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Enhancing sustainability and resilience of elderly dwellings: Optimized refurbishing parameters and air conditioning operation

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ABSTRACT

Refurbishing buildings to minimize lifecycle costs and increase reliance on natural ventilation may reduce building resilience to extreme weather. This is critical for elderly whose health is affected by exposure to thermally stressful conditions. This study proposes a novel approach for refurbishing elderly houses to enhance their sustainability and heatwave resilience with the aim of supporting low-income groups. This approach involves using multi-objective optimization to identify refurbishment parameters and an autonomous control strategy to provide thermoneutral indoor conditions at a low cost.

The optimization procedure and control strategy were applied to a case study for a representative apartment in the Mediterranean climate using a validated building model. The strategy led to substantial reduction (61%) in cooling energy, while the optimization yielded Pareto solutions that showed trade-offs between lifecycle cost and resilience. A selected solution resulted in reduced electrical usage for heating (37%) and cooling (45%) and decreased indoor overheating during heatwaves. The study recommends design features for cost-effective and resilient elderly housing in the Mediterranean climate, such as limited window area, enhanced thermal properties, and a modest air conditioning system for low-income populations. Larger windows and AC systems are recommended for high income populations seeking reduced operational expenses and improved sustainability.

1. Introduction

Older individuals in unregulated thermal environments are particularly vulnerable to extreme weather events and climate change [1,2]. The underlying factors for this vulnerability include age-related impairments in body thermoregulation [3,4]; diminished thermal sensitivity that leads to hindered behavioral adaptations [5,6]; decline in cognitive functions [7–9] associated with increased risk of fall injury [10]; and adverse effects of certain chronic diseases [11] or medications [12]. The risk of extreme thermal conditions on elderly from low-income groups is even higher [2,13–16], because they may not have access to cooling or heating, and even if they do, many may not be able to afford the cost of energy [17–19]. On the other hand, the proportion of elderly in societies is rising at unprecedented rates due to the increase in life expectancy and the decrease in human fertility [20]. Additionally, elderly spend much of their time indoors, making it vital to maintain favorable thermal conditions within their living spaces. With the current energy crisis and growing concerns about global warming, it is crucial to implement low-cost and energy-efficient measures to promote sustainability in elderly housing and support low-income groups. Such measures may involve utilizing natural ventilation and ensuring appropriate sizing of Heating, Ventilation, and Air Conditioning (HVAC) systems. However, applying these measures can negatively impact building's resilience to extreme weather events. Even with the operation of HVAC systems, indoor conditions may become thermally uncomfortable or stressful for occupants under extreme weather. This is because HVAC systems are most often designed based on typical meteorological year (TMY) data and may not have the necessary capacity to handle exceptional weather occurrences, as recent research has shown [21].

Researchers have addressed achieving the desired indoor conditions at a lower cost by relying on alternatives to conventional energy-intensive mechanical HVAC systems. These alternatives include air pressure natural ventilation, in which differences in air pressure drive the movement of air between indoor and

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Nomenclature

A_{win}	Total area of windows (m^2)
AC_i	Type of air conditioning system (-)
C_{opr}	Predicted building annual operating cost – current year (/yr)
C_{ini}	Total initial cost for refurbishment ($)
C_{win}	Cost of window per area ($/$m^2$)
C_{ins}	Cost of insulation per volume ($/$m^3$)
C_{AC}	Initial cost of air conditioning system ($)
COP_{rated}	Rated coefficient of performance (-)
f_1	lifecycle cost of refurbishment ($)
f_2	Number non-thermoneutral hours experienced during a heatwave year (hrs.)
h_c	Convective Heat Transfer Coefficient ($W/m^2 \cdot K$)
h_e	Evaporative Heat Transfer Coefficient ($W/m^2 \cdot K$)
i	Interest rate (%)
k	Occupied hours counter (-)
LR	Lewis Ratio (-)
n	Number of Years (year)
N	Total number of occupied hours (hrs.)
PWF	Present Worth Factor (-)
SHGC	Solar Heat Gain Coefficient of Glazed Area (-)
S_{deb}	Temperature threshold that defines the start and end of the heatwave (℃)
S_{int}	Heatwave interruption threshold (℃)
S_{pic}	Temperature threshold beyond which a heatwave is identified (℃)
TS	Thermal Sensation (-)
T_{in}	Indoor Temperature (℃)
T_i	Indoor air temperature thresholds for the proposed control strategy (℃)
$\bar{T}_{day}$	Mean daily dry bulb temperature (℃)
$T_{sk,av}$	Mean skin temperature (℃)
$T_{sk,av,limit}$	Mean skin temperature limit (℃)
Tp_i	Windows type (-)
t	Time step (hrs.)
U-Value	Thermal transmittance ($W/m^2 \cdot K$)
V_{air}	Velocity of Air (m/s)
V_{ins}	Total volume of installed insulation (m^3)
x	Combination of design variables being optimized (-)
x_1	Thickness of insulation layer at exposed walls (-)
x_2	Size of windows at south wall (m^2)
x_3	Size of windows at west wall (m^2)
x_4	Type of windows in the apartment (-)
Greek SymbolsΔP	Pressure Rise Across the Fan (Pa)
η	Fan Total Efficiency (-)
AbbreviationsAC	Air Conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	Computational Fluid Dynamics
HVAC	Heating, Ventilation, and Air Conditioning
NOAA	US National Oceanic and Atmospheric Administration
TMY	Typical Meteorological Year

outdoor spaces [22], and elevated air movement, in which increased convective and evaporative heat losses from the body allow for improved thermal comfort in warm conditions at a low cost [23,24]. Furthermore, to reduce costs, some researchers have adopted using a high HVAC setpoint temperature combined with elevated air movement known as ceiling-fan-integrated air Conditioning [25]. The extent to which these measures allow for reducing the operational costs while maintaining the desired indoor conditions is contingent on building parameters such as window size and type, as well as the thermal characteristics of the envelope. Refurbishing buildings with the optimal combination of building parameters can help achieve the desired indoor conditions at a lower cost. In the context of low-income housing, an optimal combination of building parameters would be one that has a minimal capital cost and results in minimal operational costs. Nevertheless, minimizing capital and operational costs can negatively impact building's resilience to extreme weather events. For instance, a large-windowed apartment with a small air conditioning system may have low capital and operational costs but could be vulnerable to heatwaves. Conversely, an apartment with smaller windows and a larger air conditioning system may not benefit as much from natural ventilation and would incur higher operational and capital costs but will be more resilient to heatwaves. Given the increasing intensity, frequency, and duration of extreme weather events [26] and the vulnerability of the elderly population, the following question arises: Would it be possible to refurbish elderly houses in a way that results in low capital and operational costs without impeding their resilience to extreme weather events?

The literature contains studies that either concentrate on enhancing the heatwave resilience of housing for vulnerable groups or optimizing the refurbishment of such houses to achieve low operational or lifecycle costs. For instance, *Loughnan et al.* conducted a study to explore how the housing characteristics of older individuals in a regional Australian town relate to their self-reported thermal comfort during periods of extreme heat [27]. They concluded that factors like building age, insulation, and number of air-conditioning units are significant contributors to maintaining indoor thermal comfort and can impact the heat exposure risks of older people during extreme weather [27]. *Kovacs et al.* examined thermal resilience of built environments in an Australian city and potential mitigation measures. They found that focused building and planning regulations has the potential to significantly increase heat stress resilience [28]. *Sun et al.* assessed passive cooling measures to enhance residential building heat resilience during heatwaves and power outages for vulnerable groups such as low-income and elderly groups [29]. They found that the performance of mitigation measures varies by building characteristics, surrounding environment, and power scenario, with window films that reduce solar heat gain and added roof insulation being among the most effective measures [29]. *Lores-Larsen* and *Filippín* conducted a case study in a low-income housing apartment building in Argentina to evaluate passive cooling measures that improve energy efficiency and heat resilience during extreme hot periods [30]. They found that favouring night ventilation, shading the envelope, and improving roof characteristics are highly effective in enhancing resilience [30]. *Sarkar and Bardhan*, on the other hand, employed a mixed-mode framework with multi-objective optimization to optimize the architectural layout of a low-income resettlement unit in order to maximize cooling savings through relying on natural ventilation [31]. In another study, *Kumar and Bardhan* conducted an optimization study on fenestration design to achieve both daylight and energy savings in low-income housing, focusing on a case study in Mumbai, India. According to *Contreras et al.*, energy efficiency should not be the single determinant when determining building parameters for vulnerable elderly facilities [32]. Studies that considered both energy efficiency and

heatwave resilience in the literature are very rare. *Alam et al.* stressed the importance of considering the impact of different heatwave adaptation measures on the energy consumption of the building while selecting the most suitable combination of measures [33]. *Sun et al.* investigated thermal resilience and energy efficiency in a case study for a nursing home [34]. They found that non-energy-saving measures can significantly enhance thermal resilience and should be incorporated into building design or retrofitting [34]. These findings demonstrate the previously mentioned "trade-off" relationship between heatwave resilience and energy efficiency and motivate optimizing the retrofitting process in a way that satisfies both objectives. Nonetheless, this study did not aim to optimize the two conflicting objectives of refurbishment but rather followed a parametric design framework to investigate the effects of different combinations. Moreover, the study recommended that future research employ optimization techniques to optimize these conflicting objectives. To the best of the authors' knowledge, there have been no studies in the literature that optimized both the sustainability and resilience of elderly dwellings through a refurbishment process. To this end, a multi-objective optimization problem is posed for identifying refurbishment parameters for typical elderly apartments with the objectives of minimizing refurbishment lifecycle cost and the potential for suboptimal indoor conditions during heatwave occurrences. The study focuses on refurbishing apartments that employ natural ventilation and elevated air movement as a low-cost alternative to mechanical systems. The downside of these options is that the effectiveness of natural ventilation is dependent on outdoor conditions, and the effectiveness of elevated air movement relies on the temperature of the air being circulated. This problem can be addressed by hybrid control strategies that only employ them when ambient conditions allow [35]. As a result, a control strategy is proposed that prioritizes natural ventilation, incorporates a ceiling fan, and selectively employs an HVAC system when necessary while operating at setpoint temperatures that guarantee a thermoneutral environment for elderly without overcooling or overheating. The response of older occupants to different thermal environments is needed to develop such a strategy. Therefore, an elderly bioheat thermoregulatory model [36] and an elderly thermal sensation (TS) model [36] are used to predict the response of elderly individuals to different thermal environments and derive appropriate control actions. These considerations result in the following specific objectives of the study:

i) to minimize the lifecycle costs associated with refurbishing a typical elderly apartment and the number of non-thermoneutral hours experienced during heatwaves by identifying optimal building parameters through multi-objective optimization; and developing a control strategy that provides the elderly with thermoneutral conditions at minimal cost by prioritizing the use of natural ventilation with selective use of ceiling fans and HVAC systems.
ii) to evaluate the effectiveness of the optimization procedure and control strategy in terms of energy consumption and resilience to extreme weather through a case study on a representative building in the Mediterranean climate using a validated building model.

By addressing the objectives set forth, the study aims to meet the thermal needs of elderly occupants at a low cost, and reflect the tradeoffs between cost effectiveness, energy efficiency, and heatwave resilience in the context of elderly housing. The optimization process and control strategy can contribute to enhancing the sustainability of elderly dwellings, reducing their carbon footprint, and improving their ability to withstand extreme weather.

2. Problem statement

The problem under consideration is determining refurbishment parameters for elderly housing that minimize the total lifecycle costs while ensuring sufficient resilience against heatwave events. To address this problem, a multi-objective optimization problem is formulated for identifying optimal refurbishment parameters for typical elderly apartments with the objectives of minimizing refurbishment lifecycle costs and the number of hours the indoor conditions become non-thermoneutral for elderly occupants during heatwave occurrences.

The space considered in the study is shown in Fig. 1, which is inhabited by two elderly individuals and equipped with three systems: motorized windows **(1)**, a ceiling fan **(2)**, and an HVAC system **(3)**. The motorized windows have only two configurations: fully closed or fully open, where a half-opened glazing area for a sliding window is considered fully open. The ceiling fan has low- and high-speed modes, and the HVAC system has heating and cooling modes with adjustable setpoint temperatures.

The three systems can operate separately or together, allowing the following modes of operation: natural ventilation, ceiling fan-assisted natural ventilation, ceiling fan-integrated air conditioning, forced-air heating, and closed building modes. Setting the appropriate operation mode necessitates both understanding the thermal needs of elderly occupants and making informed decisions to trigger the appropriate mode of operation to reduce energy costs. Given that older people are less likely to adjust their behavior in response to variations in the thermal environment and their potential challenges in operating advanced HVAC systems [37,38], the appropriate mode should be determined without the need for their input. As a result, an autonomous control strategy is developed to determine the appropriate mode of operation that ensures suitable indoor conditions for the elderly with minimal energy consumption. The strategy is based on indoor temperature thresholds and takes outdoor temperature into account when determining the suitability of natural ventilation. Relative humidity and mean radiant temperatures are not included in deriving control thresholds for simple and feasible control of the hybrid system. High relative humidity values are not frequently observed in naturally ventilated spaces, particularly in the Mediterranean region, and would have to reach high levels to impact comfort [39]. Regarding the mean radiant temperature, the effects of solar radiation can be mitigated through the use of shading elements, and elderly individuals are unlikely to expose themselves to direct solar radiation. In addition, the operative temperature, which is a weighted average of the mean radiant and ambient air temperatures based on their respective heat transfer coefficients, is influenced more by the convective coefficient when a ceiling fan is being used than the radiative coefficient. This is why the operative temperature during the operation of a ceiling fan is typically very close to the air temperature. As a result, the control strategy will determine the appropriate mode of operation based on real-time readings from only indoor and outdoor temperature sensors.

3. Control strategy for space conditioning systems in elderly homes

The proposed operation of the systems in elderly houses is governed by a strategy that controls when and how each system should operate to achieve suitable indoor conditions at the lowest cost. Indoor conditions are considered suitable if they maintain thermal neutrality for elderly occupants. This means that the TS of elderly occupants should always be bound between −0.5 and 0.5 on the ASHRAE 7-point TS scale. The control strategy will be

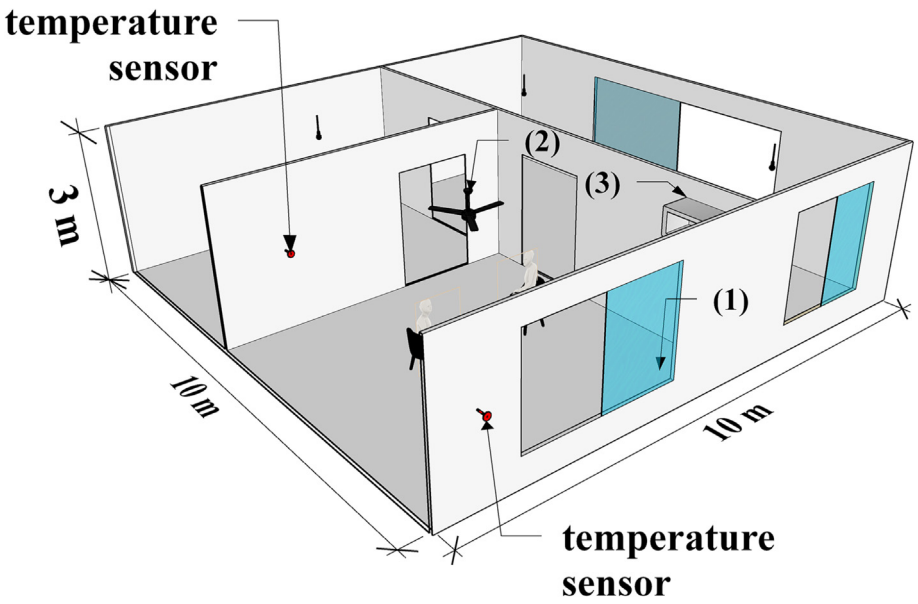

Fig. 1. Isometric view for the considered space where the proposed control strategy is implemented. Numbers in the figure: (1): motorized windows; (2): ceiling fan; (3): HVAC system diffuser.

implemented both during the day and at night, as a recent study [40] found no significant difference in elderly TS before and during sleep with or without a ceiling fan. The strategy involves evaluating the indoor temperature (T_{in}) relative to both the outdoor temperature (T_{out}) and a set of indoor temperature thresholds (T_1, T_2, T_3, T_4, and T_5). Based on this comparison, the control strategy activates one of the following modes: natural ventilation, ceiling fan-assisted natural ventilation, ceiling fan-integrated air conditioning, forced-air heating, or closed building mode. The ceiling fan will be set to run at low speed when it is adequate, with the aim of reducing energy consumption. Additionally, for the same objective, the HVAC system will run at a high temperature setpoint in the integrated fan-air conditioning mode backed by a recent study [25]. The study reported that subjects preferred the same physiological status with different ways of cooling themselves: either using the air conditioning system alone or using the air conditioning system with a ceiling fan. The strategy focuses on the thermal environment; as for ventilation needs, they are met through natural ventilation and by allowing for ASHRAE recommended air changes for residential houses when the HVAC system is in use [41]. In closed building operation, given the airtightness of the buildings in the region, as well as their spacious layout and low occupancy, infiltration will prevent the indoor air quality from dropping to hazardous levels.

The proposed control strategy is outlined in Fig. 2**,** where the state of each system is determined by T_{in} as compared to T_{out} and the indoor temperature thresholds. The first threshold, T_1, is defined as T_{in} that corresponds to elderly TS of −0.5 when wearing winter clothes. If the indoor temperature falls below T_1, the heating system is activated and T_1 is set as the setpoint temperature for the heating system. T_3 corresponds to the elderly TS of 0.5 when wearing summer clothes without fan. If the indoor temperature exceeds T_3, ceiling fan is activated at low speed. T_4 corresponds to the elderly TS of 0.5 with fan operating at low speed; it is higher than T_3 as individuals tend to tolerate higher ambient temperatures when a fan is active. If the indoor temperature exceeds T_4, the ceiling fan is operated in high mode. T_5 corresponds to elderly TS of 0.5 when the fan is operated in high mode. If the indoor temperature exceeds T_5, ceiling fan is kept at high mode and the mechanical cooling is activated with T_5 as setpoint temperature. T_2 corresponds to the thermal sensation of 0 and is used to determine when windows should be opened. If the indoor temperature is higher than the outdoor temperature and falls between T_2 and T_5, windows are opened. Windows cannot be opened at temperatures below T_2 because doing so would result in a TS less than 0. Additionally, they cannot be opened if the T_{in} exceeds T5, because the mechanical cooling system will be activated. With the implementation of the proposed method, the operational mode ensures thermoneutral conditions for elderly occupants without requiring their input. Nonetheless, occupants should be granted the ability to override the operational mode determined by the strategy if they so choose to accommodate individual differences among the elderly population. The functionality of the method is contingent upon the establishment of the indoor temperature thresholds, which will be addressed in the next section.

4. Methodology

This section outlines the approach for determining thresholds for the adopted control strategy using the bioheat and TS elderly models. It then explains the building model employed to predict indoor conditions and estimate energy usage when implementing the strategy. The section concludes by addressing the optimization procedure for elderly housing refurbishment.

4.1. Control strategy thresholds: Determination approach

Determining the air temperature thresholds for the adopted control strategy involves predicting the TS of the elderly in various thermal conditions, including variations in air temperature, clothing insulation, and air velocity. This is addressed by employing the elderly bioheat model of *Rida et al.* [36] and the elderly TS model of *Younes et al.* [42]. The adopted bioheat model accounts for age-induced changes in the metabolic rate, body fat distribution, vasoconstriction, vasodilation, and sweating [36]. Similarly, the adopted TS model takes into account the influence of aging on the response of thermoreceptors and on thermal sensitivity [42]. The two elderly models have been validated extensively under various conditions and has demonstrated strong robustness [36,42].

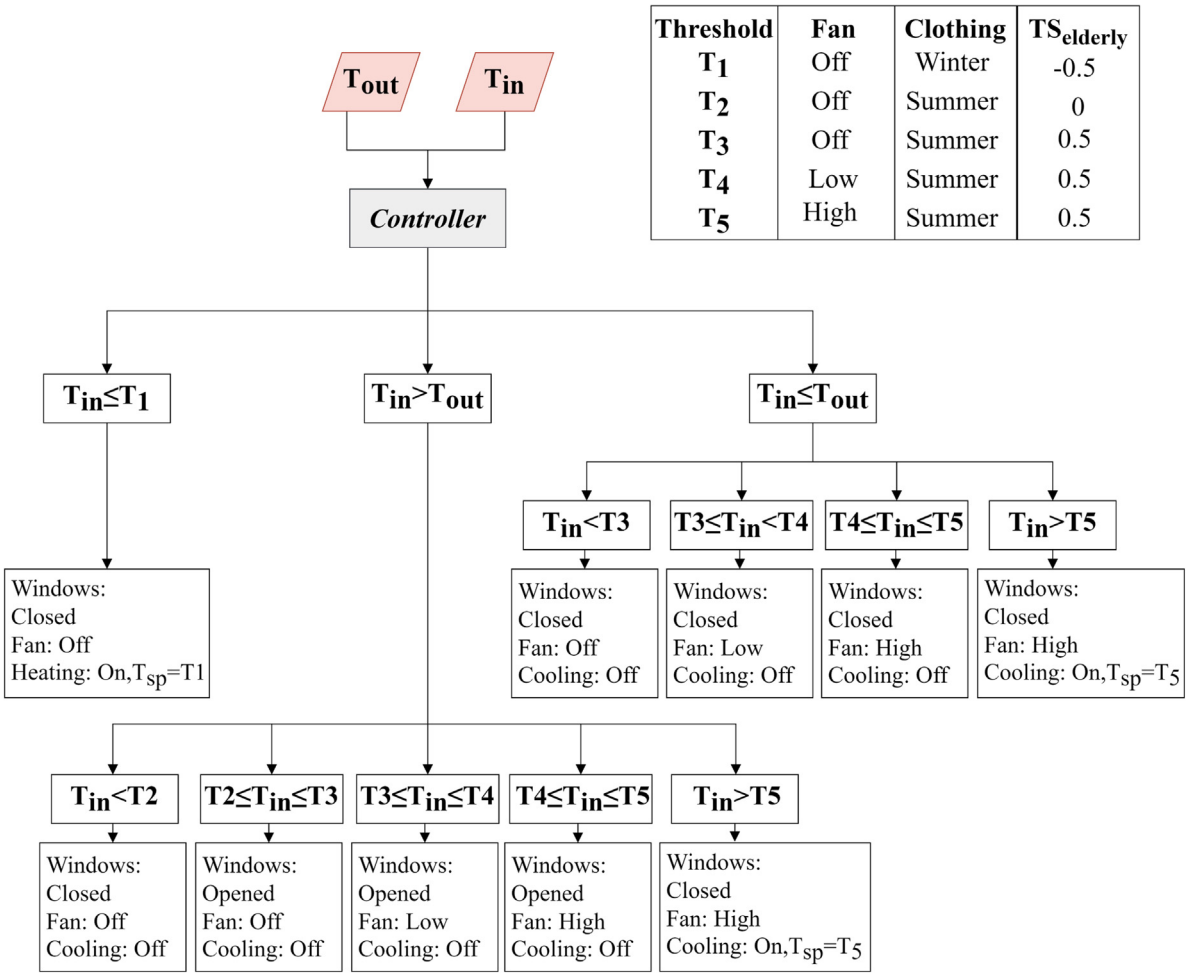

Fig. 2. Proposed autonomous control strategy for reducing energy use in elderly-occupied homes while preserving thermoneutral indoor conditions, displaying thresholds and the control actions associated with them.

The models are used in steady-state mode because the examined situations do not involve abrupt changes in the thermal environment or body heat storage.

The TS of elderly individuals is related to their mean skin temperature at steady-state [42]. Therefore, the TS model is utilized to predict the mean skin temperatures associated with each of the thresholds (T_1 to T_5) shown in Fig. 2. It is intended to predict the temperature of air that results in each of these average skin temperatures to be utilized as temperature thresholds. Therefore, the bioheat model is used in an iterative manner to determine these skin temperatures given the activity level, clothing insulation, and speed of air surrounding the body. Elderly occupants are assumed to perform sedentary work and to wear typical seasonal clothing. The thermal properties of the fabric such as the dry resistance ($m^2 \cdot ^\circ C/W$), the evaporative resistance ($m^2 \cdot kPa/W$), and the specific heat ($J/Kg \cdot ^\circ C$) are defined based on the IER project database [43]. In the presence of ceiling fan, its induced velocity around body parts is defined based on the computational fluid dynamics (CFD) simulation results of *Lin et al.* [24] who modelled a sitting human in a similar environment as the one being studied in this research, with a ceiling fan set at varying rotational speeds. When the fan and the HVAC system are jointly functioning, it is assumed that the influence of diffuser air velocity on the flow field can be neglected. The assumption is based on the fact that the localized and stronger flow induced by the ceiling fan directly impacts occupants, while the diffuser-induced flow is more diffused and weaker. As a result, the velocity at which air reaches individuals within the room is determined solely by the ceiling fan mode and the temperature of this air is the average room temperature. In the current study, two rotational speeds, 160 RPM and 240 RPM, are referred to as "low" and "high" modes. The induced velocities in these two modes are used to calculate convective and evaporative heat transfer coefficients around body segments using *Mitchell's equation* for forced convection for a seated person with moving air and the *Lewis Ratio* [41]:

$$h_c = \begin{cases} 8.3V^{0.6} if 0.2 < V_{air} < 4 \\ 3.1 if 0 < V_{air} < 0.2 \end{cases} \quad (1)$$

$$\frac{h_e}{h_c} = LR \quad (2)$$

where V_{air}, h_c, h_e, and LR are the velocity of air (m/s), the convective heat transfer coefficient ($W/m^2 \cdot K$), the evaporative heat transfer coefficient ($W/m^2 \cdot K$), and the Lewis Ratio, respectively. LR is assumed to be equal to 16.5 K/kPa, as suggested by ASHRAE for typical indoor settings [41]. Assuming that the temperature of surfaces in the considered space is similar to that of the air, the thresholds (T_1 to T_5) are calculated for the specified metabolic rate, clothing insulation, and air velocity.

4.2. Predicting indoor conditions and energy consumption in buildings

EnergyPlus 22.2.0 [44], a well-recognized energy analysis tool for buildings, is employed as a dynamic building simulation engine in this work. *EnergyPlus* employs inputs such as outdoor weather data, internal heat gains, building specifications, and HVAC system configuration to predict energy consumption, thermal zone conditions, and the HVAC system response of a building. The adopted control strategy is integrated into *EnergyPlus* to evaluate its effectiveness in maintaining desired indoor conditions while reducing energy consumption. Additionally, the building model is used in conjunction with an optimization algorithm to optimize the refurbishment of elderly housing.

This study uses three forms of weather data from *Beirut-Rafic Hariri International Airport*. The first type, TMY data, is used to assess energy consumption and size the HVAC system in the baseline scenario. The second type, extreme weather year data, is used to assess the building's resilience to heatwaves and was selected after analyzing 30 years of weather data. Both TMY and extreme weather data are derived from the US National Oceanic and Atmospheric Administration Integrated Surface Database (NOAA-ISD) [45]. The third type, specific year measured weather data, is used to validate the building energy model and was prepared by *Annan et al.* [46].

4.3. Optimizing refurbishment parameters for elderly dwellings

Multi-objective optimization is used to identify the cost-effective refurbishment parameters that minimize both lifecycle refurbishment costs and number of hours during which indoor conditions are not suitable for elderly occupants during extreme events. The parameters targeted for optimization include the insulation layer thickness on exposed walls, the sizes and types of windows, and the size of the air conditioning system. The optimization procedure is illustrated in Fig. 3 and begins with a building model that uses the proposed control strategy, modeled using *EnergyPlus* and *OpenStudio* (graphical interface for *EnergyPlus*). The model is utilized in conjunction with the *GenOpt* generic optimization software, where the optimization algorithm, cost functions, variables to be optimized, and optimization parameters are defined. The optimization procedure includes iteratively creating new sets of building parameters, running simulations under an extreme weather scenario, and evaluating the objective functions. The objective functions are related to the initial cost of design solutions (insulation, windows, AC), the operational cost of the apartment, and the number of hours the indoor conditions become non-thermoneutral for an elderly occupant during a heatwave year.

The objective functions in this analysis can be formulated as:

$$\left\{ \begin{array}{l} Min(f_1(x), f_2(x)); x = [x_1, x_2, x_3, x_4, x_5] \\ subjectto: \left\{ \begin{array}{c} x_1 \in [0,1,2,3,4,5,6,7,8,9,10,11,12,13,14,15] \\ 3 \le x_2 \le 10 \\ 4.8 \le x_3 \le 9 \\ \hline x_4 \in [\mathrm{Tp}_1, \mathrm{Tp}_2, \mathrm{Tp}_3, \mathrm{Tp}_4, \mathrm{Tp}_5, \mathrm{Tp}_6] \\ x_5 \in [\mathrm{AC}_1, \mathrm{AC}_2, \mathrm{AC}_3, \mathrm{AC}_4, \mathrm{AC}_5, \mathrm{AC}_6, \mathrm{AC}_7] \end{array} \right. \end{array} \right. \tag{3}$$

where

f_1: lifecycle cost of refurbishment for considered building ($).

f_2: Number of non-thermoneutral hours experienced during a heatwave year (hrs.).

x: Combination of design variables being optimized.

x_1: Thickness of insulation layer at exposed walls (cm).

x_2: Size of windows at south wall (m^2).

x_3: Size of windows at west wall (m^2).

x_4: Type of windows (-).

x_5: Size of air conditioning system (BTU).

The insulation thickness is assumed to be uniform across all exposed walls since the considered building is located in an urban region and surrounded by buildings that act as shading elements; this reduces the need for varying thickness per orientation. The optimization process includes three categorical variables which are the type of windows, the air conditioning system, and the thickness of insulation; and two continuous variables which are the sizes of windows in the south and west façades. The placement of windows on these two sides is a common practice in the architectural design of the Mediterranean region to benefit from winter sun [47].The types of windows considered, and the thickness of the insulation layer are fixed to options that are readily available in the market. The costs and thermal parameters of considered windows are adopted from a study done for the considered region [48] and initial cost of air conditioning system is adopted from [49]**.** the thermal insulation is considered to be polystyrene with a density, specific heat capacity, conductivity of 70 Kg/m^3, 830 $J/Kg^1 \cdot K^1$, and 0.04 $W/m^1 \cdot K^1$ [50]. Table 1 presents the refurbishment parameters being optimized in the study and the options considered for each parameter, including the thickness and cost of insulation for exterior walls, the type and size of windows on the south and west sides, and the rated cooling capacity and cost of different AC systems.

4.3.1. Lifecycle cost of refurbishment

The first objective function, f_1 is the lifecycle cost of refurbishment, which includes both the initial cost of design solutions and the corresponding lifecycle operational costs. In the current problem, the initial cost comprises the expenses associated with the windows, air conditioning system, and insulation material. The cost of windows is a function of their size and type, while the cost of the air conditioning system is determined by its capacity. The cost of insulation material is influenced by multiple factors including the material price and installation fees per unit volume, the thickness of the insulation layer, and the area of non-glazed exterior walls. The operation cost throughout the life cycle years is determined by multiplying the predicted annual operating cost of the building (C_{opr}) by a present worth factor (PWF). C_{opr} is calculated as the total electric energy consumption of the building, factoring in the electrical usage of heating and cooling systems, lights, and ceiling fan, multiplied by the electricity rate. The lifecycle cost of refurbishment can be expressed as:

$$f_1(x) = \mathrm{PWF}.\mathrm{C_{opr}} + \mathrm{A_{win}}.\mathrm{C_{win}} + \mathrm{V_{ins}}.\mathrm{C_{ins}} + \mathrm{C_{AC}} \tag{4}$$

where:

f_1: lifecycle cost of refurbishment for considered building ($).

PWF: Present worth factor; depends on lifecycle years and interest rate (-).

C_{opr} : annual operating cost of the building – current year ($).

A_{win}: Total area of windows (m^2).

C_{win} : Cost of window per unit area $(/m^2)$.

V_{ins} : Total volume of installed insulation (m^3).

C_{ins}: Cost of insulation per unit volume $(/m^3)$.

C_{AC}: Initial cost of air conditioning system ($).

4.3.2. Evaluating performance of buildings during heatwave events

The second objective function $f_2(x)$ is represented by the number of hours T_{in} exceeds the thermoneutral elderly threshold T_5 during a heatwave year. It can be formulated as follows:

$$f_2(x) = \sum_{k=1}^{N} (\mathrm{a}_k\, \mathrm{t}_k); \mathrm{a} = \{1 \text{ if } \mathrm{T}_{\mathrm{in},k} > \mathrm{T}_5,\ 0 \text{ otherwise}\} \tag{5}$$

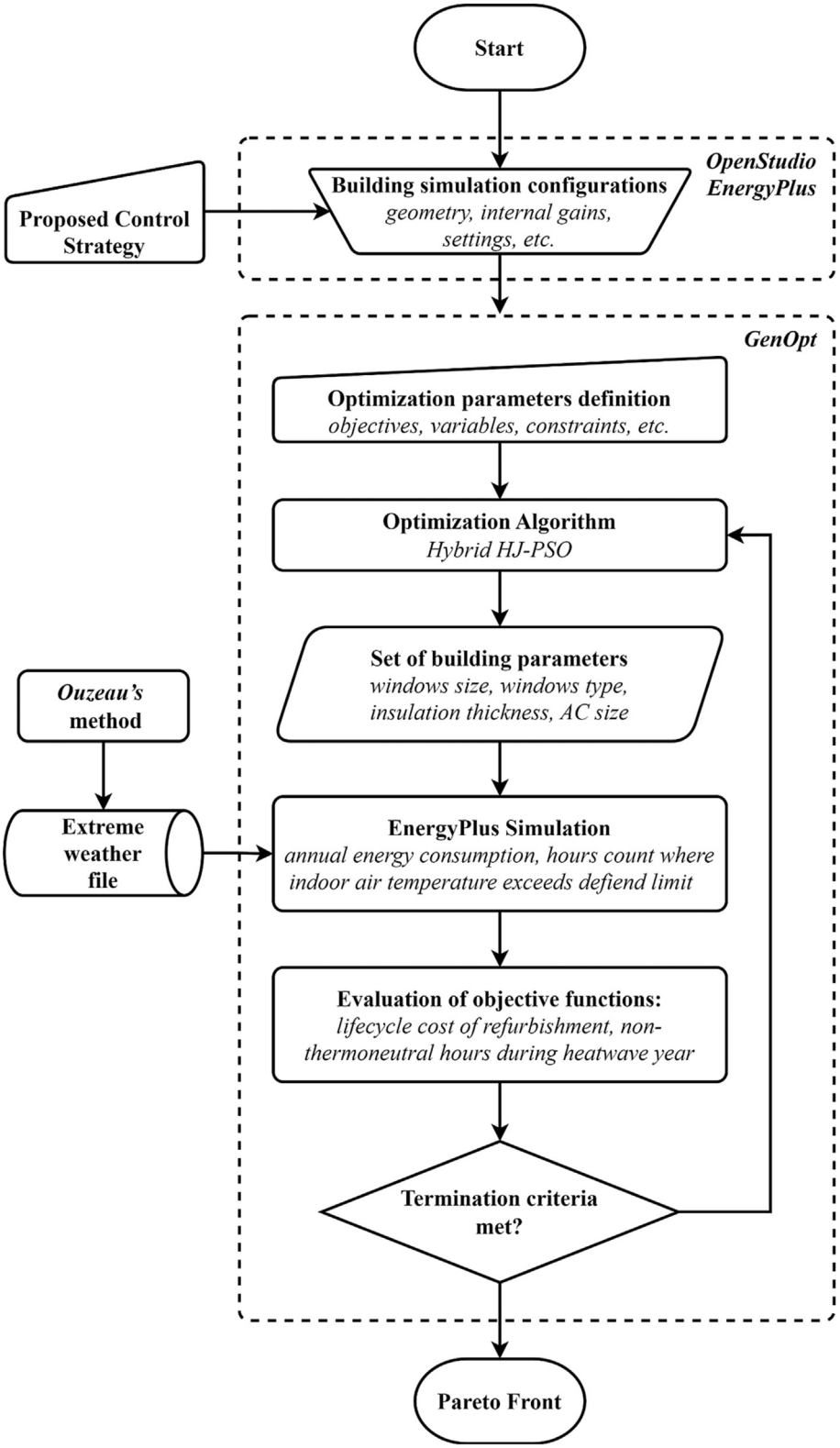

Fig. 3. Flow diagram of the multi-objective optimization procedure targeting the reduction of both the lifecycle cost of refurbishment of a typical elderly home and the number of non-thermoneutral hours during a heatwave year.

where:

f_2: Number of non-thermoneutral hours experienced during a heatwave year (hrs.)

k: Simulation time counter (-)

N: Simulation time (hrs.)

t: Simulation timestep (hrs.)

Ouzeau method [51] is employed in this research to detect and characterize heatwaves, after which a heatwave year is selected as the focus. The method, which was originally developed for France and successfully used to forecast future heatwaves in Paris [52],

Table 1
Refurbishment parameters being optimized with considered options.

Refurbishment Parameter	Options
Exterior Walls Insulation [50]	No insulation Polystyrene: $\rho = 70\,\mathrm{Kg/m^3}; k = 0.04\,\mathrm{W/m \cdot K}; Cp = 830\,\mathrm{J/Kg \cdot K}; C_{ins} = 130/m^3$;thickness (cm)$\in$ [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]
Type of Windows [48]	**Tp_1:** Single clear 6 mm; U = 5.8 $W \cdot m^2/^\circ C$; SHGC = 0.81; C_{win}= 29.97 $/m^2$ **Tp_2:** Single bronze 6 mm; U = 5.8 $W \cdot m^2/^\circ C$; SHGC = 0.65; C_{win}= 38.75 $/m^2$ **Tp_3:** Single low-e 6 mm; U = 4.270 $W \cdot m^2/^\circ C$; SHGC = 0.59; C_{win}= 72.34 $/m^2$ **Tp_4:** Double clear 6/6/6 mm; U = 3.163 $W \cdot m^2/^\circ C$; SHGC = 0.7; C_{win}= 65.88 $/m^2$ **Tp_5:** Double bronze 6/6/6 mm; U = 3.160 $W \cdot m^2/^\circ C$; SHGC = 0.55; C_{win}= 77.34 $/m^2$ **Tp_6:** Double low-e 6/12/6 mm; U = 1.658 $W \cdot m^2/^\circ C$; SHGC = 0.4; C_{win}= 102.05 $/m^2$
Size of Windows	South side window area ($h \times w$): $h = 2m, 1.5m \leq w \leq 5m$ West side window area ($h \times w$): $h = 2m, 2.4m \leq w \leq 4.5m$
Size of AC system [49]	**AC_1:** Rated cooling capacity = 5,000 BTU (1.47 kW);$C_{AC} = 293$ **AC_2:** Rated cooling capacity = 6,200 BTU (1.82 kW);$C_{AC} = 363$ **AC_3:** Rated cooling capacity = 8,000 BTU (2.05 kW);$C_{AC} = 410$ **AC_4:** Rated cooling capacity = 9,000 BTU (2.34 kW);$C_{AC} = 469$ **AC_5:** Rated cooling capacity = 10,000 BTU (2.64 kW);$C_{AC} = 527$ **AC_6:** Rated cooling capacity = 11,000 BTU (2.93 kW);$C_{AC} = 586$ **AC_7:** Rated cooling capacity = 12,000 BTU (3.52 kW); $C_{AC} = 703$

was modified for use in other climates by adjusting its thresholds based on historical meteorological data from the specific location being investigated [53]. The method examines average daily temperatures $\left(\bar{T}_{day}\right)$ and is based on three thresholds: the temperature beyond which a heatwave is identified (S_{pic}), the temperature that defines the start and end of the heatwave (S_{deb}), and an interruption threshold (S_{int}). When the temperature crosses the S_{pic}, a heatwave is recognized; its beginning is defined by the first day for which S_{deb} is exceeded; and its end is defined by going back below S_{deb} for 3 consecutive days or falling to values below S_{int}. The approach requires events that last 5 days or more. The threshold temperatures S_{pic}, S_{deb}, and S_{int} are determined as the 99.5th, 97.5th, and 95th percentiles of the distribution of daily mean temperatures over a 30-year period, respectively. Measured climatic data from 1993 to 2022 from *Rafic-Hariri International Airport* is used to calculate the thresholds. Table 2 presents the threshold temperatures for detecting and characterizing heat waves calculated for Beirut, based on *Ouzeau's* method using 30 years of measured climate data, and benchmarked with thresholds derived at different locations from the literature, including Buenos Aires, Argentina and the French territory. The temperature thresholds for Beirut are higher than those of France and Buenos Aires, which is expected due to the warmer climate.

Once a heatwave has been identified, it can be characterized by 3 parameters: its duration, intensity, defined as the highest mean daily temperature that occurred during the heatwave, and global severity, which is defined by the aggregated mean daily temperatures above S_{deb} divided the difference of S_{pic} and S_{deb}:

$$GlobalSeverity = \sum \frac{\left(\bar{T}_{day} - S_{deb}\right)^{+}}{S_{pic} - S_{deb}} \tag{6}$$

To assess the impact of refurbishment on resilience, the severity of indoor conditions during a heatwave event is compared between the refurbished case and a baseline case. The Indoor Overheating Degree (IOD) is employed as a metric to assess the intensity of indoor conditions in a heat wave; IOD is defined as the sum of positive values of the difference between the zonal indoor operative temperature and the zonal thermal comfort limit over the total number of occupied hours. The operative temperature ($T_{in,op}$) can be calculated from the air temperature, mean radiant temperature, and air velocity [54]. In this analysis, the focus is on identifying suboptimal indoor conditions for elderly occupants in a single, constantly occupied zone. Therefore, IOD is adjusted to the sum of positive values of the difference between the $T_{in,op}$ and the elderly fan-activated thermoneutral threshold T_5, over the simulation time (N):

$$IOD = \frac{\sum_{k=1}^{N}\left[\left(T_{in,op,k} - T_5\right)^{+} t_k\right]}{N} \tag{7}$$

where:
k: Simulation time counter (-).
N: Simulation time (hrs.).
t: Simulation timestep (hrs.).
$T_{in,op,k}$: Indoor operative temperature at time k (°C).
T_5 : Indoor temperature threshold corresponds to elderly TS of 0.5 under ceiling fan effect (°C).

Table 2
Thresholds for detecting and characterizing heat waves in Beirut using *Ouzeau's* method based on 30 years of measured climate data (1993–2022) benchmarked with thresholds derived at different locations from the literature.

Location and date of meteorological data	S_{pic} (°C)	S_{deb} (°C)	S_{int} (°C)
Beirut, Lebanon, 1993-2022 (*Current study*)	30.21	29.11	28.69
Buenos Aires, Argentina, 1991–2020 (*Larsen et al.* [53])	28.9	27.2	26.2
Whole French territory, 1947–2006 (Operational method in France [51])	26	23	20

4.3.3. Optimization method and algorithm

There are two methods for solving multi-objective optimization problems: Pareto and scalarization. The study opted for the Pareto method as it enables the recognition of trade-offs between conflicting objectives, leading to a better-informed decision-making process. Pareto optimal solutions (*also known as non-dominated solutions*) refers to a state where no improvement can be made in one objective function without compromising the other; these solutions can be displayed in the form of a Pareto front. Among Pareto solutions, the solution with the shortest Euclidean distance from the "Utopia point" (an ideal point that minimizes all objectives simultaneously) in the objective space is chosen as an optimal solution [55].

This study uses a hybrid algorithm of the Generalized Pattern Search (GPS) *Hooke-Jeeves* (HJ), and the Particle Swarm Optimization (PSO) algorithms within the *GenOpt* program [56]. The PSO-HJ algorithm is capable of handling mixed continuous and discrete independent variables which makes it suitable for the considered problem. The PSO algorithm is a population-based method that simulates the movement of particles in a search space with each particle, while the HJ is a direct search method that iteratively improves parameters by making small incremental changes and evaluating the objective function at each step. In a hybrid PSO-HJ algorithm, PSO is used for initial search and HJ for fine-tuning the final solution, resulting in an efficient and robust optimization process. For more information about the functioning of the HJ and PSO algorithms, refer to [57,58].

5. Case study

A case study was conducted using a validated building model to examine the effectiveness of the optimization process and the control strategy for a building located in the Mediterranean climate. A typical apartment representative for residential apartments of the city of Beirut costal Mediterranean city, is adopted from *Annan et al.* study and modeled in *EnergyPlus* [46]. The apartment is located on the fifth level of a 10-story reference residential building surrounded by urban structures and oriented 24°from the north counterclockwise as shown in Fig. 4**.** Heat transfer between the studied apartment and the above and lower floors is neglected. The neighboring buildings of the apartment understudy are modeled as shading elements as shown in Fig. 4 **(a)**. The optimization procedure and control strategy will be applied to **Thermal Zone I** shown in Fig. 4 **(b)**, which is considered to be occupied by two elderly individuals and has the outlined systems in place. The other rooms, represented by **Thermal Zone II**, are modelled to be naturally ventilated without allowing for cross ventilation between the two zones.

The construction materials and window-to-wall ratio are adjusted to Beirut city standards [59,60]. Typical construction materials for Beirut city [59] of 25 cm concrete sandwiched between lightweight 5 cm plaster layers with a U-value of 1.8 $W/m^2 \cdot K$ [46] are set as wall construction materials in *EnergyPlus*. Windows are considered single glazed, made of 6 mm clear glass [46] with solar heat gain coefficient (SHGC) of 0.81 and a U-value of 5.8 $W/m^{2\cdot\circ}C$ [48]. The thermal zone is assumed to be always occupied and the metabolic heat generation is set to that of elderly people [32]. An HVAC system consisting of an outdoor air mixer, direct expansion heating (COP_{rated} = 4.3) and cooling coils (COP_{rated} = 3.3), and a constant volume supply air fan ($\eta = 0.7$, $\Delta P = 500$ Pa) [44] is defined for heating and cooling the building in *Energy Plus*. The sizing of the HVAC system for the baseline scenario, in which the building incorporates standard building parameters, is performed using the *Energy Plus* sizing function, and is based on peak TMY weather data. During the optimization process for elderly housing design, the HVAC system size is treated as a variable, and the available options for system size are restricted to the standard sizes commonly available in the market. The life cycle of the apartment used in calculating the total operational cost is set to 25 years. As for the economic parameters, the electricity rate is set to 0.133 $/kWh and the interest rate is considered to be 5% as defined in previous work for the considered region [50]. The accuracy of the input parameters and settings in the baseline building model, which adheres to the typical building parameters for Beirut, is confirmed by comparing the predicted mean indoor temperatures for a 24-hour period on July 26, 2013 to measured indoor temperatures for the same building reported in literature [46]. The indoor temperature is selected for validation since it serves as primary parameter upon which the control strategy is based.

6. Results and discussion

The results section of this study is divided into five subsections. The first subsection focuses on the validation of building model. The second subsection describes the results of employing the elderly bioheat and TS models for obtaining control thresholds for the proposed control strategy. The third subsection discusses the results of detecting and characterizing heatwave events in Beirut city. The fourth subsection discusses the proposed control strategy's effectiveness in maintaining the thermally neutral indoor conditions while saving energy. At this stage, the control strategy is applied to an apartment with typical building parame-

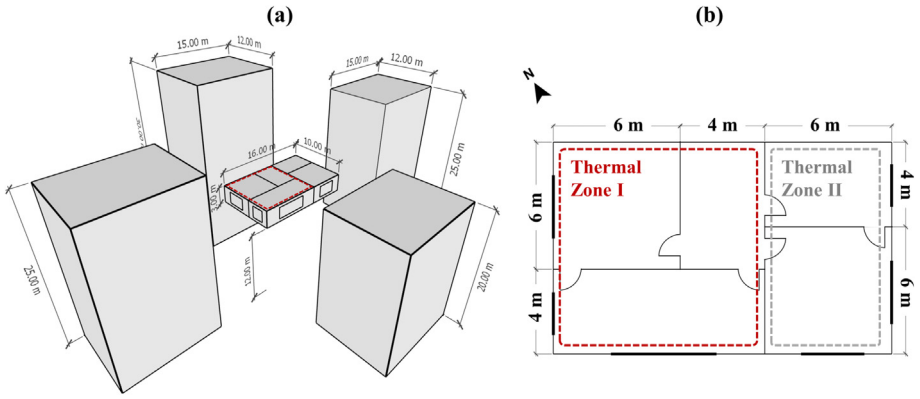

Fig. 4. (a) 3D view of the case-study apartment in urban setting, showcasing surrounding shading buildings [41] (b) Floor plan layout of the apartment understudy with the specified simulation thermal zone.

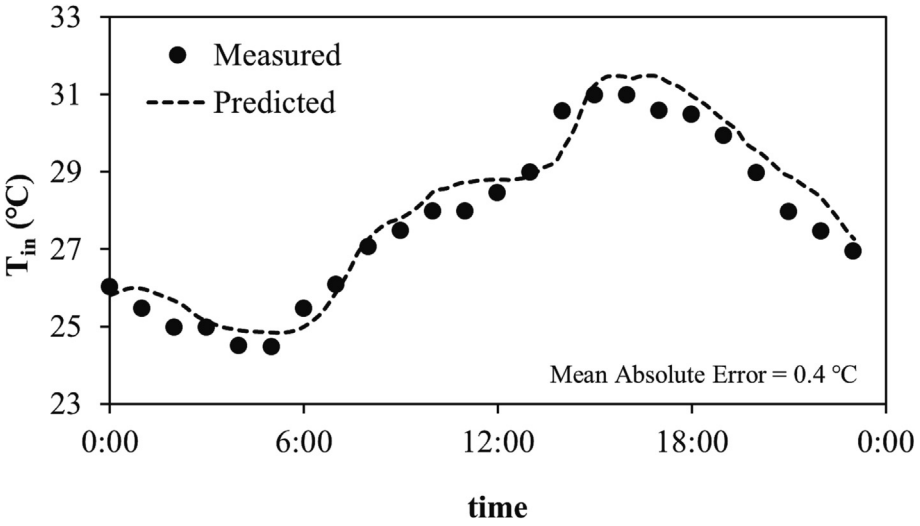

Fig. 5. Validation of the prediction of EnergyPlus dynamic building energy model against measured mean room temperature in the studied apartment on July 26, 2013 [56].

ters that adhere to standards. The final subsection presents the results of the multi-objective optimization aimed at minimizing lifecycle costs and ensuring the resilience of elderly housing through refurbishment. It discusses the lifecycle costs and resilience associated with selecting different refurbishment parameters, Pareto optimal solutions, and an assessment of the impacts of using optimal refurbishment parameters on energy consumption and the resilience of the building. To analyse the impacts of the strategy and the refurbishment separately, three cases are compared: i) a building with standard parameters- always conditioned; ii) a building with standard parameters applying the proposed control strategy; iii) a building with optimal refurbishing and operational parameters while applying the control strategy.

6.1. Building energy model validation

The *EnergyPlus* model has been widely validated in the literature; nonetheless, to check the correctness of the inputs and settings, predicted indoor temperature was compared to hourly measured data from July 26, 2013. Fig. 5 shows a comparison between the predicted room temperature by *EnergyPlus* and measured room temperature in the studied apartment. The results indicate a good agreement between the predicted and measured temperatures with a mean absolute error of 0.4 °C, confirming the accuracy of the *EnergyPlus* model for this specific use case. Validating the building model improves optimization result reliability since accuracy of optimization depends on building model accuracy. Additionally, employing a hybrid algorithm for optimization mitigates the risk of local minima and reduces the effect of initial guessed values, resulting in more reliable optimization results.

6.2. Thresholds for the proposed control strategy

Table 3 displays the air temperature thresholds for the proposed control strategy obtained via employing the elderly bioheat model and the elderly thermal sensation model. $\mathbf{T}_1$, denoting the minimum temperature that an elderly person wearing typical winter clothing should be exposed to, is determined to be 23.7 ℃. In the case of an elderly person wearing typical summer clothes, the maximum temperature they should be exposed to is 27.4 ℃ without a fan, 28.9 ℃ with a fan operating at low mode, and 29.6 ℃ with a fan operating at high mode. Consistent with recent experimental studies [61], the thermoneutral temperature for this individual is determined by the TS model to be 26.1 ℃ when a fan is not in use.

6.3. Heatwave events in Beirut city in the period (1993–2022)

Ouzeau's approach was used to detect and characterize heatwaves in Beirut throughout the period (1993–2022). Fig. 6 displays the results in the form of a bubble chart, which shows the peak daily mean temperature, duration, and global intensity of each heatwave event detected in Beirut during the specified period. Results indicate that the duration of these heatwaves varied from a minimum of 5 days to a maximum of 41 days. Additionally, the intensity of these heatwaves was found to range from 30.3 °C to 32.8 °C and the global severity of the heatwaves was found to range from 2.5 to 15.9. The majority of the heatwaves during this period were found to last less than 15 days. The longest and most severe heatwave of the studied period occurred in July 2012 and was selected for further analysis to investigate ways to increase the resilience of buildings to such extreme events.

6.4. Impact of proposed control strategy on indoor climate and energy usage

The *EnergyPlus* simulation tool was utilized to model the proposed control strategy on a baseline building that adheres to standard building parameters. The impact of the control strategy was first assessed on the indoor conditions of the building and then on its energy consumption. TMY weather data was utilized to define the outdoor environmental conditions; HVAC system capacity was based on peak TMY weather.

Fig. 7 shows the variations of T_{out} and T_{in} as well as the operational mode set by the proposed control strategy for natural ventilation (**NV**), ceiling fan (**Fan**) mechanical cooling (**AC**), and

Table 3
Thresholds for the proposed control strategy determined through the use of the elderly bioheat model and the elderly thermal sensation model.

Threshold	Fan Mode	Clothing	Elderly TS	Value (℃)
$\mathbf{T}_1$	Off	Winter	−0.5	23.7
$\mathbf{T}_2$	Off	Summer	0	26.1
$\mathbf{T}_3$	Off	Summer	0.5	27.4
$\mathbf{T}_4$	Low	Summer	0.5	28.9
$\mathbf{T}_5$	High	Summer	0.5	29.6

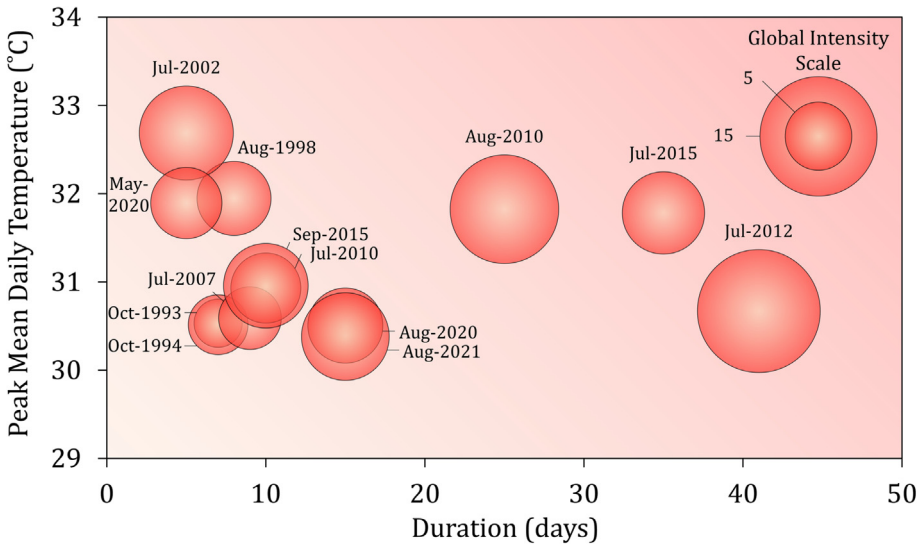

Fig. 6. Heat waves detected by Ouzeau's method in Beirut for the period 1993–2022. (*Vertical axis corresponds to the peak daily mean temperature (°C) reached during the heatwave event; Bubble size represents the global severity of the heatwave as defined by the method*).

mechanical heating (**H**) in representative days from **(a)** March, **(b)** August, and **(c)** September. The days were selected to reflect different scenarios of controller operation.

On the selected day of March, between 0:00–5:00 hr, T_{out} was 14 °C, heating was turned on to maintain T_{in} at 23.7 °C. After 5:00 hr, the building received solar heat gains, so windows were closed, and heating was turned off. T_{in} rose to 24.5 °C and gradually decreased as solar gains decreased.

On the selected day of August, natural ventilation cooled the indoor space during the night until T_{in} dropped below 26.1 °C, resulting in the predicted TS level for the elderly falling below 0, thus causing the windows to be closed. As the day progressed, T_{in} began to increase, triggering a series of actions by the controller. The windows were opened when T_{in} exceeded 26.1 °C, followed by the activation of the ceiling fan, first in low mode, then in high mode. Finally, the AC system was activated in conjunction with the ceiling fan to maintain desired indoor conditions. When T_{out} and solar heat gains began to drop at 19:00, the AC system was turned off and the windows were opened. The gray shaded areas in the figure represent the hours of natural ventilation. It is evident that utilizing natural ventilation and the ceiling fan has led to delayed and shorter usage of the AC system. Additionally, operating the ceiling fan in conjunction with the air conditioning system results in a reduced cooling load, as the AC system operates at a higher setpoint temperature (29.6 °C).

On the selected day of September, between 0:00–7:00, T_{in} was thermoneutral for elderly, thus windows were closed, and no system was operated. At 7:00, T_{in} rise above 26.1 °C causing windows to be opened. At 8:30, T_{in} rise above 27.4 °C, causing the fan to be activated at low mode. At 19:30, T_{in} dropped to below 27.4 °C, causing the fan to be turned off. It is evident that natural ventilation and the ceiling fan have achieved the desired indoor conditions without the use of mechanical systems.

The findings indicated that the available space conditioning systems were used selectively and optimally to maintain the desired indoor conditions. Natural ventilation was the preferred option and used whenever possible, while the use of mechanical HVAC systems was delayed and minimized by utilizing natural ventilation and ceiling fans. Moreover, results showed that HVAC systems were operated at optimal setpoint temperatures that met the thermal needs of elderly individuals without overheating or cooling the space. These trends in the data confirmed that using the proposed control strategy was effective in ensuring suitable indoor conditions for elderly people at a low cost.

Fig. 8 provides a clear illustration of the impact of the control strategy on energy usage in a building. It shows a comparison of the annual heating and cooling energy consumption of a building that employs the control strategy versus a building that is always conditioned and uses heating and cooling setpoint temperatures of 23.7 °C and 26.1 °C. The heating energy consumption was the same in both scenarios, as the same setpoint temperature was used. However, there was a significant reduction in cooling energy consumption when the control strategy is implemented, with a decrease of 1973 kWh per year (61%). The breakdown of the cooling energy consumption in Fig. 8 further illustrates the impact of the control strategy. The always-conditioned building consumed 3220 kWh per year for cooling, while the building with the control strategy consumed only 1247 kWh per year with the ceiling fan accounting for 95 kWh per year and the mechanical cooling accounting for 1152 kWh per year. The reduction in total cooling energy consumption was achieved by prioritizing natural ventilation, using ceiling fans, and optimizing the cooling system at a higher setpoint temperature.

6.5. Optimal refurbishment parameters for elderly homes

This subsection presents the results of the multi-objective optimization procedure for elderly housing refurbishment. The optimization procedure was carried out for an apartment that implements the proposed control strategy. The weather file used in this analysis is from 2012, which included a heatwave event.

Fig. 9 shows how the results of the multi-objective optimization are spread out in the objective space, with some solutions being grouped together based on similar refurbishment parameters. This grouping was accomplished by utilizing the K-means clustering method [62]. The method was used to generate 16 clusters, but only 6 are presented; the remaining ones are designated as "non-clustered data". The rationale behind this was that the 6 clusters were adequate to examine the influence of refurbishment parameters on the objectives and provide general recommendations with clear justification.

Cluster-1 included solutions that feature an AC unit with the lowest capacity of 5000 BTU, windows with a moderate size rang-

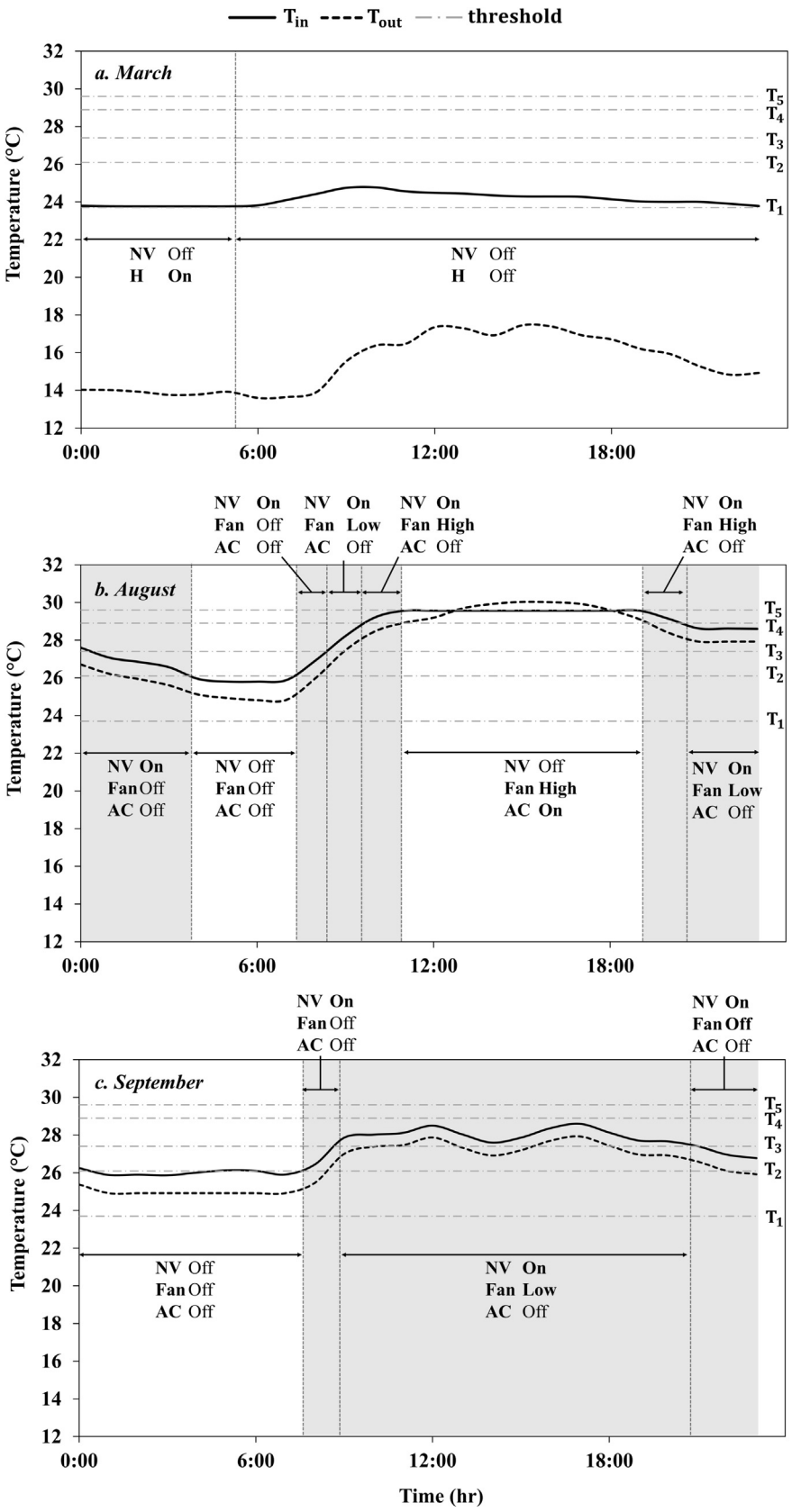

Fig. 7. Proposed control strategy implementation in elderly houses: Tin, Tout (TMY), controller thresholds and modes of operation set by the strategy for the representative days: (a) March 26, (b) August 19, and (c) September 17.

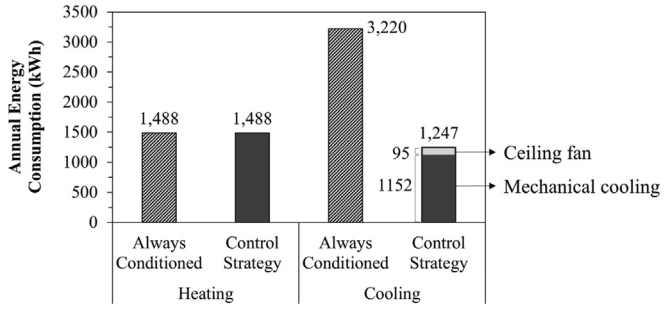

Fig. 8. Annual electricity consumption for heating, cooling, and ceiling fan in the studied apartment: comparison between the always-conditioned scenario and the scenario with the proposed control strategy.

ing from 9.96 to 12.36 m^2, basic window type (TP_1), and insulation layer thickness ranging from 0 to 2 cm. While this cluster had the lowest initial cost, ranging from \$647 to \$1094, the operational cost was the highest, ranging from \$3360 to \$3999. The figure showed that this cluster was in the low lifecycle cost – high non-thermoneutral hours region within the objective space, indicating high vulnerability to heatwave events.

Cluster-2 consisted of solutions with the smallest AC size (5000 BTU), the lowest windows sizes (7.8 to 9.8 m^2), basic or slightly enhanced window types (Tp_1 and Tp_2), and 2 cm thick insulation. Although this cluster had a higher initial cost than **Cluster-1** (\$985 to \$1125), its operational cost was lower (around \$3250). This cluster was in the optimal location in the objective space, with low lifecycle cost and low non-thermoneutral hours.

Clusters 3, 4, 5, and **6** had very low non-thermoneutral hours, near zero, indicating very good resilience to heatwave events. **Clusters 3** and **4** had a mid-range lifecycle cost, while **Clusters 5** and **6** had high lifecycle costs. **Cluster 5** was the most sustainable option with the lowest operational cost but had the highest initial cost. In this configuration, the presence of large-sized windows with large AC system allowed for enhanced natural ventilation while still maintaining resilience to heatwaves. Moreover, high insulation thickness and enhanced thermal performance of windows led to lower cooling load. This combination of improved natural ventilation and reduced cooling load led to decreased operational expenses, although the setup required high upfront investment. Having detailed the results in the figure, the following observations were deduced:

i) Increasing the size of the AC system can help improve the building's resilience to heatwaves by providing the desired indoor conditions even during extreme outdoor weather. However, this came at a higher lifecycle cost as the initial and operational costs of the AC system increased with its size.
ii) Although larger windows can enhance the cooling effect of natural ventilation, they also increase solar heat gains, which have a more prominent impact under abnormally hot outdoor conditions. The heatwave resilience of the building may be jeopardized if the enlargement of the windows is not accompanied by increasing AC size and/or enhancing envelope characteristics.
iii) The use of enhanced thermal-characteristic windows may incur higher upfront expenses for refurbishment, but it can yield long-term benefits by reducing operational expenses. This is because such windows have reduced convective and solar radiative heat gains, leading to lower cooling loads. This finding aligns with the conclusion of *Sun et. al.* study

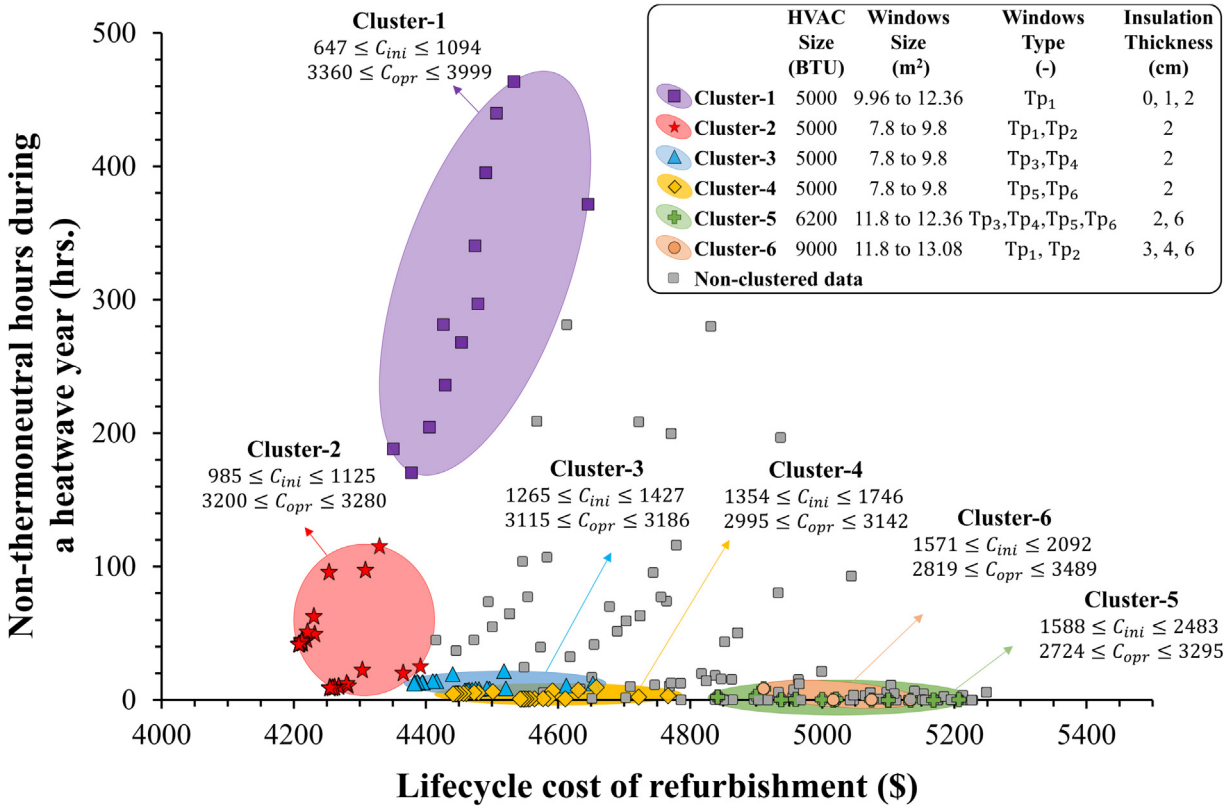

Fig. 9. Distribution of multi-objective optimization solutions in objective space grouped based on similar refurbishment parameters. C_{ini}: Initial cost of refurbishment (\$); C_{opr}: lifecycle operational cost (\$).

that enhancing the radiative properties of windows results in decreased energy consumption in cooling-dominant climates [34]. On the other hand, enhancing the conductive properties of windows led to lower cooling and heating loads, while improving the radiative properties decreased cooling load but increased heating load, which is attributed to the reduced solar heat gains during winter. This was observed through a comparison of windows with different U-values and SHGCs, including Tp_4 (double-glazed), Tp_2 (tinted), and Tp_1 (baseline).

iv) Increasing the thickness of the insulation layer can result in lower cooling and heating loads, which can lead to reduced operational costs and improved resilience. However, the initial investment must be weighed against the long-term benefits to determine the optimal thickness. This aligns with *Sun et. al.'s* study, which confirmed that insulation enhances energy efficiency and heat resilience [34].

v) Refurbishment parameters were interdependent, meaning that an optimal combination should be utilized to achieve both cost-effectiveness and heatwave resilience. For exam-

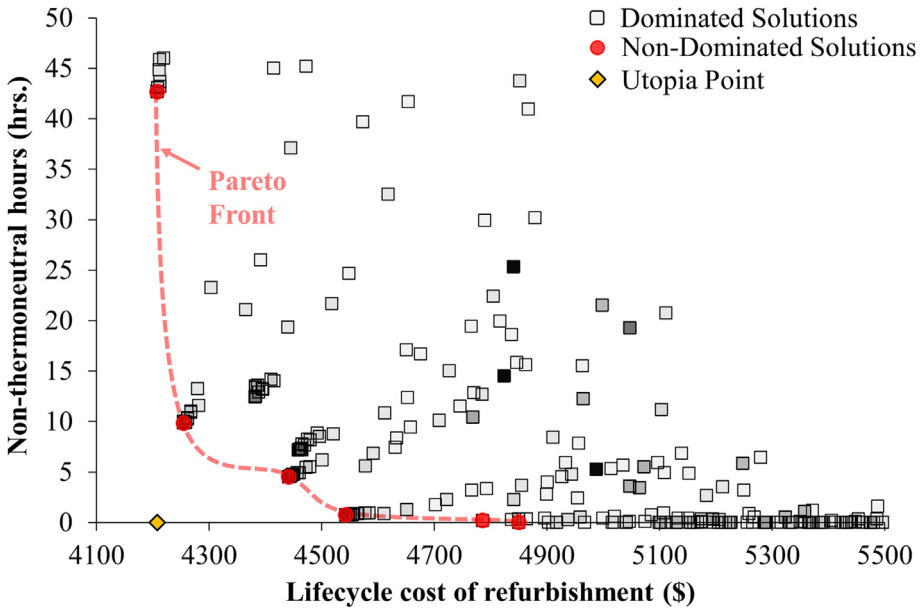

Fig. 10. Pareto Front Resulting from the Multi-Objective Optimization Procedure, Depicting the Utopia Ideal Point, Dominant Solutions, and Non-Dominated Pareto Solutions.

Table 4
Pareto solutions depicting building parameters and corresponding life cycle cost of refurbishment and non-thermoneutral hours in a heatwave year, including Euclidean distance from utopia point in a normalized objective space.

Window type	Window Size	AC size	Insulation thickness	Annual energy use	Initial cost*	Operational cost (25 years)	Lifecycle cost of refurbishment	Non-thermoneutral Hours	Distance from Utopia**
(-)	(m^2)	(BTU)	(cm)	(kWh)	($)	($)	($)	(hrs.)	(-)
T1	7.8	5,000	2	1,710	985	3,223	4,208	42.7	0.06
T2	**7.8**	**5,000**	**2**	1,698	1,053	3,201	4,255	**10.0**	**0.02**
T5	7.8	5,000	2	1,637	1,354	3,087	4,441	4.5	0.07
T6	7.8	5,000	2	1,589	1,547	2,996	4,543	0.8	0.09
T1	11.8	8,000	2	1,866	1,270	3,516	4,786	0.2	0.16
T2	11.8	5,000	2	1,845	1,373	3,477	4,850	0.0	0.18

* *The total initial cost refers to the cost of windows, air conditioning system, as well as the capital and installation costs for insulation*

** *The Euclidean distance from Utopia calculated in a normalized objective space*

ple, combining a small air conditioning system with a large window size can lead to compromised resilience. On the other hand, combining high insulation thickness with high AC capacity can lead to unnecessary and high lifecycle costs. Therefore, a careful balance between these parameters would be required to maximize refurbishment benefits.

The results obtained from the optimization process can be used to provide general recommendations for designing cost-effective, energy efficient, and heatwave resilient elderly housing under the studied Mediterranean climate. Based on the findings, it is recommended that elderly dwellings are characterized by a limited window area, modest air conditioning system, windows with some

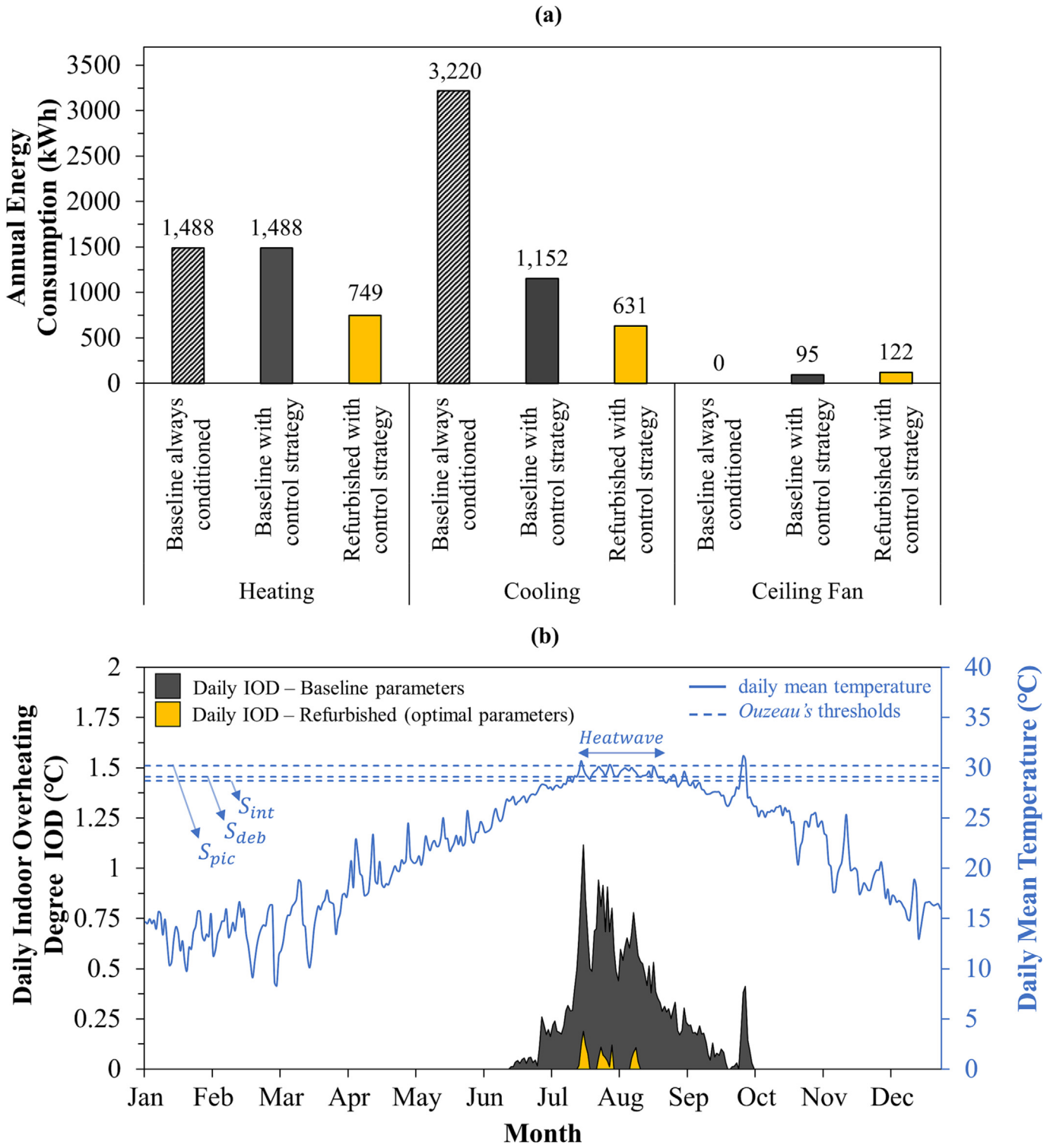

Fig. 11. (a) Annual energy consumption comparison (b) Comparison of daily indoor overheating degree for a baseline case with typical parameters versus optimal discovered parameters.

degree of enhanced thermal properties, and thin insulation layer. This configuration can lead to satisfactory results in managing heatwaves without incurring high upfront expenses, making it a viable option for the low-income population. In situations where the initial cost of investment is not a major consideration, elderly housing can benefit from reduced operational costs and improved sustainability by integrating bigger windows with better thermal properties and a larger AC system.

The next step is to systematically select an optimal combination of refurbishment parameters from the numerous solutions displayed and compare its effects on energy savings and heatwave resilience with a baseline scenario in which the building conforms to country standards [59]. Fig. 10 shows the results of a multi-objective optimization procedure in the form of a Pareto front plot, which depicts the trade-offs between two objectives. The plot reveals both dominated and non-dominated solutions, where dominated solutions were inferior to other solutions in at least one objective, and non-dominated solutions were those that were not inferior in any objective when compared to any other solution. The plot presented a range of solutions that balance two objectives: minimizing the lifetime refurbishment cost and minimizing the number of non-thermoneutral hours. The Pareto front represented the best trade-offs between these objectives, allowing decision-makers to choose the solution that best suits their needs. Within the set of non-dominated solutions, there were two solutions with distinct trade-offs. The first solution minimized the lifecycle refurbishment cost, resulting in a cost of $4,208, but had 42.7 non-thermoneutral hours during the heatwave year. The second solution minimized the non-thermoneutral hours, resulting in zero non-thermoneutral hours, but had a higher lifecycle cost of $4,850. A method of selecting the optimal solution from the set of non-dominated solutions was to choose the solution closest to the Utopia point, which represents the ideal scenario of minimizing both objectives simultaneously. The Utopia point in this case corresponded to a solution with a lifecycle cost of $4,208 and zero non-thermoneutral hours.

Table 4 presents the set of Pareto optimal solutions along with their Euclidean distance from the Utopia point, optimization variable values, and cost functions. Consistent with previous literature [34], comparing the first row (low lifecycle cost — low resilience potential) and last rows (high lifecycle cost — high resilience potential) of the table suggests that building retrofit processes should take into account measures that enhance heat resilience, even if they are not cost-effective solely in terms of energy savings and initial cost. The solution highlighted in the table was determined to be the closest to the Utopia point in a normalized objective space and was selected for further analysis. This solution involved implementing the minimum window size of 7.8 m^2, minimum capacity air conditioning system of 5,000 BTU (1.47 kW), 2 cm thick insulation layer, and T2, bronze tinted single glazed windows. The resulting lifecycle refurbishment cost was calculated to be $ 4,255 and the number of non-thermoneutral hours during the heatwave year was 10 h. This solution served as the basis for comparison against the baseline case in terms of energy efficiency and resilience to extreme weather events in the following analysis.

The fourth row in the table represents a notable combination of building parameters that resulted in the lowest yearly energy consumption and operating expenses, making it the most sustainable choice compared to others. Interestingly, this solution had the highest initial cost among the other alternatives. This particular combination of refurbishment parameters is advisable in situations where the initial cost is not the primary consideration, particularly in refurbishments that do not aim to serve low-income populations. The solution features T6 double-low-emissivity windows, small window sizes, 2 cm insulation thickness, and had a lifecycle cost of $4543, with only 0.8 non-thermoneutral hours during heatwave years.

The impact of refurbishment on energy efficiency was demonstrated by contrasting the electrical energy consumption for heating, cooling, and ceiling fan for the refurbished case with a typical apartment under TMY weather. To differentiate the effects of refurbishment from the control strategy, a further case of an always-conditioned typical apartment will be incorporated in the comparison. Fig. 11 **(a)** presents the comparison of the annual electricity usage for heating, cooling, and ceiling fans among the three described cases over a typical weather year. Refurbished buildings with the control strategy implemented resulted in a decrease of 35% (494 kWh/year) in heating energy consumption and 80% (2,589 kWh/year) in cooling energy consumption compared to the baseline always-conditioned building. These savings were caused by both the control strategy and the refurbishment. Comparing a refurbished and a typical building that both implement the control strategy reveals the distinct effect of refurbishment. This comparison showed a decrease in heating electricity consumption of 37% (554 kWh/year) and cooling electricity consumption of 45% (521 kWh/year) due to refurbishment. The reduction is attributed to the decrease in solar heat gains, heat transfer through walls, and the smaller air conditioning system size. The optimal parameters case also showed a 31% (29 kWh/year) increase in ceiling fan usage, indicating that the optimization improved the performance of the control strategy by increasing the reliance on the ceiling fan.

The Indoor Overheating Degree (IOD) for the refurbished apartment was compared to the IOD typical apartment during heatwave conditions to assess the impact of refurbishment on heatwave resilience as shown in Fig. 11 **(b)**. The HVAC system for the typical apartment was sized based on peak TMY weather data (1.82 kW). It is evident from the figure that IOD was non-zero during the heatwave period from July 15, 2012, to August 24, 2012, for both cases, signifying an undersized HVAC system for the heatwave event. Refurbishment reduced both the duration where IOD was non-zero and the IOD value itself. The baseline scenario resulted in a peak daily IOD of about 1 °C, whereas the optimal parameters scenario resulted in a peak daily IOD of around 0.2 °C, which was limited to a short time period.

The findings presented in this section suggest that the energy efficiency of a building can be improved, and its resilience to extreme weather events can be enhanced by selecting appropriate refurbishment parameters. This can be achieved without incurring high upfront costs. In other words, informed decision-making regarding the selection of refurbishment parameters can lead to a building that is both cost-effective and resilient to heatwaves.

7. Conclusions

In conclusion, the study proposed a novel approach to improving the sustainability and resilience of elderly housing while balancing cost-effectiveness and resilience to extreme weather conditions. This approach involved applying multi-objective optimization to identify optimal refurbishment parameters and proposing a control strategy to manage space conditioning systems in elderly houses.

The approach was applied to a case study of a representative elderly-occupied apartment in the Mediterranean climate. The results obtained from modelling the implementation of the control strategy demonstrate that, by utilizing real-time readings, an automated control system can maintain an optimal thermal environment for elderly residents in their apartments. This is achieved without requiring any input from the elderly residents themselves,

while also keeping costs low by utilizing natural ventilation and low-cost alternatives to mechanical HVAC systems wherever possible. To accommodate individual differences in thermal sensation among elderly occupants in this study, they were given the ability to alter the controller's settings. Future research could focus on developing adaptive techniques to learn each occupant's preferences from controller tweaks. As for the results for the optimization procedure, the following main findings were concluded:

- Choosing an optimal combination of building refurbishment parameters can result in a substantial reduction in heating energy (37%) and cooling energy (45%), while also preventing indoor overheating during heatwaves.
- Refurbishing low-income elderly houses in the Mediterranean climate with small windows featuring normal or slightly enhanced thermal properties glazing, thin insulation, and a moderate-sized air conditioning system can result in low-cost and heatwave-resilient designs.
- Refurbishing high income elderly houses in the Mediterranean climate with larger windows, improved thermal properties, and a larger air conditioning system can result in more sustainable, cost effective, and heatwave-resilient designs.

The control strategy proposed in this study can be applied to various climates. The associated energy savings, however, are climate-specific, as the use of natural ventilation and ceiling fans is strongly dependent on outdoor conditions. Additionally, the optimization methodology employed in this study can be adapted to other climates by adjusting parameters such as climatic inputs, economic factors, and market options. Furthermore, this optimization methodology can also be expanded to optimize design parameters such as building orientation and geometry during the design phase, thereby further improving the energy efficiency and resilience of buildings.

Findings from this study highlighted the importance of balancing the objectives of cost-effectiveness and resilience to extreme weather and suggested that architects and designers should consider these aspects concurrently during the design phase for a more holistic design. Ultimately, this study can contribute to enhancing the functionality of elderly-occupied built environments and providing more sustainable and resilient design solutions for constructing and renovating these structures.

Data availability

Data will be made available on request.

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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