are used to share the findings with the public and key stakeholders. This method is based on a dynamic building energy model of a case study building, which has been calibrated through on-site hourly measurements. This model is later parameterized, incorporating social building stock information obtained from an extensive database, as variable model inputs. Thus, multiple building archetypes representative of the stock are generated, instead of the more common single-building approach used widely in existing literature. The study objectives are as follows:

- Given the lack of HVAC systems in the social housing stock of southern Spain, analyse and optimise thermal comfort under the adaptive comfort model proposed in EN 16798–1:2019 [20], which replaced the EN 15251:2007 [21] assessed in similar works.
- Target annual overheating and undercooling hours, as well as investment costs, in a multi-objective decision analysis approach to retrofit the existing social housing stock, in contrast to other studies which have focused on energy-related issues.
- Propose and assess several retrofit strategies using an evolutionary optimisation algorithm, analysing different climatic areas in southern Spain.
- Provide useful and open-access information for public stakeholders and users in the retrofit decision-making process.

2. Methods

The presented research was carried out in several stages as shown in Fig. 1.

Statistical analysis of an extensive database is combined with on-site measurements, energy simulation modelling and numerical optimisation tools. The following subsections provide a description of each stage of the methodology.

2.1. Stage 1: Characterisation of southern Spain social housing stock

In stage 1, the social housing stock has been typological, constructive and energy assessed and characterized through a statistical analysis of an extensive database provided by AVRA (The Andalusian Agency of House and Retrofitting, in Spanish) [23]. This database contains information on several variables of 39,486 dwellings built in 1970–2005. The variables included are cadastral

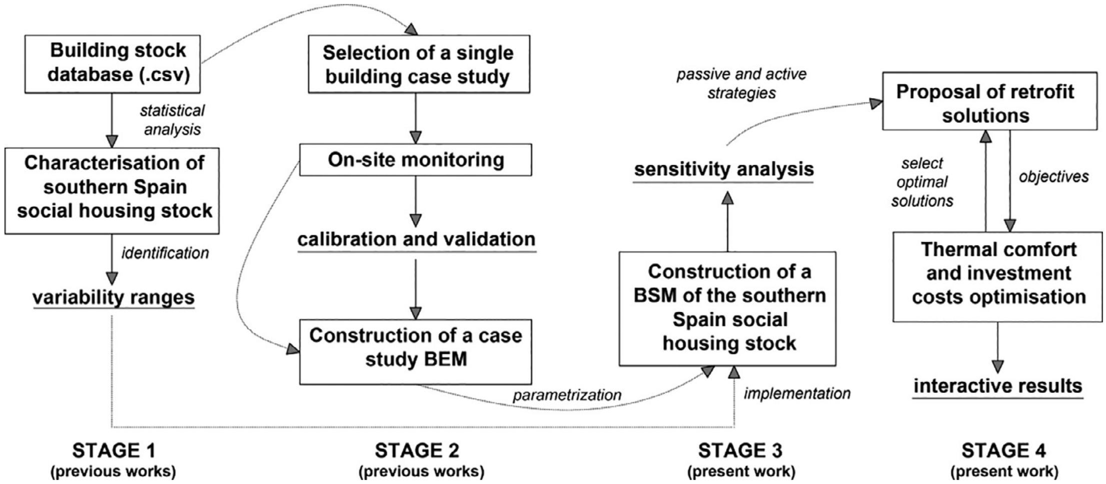


Fig. 1. Work plan followed. Previous works refers to [22].

data, address information, number of dwellings, number of building storeys, building height, building typology, year of construction, percentage of glazing surface, type of window frame and glass, cooling and heating demand and thermal building systems. Once this information was compiled and rearranged, new variables were incorporated into the database: orientation, total built area, average dwelling built area and architectural and urban typology (obtained from the Spanish Cadastral Online Platform) [24] and climate area (obtained from the Spanish Building Technical Code) [25]. This code classifies the climatic areas of southern Spain considering two indexes: Climatic Severity in Winter (SCI) and Climatic Severity in Summer (SCV), which are related to temperatures and solar radiation levels. The SCI is identified with a letter (A to E): A refers to milder winters and E defines colder winters. The SCV is represented by a number (1 to 4): 1 corresponds to milder summers and areas identified as 4 have warmer summers. In southern Spain, once these two indices are combined, the climatic areas correspond to A3, A4, B3, B4, C3, C4, D2 and D3 (Fig. 2), all included in the database.

The content of the AVRA database was analysed in previous works [26,27] and is used to characterize the stock. This paper implements the main conclusions of these publications for the climatic areas B4, A3, C3 and A4, since they have the highest percentage of multi-family dwellings. Following the conclusions of the mentioned publications, efforts are put into the H-block typology, which was found to be generally dominant in southern Spain (35 % of the database, compared to 27 % linear-blocks).

2.2. Stage 2: Construction of a case study BEM

In this stage, a representative case study of the H-typology in southern Spain was selected. Specifically, a 4-storey building built in 1973, located in the B4 climatic area, where the H-typology which represents 61.4 % of the total residential buildings (Fig. 3).

A BEM of the case study was constructed using the EnergyPlus v. 9.0.1 [28] open access tool, importing the geometrical, constructive and morphological data, as well as information on several monitored ambient variables. The BEM was later calibrated and validated considering the procedure included in ASHRAE Guideline 14:2002 [29]. This guideline defines three uncertainty indices: Normalized Mean Bias Error (NMBE), Coefficient of Variation of the Root Mean Square Error (CVRMSE) and Coefficient of Determination (R^2).

According to the results obtained (Table 1), the BEM was considered to be well calibrated and validated. Specifically, indoor air temperatures monitored in a flat on an hourly basis were compared to simulated air temperatures. The model was calibrated in both summer and winter seasons using Bayesian techniques [30]. The calibration methodology is explained in detail elsewhere [22,31]. In brief, a sensitivity analysis was conducted to identify

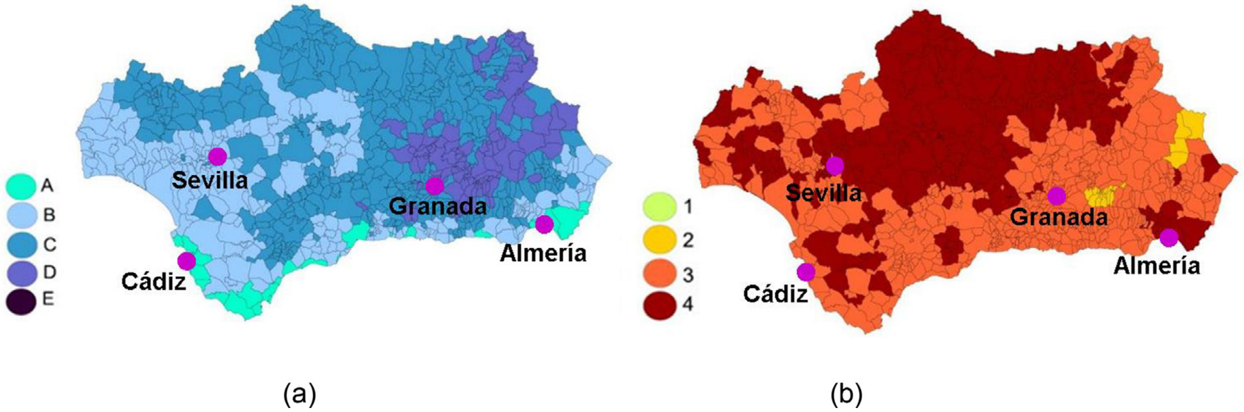


Fig. 2. Climatic areas in southern Spain according to the Spanish Technical Building Code [25]: (a) Climatic severity in winter; (b) Climatic severity in summer. The purple dots indicate the selected climatic areas: Sevilla (B4), Cádiz (A3), Granada (C3), Almería (A4). (For interpretation of the references 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.

Table 1
Uncertainty indices of BEM case study obtained for summer and winter periods for modelled vs monitored hourly temperatures. ASHRAE Guideline [30] hourly calibration thresholds are indicated in brackets.

Period	Model	NMBE (±10%)	CVRMSE (less than30%)	R^2 (>0.75)
Summer	Un-calibrated	7.90	8.50	0.36
	Calibrated	0.66	1.61	0.82
Winter	Un-calibrated	13.00	14.10	0.58
	Calibrated	1.87	3.74	0.75

the top-four most influential parameters on indoor air temperatures (building infiltrations [ACH], natural ventilation through the window opening [ACH], occupant density [people/m^2] and façade thickness [m]). Prior distributions for these input parameters were generated based on building information, surveys and on-site tests. Finally, posterior distributions were identified using Bayesian calibration which provides improved agreement of simulated temperatures to field data. Fig. 4 presents a visual comparison between the uncalibrated and calibrated models contrasting on-site measurements and simulated outputs during a representative summer and winter week.

2.3. Stage 3: Construction of the BSM

This stage presents the modelling representation of the existing social housing stock of southern Spain through the construction of parameterized building archetypes. To do so, the calibrated and validated case study BEM has been used as baseline to construct a parameterized BSM which is representative of the existing H-typology residential buildings in southern Spain, through a bottom-up approach. Building archetypes have been defined, incorporating the variability ranges of the geometrical, physical, constructive and morphological properties of the social housing building stock.

Table 2 shows the variability ranges and distributions of building characteristics obtained for the analysed climatic areas in southern Spain (B4, A3, C3 and A4, identified by the purple city points in Fig. 2). These data were obtained in the statistical analysis of the AVRA database for H-blocks in southern Spain [27]. The variables listed in Table 2 have been varied within the energy models as inputs parameters. Thus, instead of analysing a single building case, a range of building models are created per each climatic area, representing the H-block buildings within the existing stock. The number of dwellings considered the database for each climatic area is included in the aforementioned table.

2.4. Stage 4: Multi-objective decision analysis for retrofitting the social housing stock

This section explains the use of multi-objective decision analysis to obtain optimised retrofit solutions for the social housing stock of southern Spain. Firstly, the optimisation objectives were defined. Later, a sensitivity analysis was conducted to determine the most influential variables for the optimisation objectives selected. Subsequently, retrofit solutions were proposed according to the results obtained from the sensitivity analysis and their implementation opportunities taking into consideration public retrofit programmes and the low economic resources of social housing users. The following subsections present a more detailed description of these tasks.

2.4.1. Optimisation objectives

In the multi-objective decision analysis for retrofitting the social housing stock of southern Spain, three objectives were considered: annual percentage of overheating hours (%), annual percentage of undercooling hours (%) and investment costs (€/m^2, where area refers to the built area per housing unit) of the retrofitting actions.

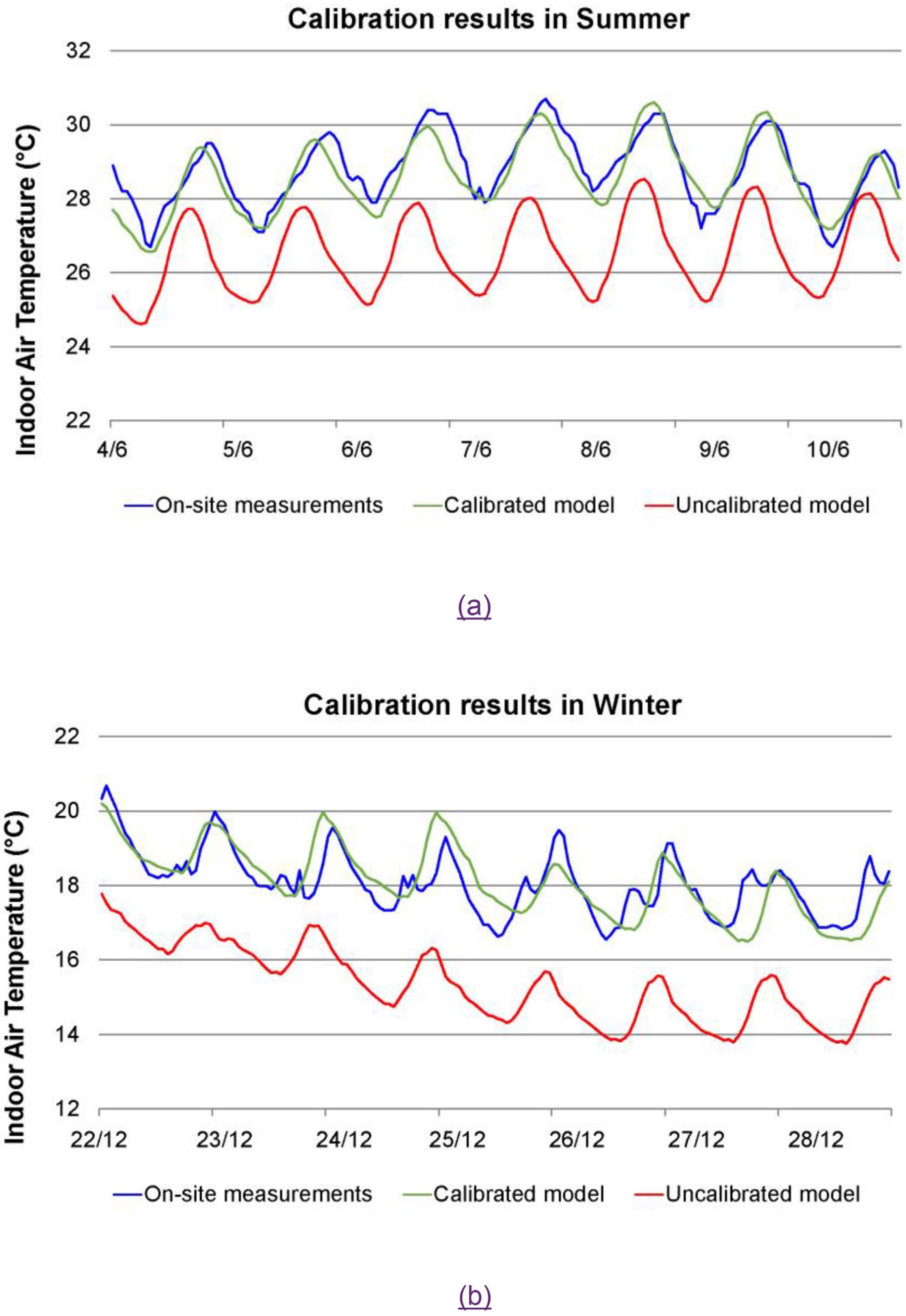


Fig. 4. Comparison of simulated and monitored indoor air temperatures during the calibration process. A representative week during: (a) summer; (b) winter.

The adaptive thermal comfort model established in EN 16798-1:2019 [20] was implemented, so that adaptive comfort temperature (T_{co}) is derived from the running mean dry bulb outdoor temperature ($T_{ext,ref}$) (Eqs. (1) and (2)). Hourly indoor temperatures are considered to be thermally comfortable if within an interval of T_{co} + 3 °C (upper limit) and T_{co}-4 °C (lower limit). This band

Table 2
Building characterisation of the H-typology social housing stock in southern Spain.

Variables			**BSM (AVRA database)**				**Distr.**
General	–	Construction year	1970–2005				–
	–	Building typology	H				–
	–	Spanish climatic area	B4 (Sevilla)	A3 (Cádiz)	C3 (Granada)	A4 (Almería)	–
	–	Number of dwellings	5,935	3,185	1,624	349	–
	–	Urban typology	Terraced		Isolated		–
Geometry	P1	Orientation (°)	10, ±30, ±60, 90				U
	P2	Floor area (m^2)	60–122.50	50–95	60–85	70–90	U
	P3	Floor height (m)	2.50–3.00				U
	P4	Window-to-wall ratio (%)	10–30	10–25	10–20	10–20	U
	P5	Number of storeys	4–5	3–5	4–5	4	U
Building envelope	P6	Roof solar absorptance	0.1–0.9				N (0.5,0.1)
	–	Roof U-value (W/m^{2}K)	1.2–2.4				–
	P7	Roof thickness (m)	0.25–0.40				N (0.30,0.02)
	P8	Roof thermal conductivity (W/mK)	0.3–0.6				N (0.45,0.04)
	P9	Roof density (kg/m^3)	1000–1800				N (1400, 125)
	P10	Roof specific heat (J/kgK)	500–1500				N (1000, 150)
	–	Floor U-value (W/m^{2}K)	3.0–7.00				–
	P11	Floor thickness (m)	0.15–0.30				N (0.20,0.03)
	P12	Floor thermal conductivity (W/mK)	0.7–1.8				N (1.2,0.2)
	P13	Floor density (kg/m^3)	1200–1800				N (1500, 100)
	P14	Floor specific heat (J/kgK)	500–1500				N (1000, 150)
	P15	Facade solar absorptance	0.1–0.9				N (0.5,0.1)
	–	Facade U-value (W/m^{2}K)	1.2–2.5				–
	P16	Facade thickness (m)	0.10–0.35				N (0.25,0.05)
	P17	Facade conductivity (W/mK)	0.2–0.4				N (0.3,0.03)
	P18	Facade density (kg/m^3)	1000–3000				N (2000,250)
	P19	Facade specific heat (J/kgK)	500–1500				N (1000, 150)
	P20	Partition thickness (m)	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^{2}K)	5.50–5.70				–
	P23	Infiltration rate (ACH)	0.30–1.00				U
Oper.	P24	People density (people/m^2)	0.01–0.15				N (0.08,0.02)
	P25	Natural ventilation rate (ACH)	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.

corresponds to a predicted percentage dissatisfied of <10 % (in other words, building category II according to the standard).

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

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

where:

$T_{ext,ref}$: running mean dry bulb outdoor temperature on a given day

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

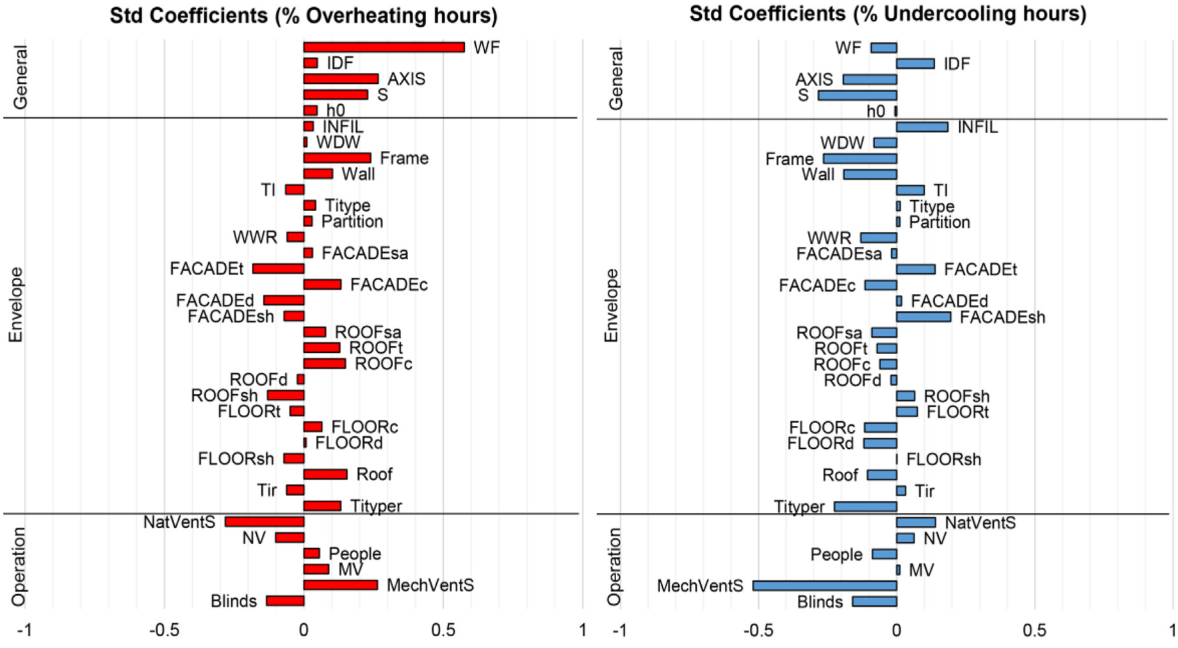
- Overheating hours were determined as the annual percentage of hours when indoor air temperatures were above the adaptive comfort upper limit (>T_{co} + 3).
- Undercooling hours were obtained by the annual percentage of hours when the indoor air temperatures were below the adaptive comfort lower limit (<T_{co} - 4).

Regarding the investment costs objective, economic data from the public Spanish Price Construction Generator was collected [32]. This database includes direct (materials) and indirect (installation and replacement) costs related to construction and building systems. Costs related to constructive elements (wall and roof) were obtained in €/m^2 and later multiplied by the area of the specific construction element (m^2). Finally, general costs (€) were divided by the total dwellings' built area (m^2). Costs relating to window systems were obtained in €/element and multiplied by the number of elements in the building. Costs regarding the MV system only include the installation of the ventilation system, thus operational costs were not considered in this research.

2.4.2. Sensitivity analysis

The most influential variables on thermal overheating and undercooling were determined. This was conducted to identify retrofit actions that result in the most significant changes in thermal comfort when compared to the unretrofitted stage. The Standard Rank Regression Coefficients (SRRC), based on the rank transformation of outputs and inputs in a multiple linear regression model with a standardized input–output matrix [33], was used to calculate the influence of each parameter on thermal overheating and undercooling outputs. This parameter ranges from −1 to + 1, so a positive value means that the variable is directly related to the output, while a negative value indicates an inverse relationship.

Up to 36 variables related to general building aspects, envelope properties and operation were assessed. In the case of overheating hours (Fig. 5a), the most influential variables were found to be as follows: weather file (which is directly related to the climatic area), natural and mechanical ventilation schedules, building orientation, type of window frame, average dwelling built area and several physical properties of the building's envelope. In relation to the undercooling hours (Fig. 5b), the most important variables are related to the weather file, building orientation, average dwelling built area, type of window frame, mechanical and natural ventilation schedules and blind aperture schedule. Several physical properties referring to the building's envelope were also of great importance. The specific results obtained in the sensitivity analysis are extensively included in the Appendix A (Tables A.1-A.2).



(a) (b)

Fig. 5. Visual results of the SRRC sensitivity analysis according to the objective function: (a) overheating hours (%); (b) undercooling hours (%). Abbreviations: WF (weather file), IDF (urban typology), AXIS (orientation), S (average dwelling built area), h0 (floor height), INFIL (infiltrations), WDW (window glass), Frame (window frame), Wall (wall solution), TI (wall insulation thickness), Titype (wall insulation type). Partition (partition thickness), WWR (window-to-wall ratio), FAÇADE, ROOF and FLOOR (sa: solar absorption, t: thickness; c: conductivity; d: density; sh: specific heat), Roof (roof solution), Tir (roof insulation thickness), Tityper (roof insulation type), NatVentS (natural ventilation schedule), NV (natural ventilation rate), People (people density), MV (mechanical ventilation rate), MechVenS (mechanical ventilation schedule), Blinds (blinds aperture schedule). See Appendix A.

2.4.3. Proposal of retrofit solutions

To retrofit the social housing stock of southern Spain, passive and operation-related strategies were proposed, following results of the sensitivity analysis and public retrofit programmes initiatives for social dwellings. Proposed passive strategies targeted the natural ventilation, blind aperture schedule and several building envelope aspects, which were found to be fundamental in the sensitivity analysis (subsection 2.4.2). Up to 20 different roof solutions were assessed (including the unretrofitted case), considering the addition of several thermal insulation types (MW: mineral wool, XPS: extruded polystyrene), thermal insulation positions (In: Internal, Out: External), thermal insulation thickness (0.05, 0.06, 0.08, 0.09, 0.10 and 0.12 m) and floor coverage (pavement or green roof). Likewise, 18 wall solutions were proposed (included the retrofitted case). The addition of different thermal insulation types (MW: mineral wool, PUR: polyurethane, EPS: expanded polystyrene), thermal insulation positions (In: Internal, Out: External), thermal insulation thickness (0.04, 0.05, 0.06, 0.08, 0.09 and 0.10 m) were assessed (Table 3). The label column firstly specifies thermal insulation position, then thermal insulation type and, finally, the thermal insulation thickness that have been considered in each solution.

Another passive retrofit solution studied was window replacement. Table 4 shows the possible combination of different glazing and frames types: 16 solutions including the unretrofitted case (4 mm single glazing window with aluminium no thermal bridge frame). Only double glazing windows both with and without low-emissivity (LE) glazing surfaces were included due to economic reasons (high performance windows are unlikely to be an option for low-income occupants).

All the proposed wall, roof and window retrofit solutions meet the minimum energy requirements established in the Spanish Building Technical Code [25].

Strategies relating to the building's operation were also considered (Table 5). Both natural and mechanical ventilation were included into the retrofit scenarios, proposing different operation schedules. Four natural ventilation schedules were determined, based on use schedules and solar radiation gains during the year. Regarding the addition of mechanical ventilation, two schedules were considered: ON (continuous), based on the Spanish Building Technical Code indoor air requirements [25], and OFF. Mechanical ventilation rates were also calculated according to this code' specifications. Since social housing buildings in southern Spain do not normally have mechanical ventilation systems, the incorporation of this retrofit measure was considered as a low-cost strategy. Finally, the application and operation of the most common solar shading systems in southern Spain was also accounted for: external solar blinds. Three different blind operation schedules were considered, based on previous studies focused on the Mediterranean area [34], and applied according to season.

2.4.4. Optimisation analysis

For optimising the social building stock retrofit solutions according to the annual percentage of overheating hours (%), annual percentage of undercooling hours (%) and investment costs (€/m^2), the jEPlus + EA open access tool [35] was used. This software allows parametric analysis and relies on the JEA online optimisation engine (ENSIMS Web Services Platform). A multi-objective analysis was performed, providing a set of feasible solutions for two or more simultaneous optimisation targets [36], normally known as trade-off or Pareto-optimal solutions [37], which are non-dominating to each other, but superior to the rest of search space solutions [38]. In this research, the non-dominated sorting genetic algorithm (NSGA-II), developed by Deb et al. [39], was implemented. This algorithm can be used in building's optimisation as highlighted by Evins [40], and proven by Carlucci et al.

Table 3
Retrofit roof and wall solutions considered.

Construction solutions	Label	TI position	TI type	TI thickness (m)	Pavement	Green coverage	Rendering	U-value (W/m2·K)
Roof	Unretrofitted	–	–	–	X	–	–	1.2–2.4
	InMW_0.05	Internal	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	External	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	External	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	Internal	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	External		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

Note: TI refers to thermal insulation. All roof solutions maintain the existing base roof solution, with the possibility of removing the external coverage (pavement or green coverage). All wall solutions maintain the existing base wall solution.

Table 4
Window retrofit solutions considered.

Window	**Glazing**			**Frame**	**U-value (W/m2·K)**
Label	Glass (mm)	Gap (mm)	Glass (mm)		
Unretrofitted	4	–	–	Aluminium	5.5–5.7
4LE-Air8-6	4LE	Air8	6	Wood / PVC / Aluminium with thermal bridge break	2.0–2.3
4LE-Air10-6	4LE	Air10	6		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

Note: 6-Air12-8 window was only considered in B4 climatic area meeting energy requirements of the Spanish Building Technical Code. Xe: Xenon. LE: Low emissivity.

[41], who reviewed 68 papers where the NSGA-II was used for optimising the building envelope and systems.

To construct the sample set in the simulations, the Latin Hypercube Sampling (LHS) method was used. The population size (number of solutions evaluated in each iteration) was set at 10 LHS samples per parametrized variable, which is a generally accepted rule [42]. The maximum number of generations (iterations the optimisation runs) was 100. The crossover rate, which is related to how often new solutions are created merging features of existing ones, was 100 %. Mutation rate, which specifies how often random changes occur to the new solutions, was 20 %, and the tournament selection size was 2, meaning that from two random solutions in the existing population, the algorithm only keeps the best one based on its fitness. These values were set considering the computational resources available and recommendations included in the tool manual [37].

3. Results and discussion

Table 6 shows the number of simulations and optimised solutions per each climatic area.

In each case, convergence of optimal results were obtained in an approximately 6-hour computation period, using a computer with i7-8700 CPU 3.20 GHz of 12 cores and 32 GB RAM.

Fig. 6 shows the results of the multi-objective decision analysis for each climatic area in southern Spain (B4 Seville, A3 Cádiz, C3 Granada and A4 Almería), through a 3D dispersion plot, represent-

Table 5
Building operation solutions considered.

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
Mechanical Ventilation Schedule		
Label	Summer	Winter
MechVent	On (continuos)	
Off	Off	
Blinds aperture schedule		
Label	Summer	Winter
Blinds 1|1	50% opened	
Blidns 2|2	0% from 8:00–16:00	
50% from 16:00–21:00		
100% 21:00–7:00	100% from 9:00–19:00	
0% from 19:00–9:00		
Blinds 3|3	0% from 7:00–21:00	
100% from 21:00–7:00	100% from 9:00–19:00	
0% from 19:00–9:00		

Note: 0% blinds aperture level means totally closed.

Table 6
Total simulations and optimised solutions.

Climatic area	Total number of simulations	Number of optimised solutions	Optimised solutions (%)
B4	991	121	12.2
A3	969	67	6.9
C3	976	99	10.1
A4	977	77	7.9

ing the values of annual overheating hours (%), annual undercooling hours (%) and investment costs (€/m^2). The results obtained in the optimisation process (Pareto's front) are indicated in red colour.

Parameter combinations for retrofit solutions are shown in Fig. 7(a-d), per each climatic area through parallel coordinates plots. Orange colours represent Pareto optimal (best) solutions.

In all climatic areas, optimised retrofit strategies cost in the range 17–200 €/m^2. Generally, the most expensive optimised solutions (over 100 €/m^2) normally included green roof strategies and the addition of MW insulation to the vertical envelope. None of the Pareto's solutions included blind aperture schedule number 1 (half opened for the whole year) in any climatic area.

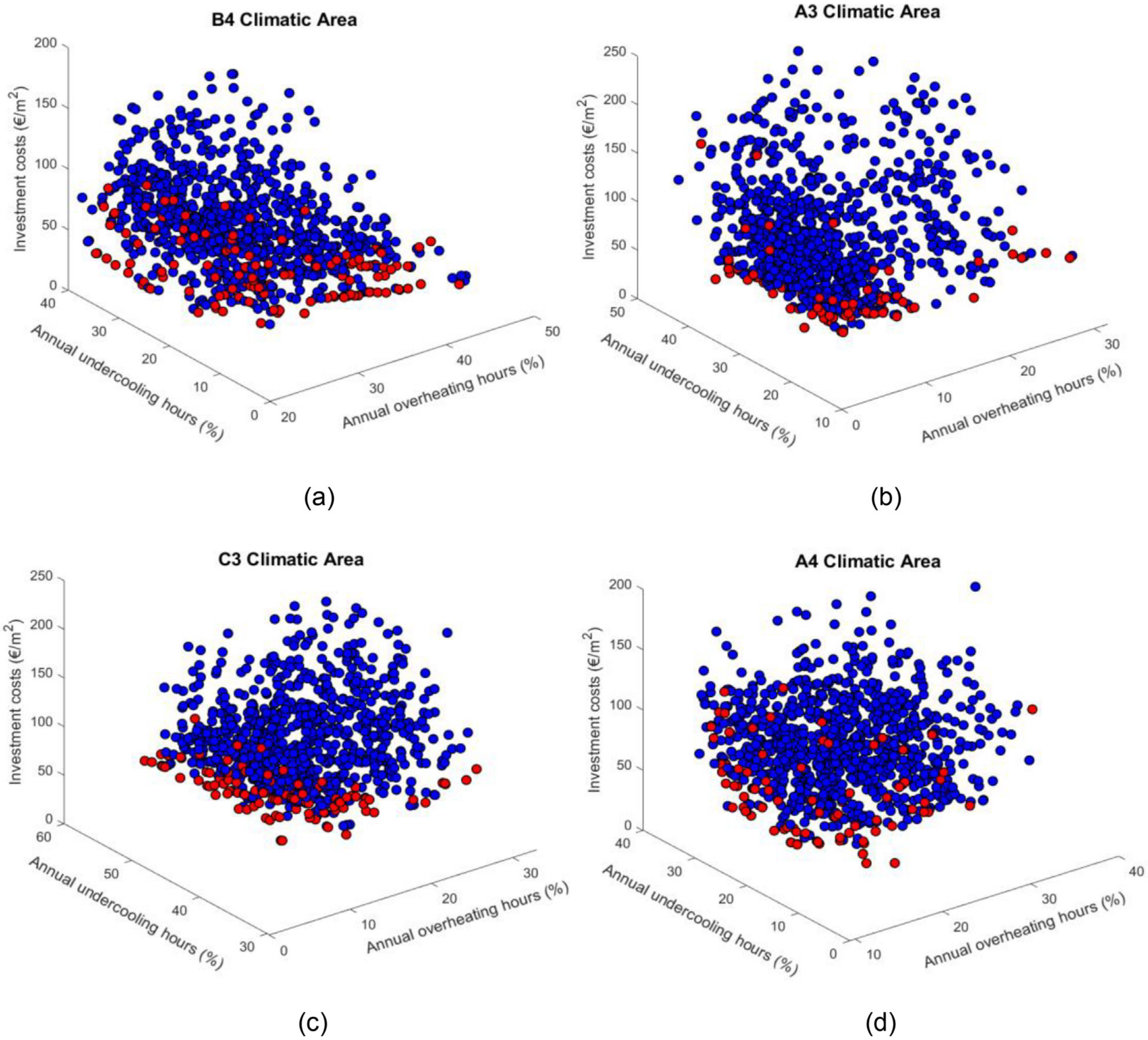
In B4 climatic area (Sevilla) (Fig. 6a), with unretrofitted roof, optimised results were obtained with mechanical ventilation OFF, natural ventilation schedule 3 (summer from 22:00–8:00 and winter from 8:00–9:00), blind aperture level 3 (summer: 0 % from 7:00–21:00 and 100% from 21:00–7:00; winter: 100 % from 9:00–19:00 and 0 % from 19:00–9:00),external thermal insulation in facades and window replacement (4LE-Air10-6 glass with PVC frame), leading to low-cost investments (up to 50 €/m^2), generally around 30 €/m^2, with 26 % overheating hours and 20 % undercooling hours. This leads to an improvement of approximately 10 % and 20 % of overheating and undercooling hours, compared to the unretrofitted scenario. Medium-cost (50–100 €/m^2) and high-cost (100–200 €/m^2) strategies do not provide a significant improvement: overheating hours are reduced by 2 % and 3 %, respectively, while similar undercooling hours are obtained compared to the low-cost scenario.

In A3 climatic area (Cádiz) (Fig. 6b), unretrofitted wall and roof scenario reported optimised solutions under the following criteria: mechanical ventilation OFF, natural ventilation schedule 1 (from 8:00–9:00 in summer and winter), blinds aperture level 2 (summer: 0 % from 8:00–16:00, 50 % from 16:00 to 21:00 and 100 % from 21:00 to 7:00; winter: 100 % from 9:00–19:00 and 0 % from 19:00–9.00). This solution included low-cost strategies (investment costs below 50 €/m^2), normally around 20 €/m^2, since window replacement was not considered either, reporting approximately 13 % of overheating hours and 39 % of undercooling hours. These low-cost solutions improve overheating and undercooling hours by 10 % and 5 % compared to the unretrofitted scenario (without operation strategies optimised). Applying medium-cost retrofit solutions (50–100 €/m^2), clearly reduces undercooling hours by an average of 24 % compared to the low-cost case. Nonetheless, overheating hours obtained are quite similar in both cases. In addition, high-cost retrofit measures (100–200 €/m^2) do not report a significant improvement in comparison to the medium-cost scenario in terms of discomfort.

In C3 climatic area (Granada) (Fig. 6c), when walls and roof were unretrofitted, if blinds were set at schedule 3 (summer: 0 % from 7:00–21:00 and 100 % from 21:00–7:00; winter: 100 % from 9:00–19:00 and 0 % from 19:00–9:00), mechanical ventilation turned OFF, natural ventilation schedules 3 or 4, and window replacement (6-Air12-8 with aluminium thermal bridge break), Pareto solutions were obtained, considering investment costs of approximately 20 €/m^2 (low-cost cases up to 50 €/m$^{2)}$, 14 to 18 % overheating hours and 40–50 % undercooling hours. Overheating and undercooling is improved by almost 15 % and 10 %, respectively to the unretrofitted scenario. Applying medium-cost solutions (50–100 €/m^2), leads to a reduction of around 10 % of both overheating and undercooling hours in comparison to the low-cost scenario. Despite implementing high-cost measures (100–200 €/m^2) overheating and undercooling hours are only improved by around 5% when compared to the medium-cost scenario.

In A4 climatic area (Almería) (Fig. 6d), maintaining existing walls and roof and applying low-cost retrofit solutions (up to 50 €/m^2), lead to 16–24 % of overheating hours and 14–32 % of undercooling hours. Applying medium-cost retrofit solutions (50–100 €/m^2), either improves overheating hours, with a reduction of 13 %, or decreases undercooling hours, reducing them around 19 %, compared to the low-cost scenario. If high-cost solutions are implemented (100–200 €/m^2), both overheating and undercooling hours are improved in a similar way, with values of 11–13 % and 10–15 % discomfort hours, respectively. Optimised parameter combination could be mechanical ventilation ON or OFF, natural ventilation schedules 3 (summer from 22:00–8:00 and winter from 8:00–9:00) or 4 (summer 22:00–8:00 and winter from 14:00–15:00), blind aperture 2 (summer: 0 % from 8:00–16:00, 50 % from 16:00–21:00 and 100 % from 21:00–7:00; winter: 100 % from 9:00–19:00 and 0 % from 19:00–9:00) or 3 (summer: 0 % from 7:00–21:00 and 100% from 21:00–7:00; winter: 100% from 9:00–19:00 and 0% from 19:00–9:00) and window replacement (4LE-Air10-6 or 4LE-Xe6-6 with aluminium thermal bridge break).

These conclusions have been compared to others reported in similar studies focused on the Mediterranean area and thermal comfort optimisation. Ortiz et al. [43] established that external insulation applied to a single residential building located in Catalonia (northern Spain), despite higher economical costs, has a better thermal performance in contrast to internal insulation and that window replacement and roof insulation have a great impact of annual thermal comfort. These facts were also reported in the presented research for the social housing stock in southern Spain. Similarly, Ascione et al [44] drew the conclusion that thermal insulation of walls significantly reduced thermal discomfort hours. Moreover, these authors confirmed that insulation of the roof and mechanical ventilation were basic retrofit strategies. Penna el et al. [45] also concluded that the implementation of a mechanical ventilation system, besides leading to lower energy consumption compared to other HVAC systems, provided improved indoor thermal comfort for a residential building located in Italy. Notwithstanding,



(a) (b)

(c) (d)

Fig. 6. Optimization results of the multi-objective decision analysis for each climatic area: (a) B4 (Sevilla), (b) A3 (Cádiz), (c) C3 (Granada), and (d) A4 (Almería). Optimal results obtained in the optimisation process (Pareto front) are indicated by red dots, whilst blue dots show non-optimal solutions. 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 presented research has proven that mechanical ventilation was not always among the optimised retrofit solutions for southern Spain climatic areas.

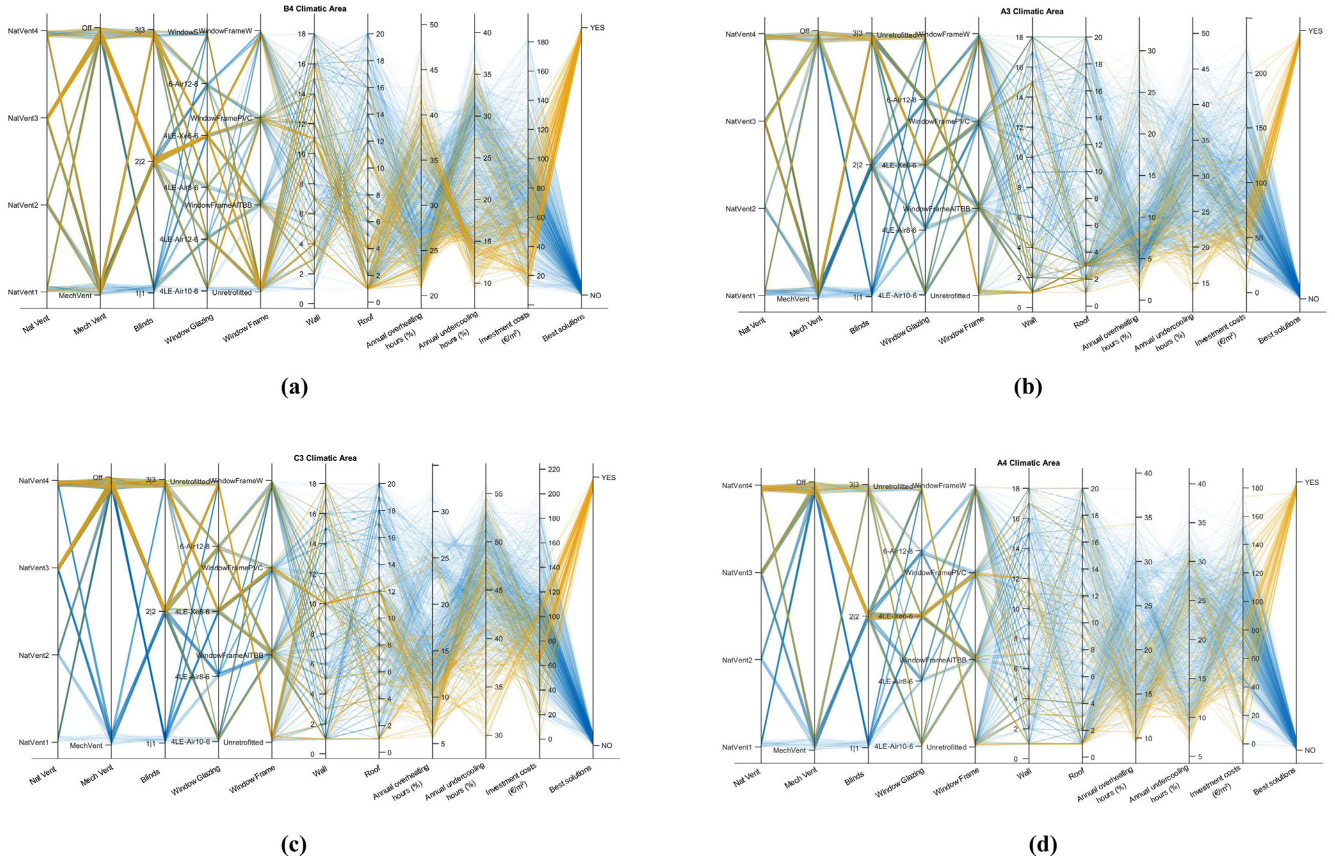
4. Strengths, limitations & future research

This research has highlighted optimal retrofit strategies obtained through dynamic simulation which can be applied at building stock level to social housing in southern Spain. The use of parameterised energy simulation modelling allows the incorporation of different variability ranges at stock level, thanks to the statistical analysis of an extensive database. Thus, different residential buildings from other cities and climates may be easily incorporated into the model through the modification of the variability ranges. Additionally, this research addresses the literature gap relating to the optimisation of thermal comfort, in contrast to the more common energy-related approach.

Interactive optimisation results (Figs. 5 & 6 included in the Supplementary Data section) have been made openly accessible for easy public and stakeholder dissemination. Fig. 5 can be easily zoomed in and rotated. Specific results of the objectives per simulation can be observed by placing the mouse over data points. Fig. 6 also allows the identification of specific results by placing the mouse over parallel lines and thermal comfort results for certain intervention costs can be easily filtered. Stakeholders and public administrations may use these data to easily explore different optimal retrofit solutions when considering Retrofit Programmes and Initiatives.

Among the main drawbacks, it must be stated that the multi-objective decision analysis is focused on retrofitting the existing social housing stock of southern Spain (Mediterranean area) and, specifically, results were reported only on the H-block typology. In addition, no data was available on retrofitted buildings and, consequently, the calibration and validation of the BSM after the implementation of retrofit strategies was not possible.

Another drawback is that operational costs of the mechanical ventilation systems were not included in this research, since it was only focused on initial investment cost.



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

Fig. 7. Optimization parameter combination of the multi-objective decision analysis for each climatic area: (a) B4 (Sevilla), (b) A3 (Cádiz), (c) C3 (Granada), and (d) A4 (Almería). Optimal results obtained in the optimisation process (Pareto front) are indicated by orange lines, whilst blue lines show non-optimal solutions. 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.)

Future works should assess the incorporation of second-level retrofit solutions in the social housing stock of southern Spain, including active HVAC systems and renewable energy sources. Consequently, new objectives functions may be included into the optimisation process, in particular primary energy consumption in agreement with the EU energy targets. Other parameters such as life cycle costs and variables related to indoor environmental quality (e.g. moisture, indoor pollutants…), may also be interesting to assess. In addition, assessing retrofit solutions of the social housing stock in response to future climate change scenarios may also report interesting conclusions.

5. Conclusions

This research presents numerically optimised retrofit strategies for thermal comfort and intervention costs applied to the social housing stock of southern Spain (Mediterranean area). Statistical information obtained from an extensive public database was incorporated into energy dynamic models of the existing building stock through a parameterisation method. A multi-objective decision analysis was conducted to determine which were the best combination of building retrofits, through the implementation of a genetic algorithm. Three optimisation objectives were considered: annual overheating hours (%), annual undercooling hours (%) and investment costs (€/m^2).

Specific results of the optimization process may be observed in an interactive open-access tool provided in the Supplementary Data section, which can be accessed through any .html visualizer. Overheating and undercooling discomfort hours, as well as investment costs can be easily filtered in the tool by selecting a desirable value range for the intervention plan. Then, specific optimal retrofit packages will be reported by the tool (several envelope retrofit options and operational aspects). Each one of those will have specific values of thermal discomfort and investment costs associated. Consequently, stakeholders and public administrations may compare possible results and choose the package combination among the optimal retrofit solutions which may consider more suitable according to their retrofit programmes and initiatives.

Generally, it can be concluded that all optimised retrofit strategies consider investment costs up to 200 €/m^2. In B4 climatic area (Sevilla), low-cost solutions (up to 50 €/m^2) improved by 10 and 20 % overheating and undercooling hours compared to the unretrofitted scenario. On the contrary, medium and high cost solutions (50–100 and 100–200 €/m^2, respectively) do not provide a significantly high improvement of discomfort when compared to the low-cost case, especially in terms of undercooling. Nonetheless, high-cost solutions reduced overheating by 11% in comparison to the low-cost scenario. In A3 area (Cádiz), applying medium-cost retrofit solutions (50–100 €/m^2) reported the highest improvements in overheating and undercooling hours, with a reduction of around 20 and 24 %, respectively, compared to the unretrofitted scenario. High-cost measures reported similar results as to the medium-cost case, while low-cost strategies slightly improved overheating hours. In C3 climatic area (Granada), implementing low-cost solutions significantly improved the unretrofitted performance, reducing overheating and undercooling hours by 15 % and 10 %, respectively. Even though, medium-cost strategies lead to an improvement of 20 % of both overheating and undercolling hours in comparison to the unretrofitted scenario, benefits obtained from high-cost solutions are not significant when compared to the medium-cost case. In contrast, low-cost strategies in A4 climatic area (Almería) reported an improvement of less than 10 % of discomfort hours, while medium-cost solutions significantly improved both overheating and undercooling. Nonetheless, high-cost measures are more relevant since a balanced improvement is reached in overheating and undercooling hours, with a reduction of almost 20 % and 15 %, respectively, when compared to the unretrofitted case.

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.

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Author Contributions

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2022.111915.

References

[1] Energy Statistics: an Overview. Eurostat Statistics Explained. European Commission. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Final_energy_consumption (accessed May 19 2021).

[2] Z. Ma, P. Cooper, D. Daly, L. Ledo, Existing building retrofits: Methodology and state-of-the-art, *Energy Build.* 55 (2012) 889–902, https://doi.org/10.1016/j.enbuild.2012.08.018.

[3] European Parliament resolution of 15 January 2020 on the European Green Deal (2019/2956 (RSP)) https://oeil. secure. europarl. europa. eu/oeil/ popups/ficheprocedure. do? lang= en&reference= 2 019/2956 (RSP) (accessed 4 September 2021).

[4] K.G. Burkart, M. Brauer, A.Y. Aravkin, W.W. Godwin, S.I. Hay, J. He, V.C. Iannucci, S.L. Larson, S.S. Lim, J. Liu, C.J.L. Murray, P. Zheng, M. Zhou, J.D. Stanaway, Estimating the cause-specific relative risks of non-optimal temperature on daily mortality: a two-part modelling approach applied to the Global Burden of Disease Study, The Lancet 398 (10301) (2021) 685–697, https://doi.org/10.1016/S0140-6736(21)01700-1.

[5] R. Escandón, R. Suárez, J.J. Sendra, Field assessment of thermal comfort conditions and energy performance of social housing: The case of hot summers in the Mediterranean climate, Energy Policy 128 (2019) 377–392, https://doi.org/10.1016/j.enpol.2019.01.009.

[6] M.K. Singh, S. Attia, S. Mahapatra, J. Teller, Assessment of thermal comfort in existing pre-1945 residential building stock, Energy 98 (2016) 122–134, https://doi.org/10.1016/j.energy.2016.01.030.

[7] International Energy Agency. Tracking buildings 2020 https://www.iea.org/reports/tracking-buildings-2020 (accessed 4 September 2021)

[8] G.G. Akkurt, N. Aste, J. Borderon, A. Buda, M. Calzolari, D. Chung, V. Costanzo, C. Del Pero, G. Evola, H.E. Huerto-Cardenas, F. Leonforte, A. Lo Faro, E. Lucchi, L. Marletta, F. Nocera, V. Pracchi, C. Turhan, Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions, *Renew. Sust. Energ. Rev.* 118 (2020) 109509, https://doi.org/10.1016/j.rser.2019.109509.

[9] M.K. Singh, S. Mahapatra, J. Teller, An analysis on energy efficiency initiatives in the building stock of Liege, Belgium, Energy Policy. 0–0 (2013), https://doi.org/10.1016/j.enpol.2013.07.138.

[10] N. Hashempour, R. Taherkhani, M. Mahdikhani, Energy performance optimization of existing buildings: A literature review, *Sustain. Cities Soc.* 54 (2020) 101967, https://doi.org/10.1016/j.scs.2019.101967.

[11] M. Singh, S. Mahapatra, J. Teller, Relation between indoor thermal environment and renovation in Liege residential buildings, Therm. Sci. 18 (3) (2014) 889–902, https://doi.org/10.2298/TSCI1403889S.

[12] I. Ballarini, S.P. Corgnati, V. Corrado, Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project, Energy Policy 68 (2014) 273–284, https://doi.org/10.1016/j.enpol.2014.01.027.

[13] F. Ascione, M. Canelli, R.F. De Masi, M. Sasso, G.P. Vanoli, Combined cooling, heating and power for small urban districts: An Italian case-study, Appl. Therm. Eng. (2014), https://doi.org/10.1016/j.applthermaleng.2013.10.058.

[14] V. Corrado, I. Ballarini, Refurbishment trends of the residential building stock: Analysis of a regional pilot case in Italy, Energy Build. 132 (2016) 91–106, https://doi.org/10.1016/j.enbuild.2016.06.022.

[15] D. Manjarres, L. Mabe, X. Oregi, I. Landa-Torres, Two-stage multi-objective meta-heuristics for environmental and cost-optimal energy refurbishment at district level, Sustainability (Switzerland) 11 (5) (2019) 1495, https://doi.org/10.3390/su11051495.

[16] R. Escandón, F. Ascione, N. Bianco, G.M. Mauro, R. Suárez, J.J. Sendra, Thermal comfort prediction in a building category: Artificial neural network generation from calibrated models for a social housing stock in southern Europe, Appl. Therm. Eng. 150 (2019) 492–505, https://doi.org/10.1016/j.applthermaleng.2019.01.013.

[17] F. Ascione, N. Bianco, C. Stasio, G. Mauro, G. Vanoli, Addressing large-scale energy retrofit of a building stock via representative building samples: Public and private perspectives, Sustainability (Switzerland) 9 (6) (2017) 940, https://doi.org/10.3390/su9060940.

[18] R. Escandón, R. Suárez, J.J. Sendra, Protocol for the Energy Behaviour Assessment of Social Housing Stock: The Case of Southern Europe, Energy Procedia 96 (2016) 907–915, https://doi.org/10.1016/j.egypro.2016.09.164.

[19] T. Blázquez, S. Ferrari, R. Suárez, J.J. Sendra, Adaptive approach-based assessment of a heritage residential complex in southern Spain for improving comfort and energy efficiency through passive strategies: A study based on a monitored flat, Energy 181 (2019) 504–520, https://doi.org/10.1016/j.energy.2019.05.160.

[20] European standards committee EN 16798–1:2019 Energy Performance of Buildings – Ventilation for buildings - Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality 2019 Thermal Environment Lighting and Acoustics - Module M1 6.

[21] BS EN 15251. Indoor environmental input parameters for design and assessment of energy performance of buildings-addressing indoor air quality, thermal environment, lighting and acoustics 2007.

[22] C.M. Calama-González, R. Suárez, Á.L. León-Rodríguez, Thermal comfort prediction of the existing housing stock in southern Spain through calibrated and validated parameterized simulation models, Energy Build. 254 (2022) 111562, https://doi.org/10.1016/j.enbuild.2021.111562.

[23] A.V.R.A. Andalusian Agency of House and Retrofitting (Agencia de Vivienda y Rehabilitación de Andalucía, in Spanish) 2021 (accessed September 05.

[24] Online Cadastral Office (Sede Electrónica del Catastro, in Spanish), https://www.sedecatastro.gob.es (accessed May 19 2021)

[25] Spanish Technical Building Code (Código Técnico de la Edificación., in Spanish), 2017 Spanish Government Madrid Spain, https://www.codigotecnico.org (accessed May 19 2021).

[26] C.M. Calama-González, R. Suárez, A.L. León-Rodríguez, Building characterisation and assessment methodology of social housing stock in the warmer Mediterranean climate: the case of southern Spain, IOP Conference Series: Earth and Environmental Science 410 (1) (2020) 012049, https://doi.org/10.1088/1755-1315/410/1/012049.

[27] C.M. Calama-González, Á.L. León-Rodríguez, R. Suárez, (2021). Energy and Typological Building Characterization of the Social Housing Stock in Southern Spain, pp.1-6, https://dx.doi.org/10.6084/m9.figshare.14810292.

[28] U.S. Department of Energy. *EnergyPlus Energy Simulation Software*, 2017 http://apps1.eere.energy.gov/buildings/energyplus (accessed 20 March 2021).

[29] ANSI/ASHRAE. ASHRAE Guideline 14-2002 Measurement of Energy and Demand Savings. ASHRAE 2002.

[30] M.C. Kennedy, A. O’Hagan, (2001). Bayesian calibration of computer models. Journal of the Royal Statistical Society. Series B: Statistical Methodology. https://doi.org/10.1111/1467-9868.00294.

[31] C.M. Calama-González, P. Symonds, G. Petrou, R. Suárez, Á.L. León-Rodríguez, Bayesian calibration of building energy models for uncertainty analysis through test cells monitoring, Appl. Energy 282 (2021) 116118, https://doi.org/10.1016/j.apenergy.2020.116118.

[32] C.Y.P.E. Ingenieros, Generador de precios de la construcción. España. http://www.generadordeprecios.info/#gsc.tab=0 (accessed 4 September 2021).

[33] X. Chen, H. Yang, K. Sun, Developing a meta-model for sensitivity analyses and prediction of building performance for passively designed high-rise residential

buildings, Appl. Energy 194 (2017) 422–439, https://doi.org/10.1016/j.apenergy.2016.08.180.

[34] A. Gómez Gómez, Generación de protocolos de funcionamiento de persianas para la reducción de la demanda energética en edificios VPO de Andalucía Masters dissertation, Universidad de Sevilla, Spain, 2012.

[35] Y. Zhang, L. Jankovic, JEA, An interactive optimisation engine for building energy performance simulation, Building Simulation Conference Proceedings, 2017.

[36] S. Attia, M. Hamdy, W. O'Brien, S. Carlucci, Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design, Energy Build. 60 (2013) 110–124, https://doi.org/10.1016/j.enbuild.2013.01.016.

[37] V. Pareto, Rapport sur les bases de l'assurance de la Fraternité, Société de secours en cas de décès, à Lausanne, Cahiers Vilfredo Pareto 1 (1) (1963) 107–120.

[38] H. Bagheri-Esfeh, H. Safikhani, S. Motahar, Multi-objective optimization of cooling and heating loads in residential buildings integrated with phase change materials using the artificial neural network and genetic algorithm, J. Storage Mater. 32 (2020) 101772, https://doi.org/10.1016/j.est.2020.101772.

[39] K. Deb, A. Pratap, S. Agarwal, T. Meyarivan, A fast and elitist multiobjective genetic algorithm: NSGA-II, IEEE Transactions on Evolutionary Computation. doi 6 (2) (2002) 182–197.

[40] R. Evins, A review of computational optimisation methods applied to sustainable building design, *Renew. Sust. Energ. Rev.* 22 (2013) 230–245, https://doi.org/10.1016/j.rser.2013.02.004.

[41] S. Carlucci, G. Cattarin, F. Causone, L. Pagliano, Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II), Energy Build. 104 (2015) 378–394, https://doi.org/10.1016/j.enbuild.2015.06.064.

[42] J.L. Loeppky, J. Sacks, W.J. Welch, Choosing the sample size of a computer experiment: A practical guide, Technometrics 51 (4) (2009) 366–376, https://doi.org/10.1198/TECH.2009.08040.

[43] J. Ortiz, A. Fonseca, J. Salom, N. Garrido, P. Fonseca, V. Russo, Comfort and economic criteria for selecting passive measures for the energy refurbishment of residential buildings in Catalonia, Energy Build. 110 (2016) 195–210, https://doi.org/10.1016/j.enbuild.2015.10.022.

[44] F. Ascione, N. Bianco, C. De Stasio, G.M. Mauro, G.P. Vanoli, A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance, Energy Build. 88 (2015) 78–90, https://doi.org/10.1016/j.enbuild.2014.11.058.

[45] P. Penna, A. Prada, F. Cappelletti, A. Gasparella, Multi-objectives optimization of Energy Efficiency Measures in existing buildings, Energy Build. 95 (2015) 57–69, https://doi.org/10.1016/j.enbuild.2014.11.003.