

How effective are regulation-based passive retrofits in adapting social housing to overheating scenarios? [☆]

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ABSTRACT

Rising temperatures pose a significant challenge for obsolete buildings, which constitute up to 30% of Europe's building stock. Current energy renovation policies, while effective for decarbonization, exhibit a critical 'winter bias.' By prioritizing thermal insulation without mandating adaptive cooling strategies, these regulations risk locking social housing stock into a trajectory of structural overheating, exacerbating health risks in increasingly warm climates. Moreover, in situations where households cannot afford or use air-conditioning systems and high temperatures are frequent, building retrofits should prioritise both reducing winter heat losses and passively lowering indoor temperatures during the warmer season. This research, therefore, evaluates the effectiveness of these standards under climate change conditions by projecting towards a 2080-time horizon, analysing an archetypal mid-20th century social housing case, which operates passively like many of those in temperate and warm climates. Through an assessment with a prior diagnosis based on climate evolution scenarios, a thermo-energy analysis focused on passive comfort is carried out, analysing all representative dwellings of a whole neighbourhood. The results show that, while the initial retrofit based solely on current standards results in improvements in the cold season, summer conditions worsen and there is limited improvement on the annual average. As an alternative, this study proposes an adapted improvement based on intelligent ventilation control. This could be easily implemented in refurbished buildings, ensuring thermal comfort for more than 90% of the hours of the year without relying on active climate control systems.

1. Introduction

The escalating global temperatures driven by climate change (CC) are a stark warning to humanity. This worrisome trend is most obvious in cities, where overheating is magnified by the urban heat island (UHI) effect. Since the late 19th century, global mean air temperatures have increased by around 1.1°C [1] and according to the latest IPCC projections [2] are expected to rise further, with prolonged and more extreme warm seasons [3]. Accordingly, recent studies [4] suggest a shift in annual climatization demand in temperate regions, with cooling energy now outpacing heating needs. According to NASA maps [5], two vectors converge in the UHI phenomenon: population density and per capita income level. In certain regions, such as Europe, both vectors feed into each other. In this scenario, understanding near-future projections

to improve the thermal energy performance and efficiency of buildings and their envelopes becomes crucial to providing the most comfortable conditions [6].

1.1. Status of building stock and applicable energy regulations

Europe is often considered one of the most developed areas in terms of environmental protection and energy efficiency policies. Historically, several legislative initiatives were developed in order to enhance the environmental condition and human wellness while protecting the built and cultural heritage [7]. However, this contrasts with its aged housing stock [8]. According to the European Commission's Joint Research Centre reports [9], approximately half of Europe's residential stock was built before 1971, corresponding with the massive post-war construction boom period. This means that these residential buildings were

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Nomenclature

abbreviations

BEM	Building energy modelling
CC	Climate change
HVAC	Heating, ventilation, and air conditioning
IOT	Indoor operative temperature
IPCC	Intergovernmental panel on climate change
IWEC	International weather for energy calculations
LBT	Ladybug tools
MoMo	Modern movement
MICT	Mean indoor comfortable temperature
OAT	Outdoor air temperature
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
SC	Scenario
SHGC	Solar heat gain coefficient
UHI	Urban heat island
UWG	Urban weather generator

constructed before any energy efficiency regulation [9], and therefore, a very high percentage of them are still today thermally obsolete [10,11]. Many of these homes were initially designed to be used in free-running passive mode in temperate climates, without heat, ventilation and air conditioning (HVAC) systems [12]. However, incipient CC and UHI, and the accompanying worsening of indoor comfort conditions, have meant that comprehensive energy retrofitting is becoming crucial to avoiding uncomfortable situations and excessive energy consumption from climatization [13].

In order to mitigate this situation, further exacerbated by the current context of net energy dependency, the European Union is developing policies aiming to ensure efficient cities and buildings. In Europe, the “Renovation Wave” [14] is a significant initiative aimed at improving the energy efficiency of buildings, driven by the European Green Deal. This strategy seeks to renovate 35 million buildings by 2030, doubling the annual rate of energy renovations. In this regard, a recently revised directive (EU/2024/1275) [8] focuses on the energy consumption of buildings, which accounts for 40% of Europe’s total energy use, setting ambitious renovation targets for existing building stock [8]. This Directive, together with the revised Energy Efficiency Directive (EU/2023/1791) [15] establish binding energy reduction targets at EU level, and the corresponding European and national standards [16–18]. These propose stricter strategies to improve energy efficiency. However, although the Directive explicitly prioritises existing building retrofitting, the performance assessment methods and requirements in these standards remain primarily oriented towards actively climatized spaces. They are, therefore, mainly focused on active HVAC systems efficacy and envelope transmittance requirements depending on local climate. The logic behind this, consistent with prior literature [19,20], is that most of the approaches presented in current technical standards are still designed for application based on winter design, indoor climate set-points, and HVAC energy consumption savings. This can lead to detrimental effects in temperate zones and is in contrast with the real conditions of the obsolete housing stock, where a high percentage of dwellings in mild-temperate climates still have no active cooling HVAC systems [21]. Consequently, the problematic indoor overheating which can be observed during warm seasons worsens after a normative retrofit [22], and will be heightened under near-future CC.

Therefore, this situation requires an adapted approach that contemplates the real possibilities and effects of retrofitting the existing housing stock, based on building characteristics [23], while also considering local climate projection due to CC [24]. A realistic comfort-focused intervention is needed to counter this, as even today many of

these dwellings lack active cooling systems or are affected by energy poverty conditions which make this solution practically impossible for them [25]. Furthermore, by developing comfort conditions suitable for non-air-conditioned buildings retrofit effects can be assessed in terms of the simultaneous improvement of indoor environmental quality and energy savings [26,27]. Thus, while these obsolete buildings are seen as a technical problem, they also provide an opportunity to improve any intervention, adapting to the upcoming climate scenarios. Much of this housing stock falls under the category of mid-20th century buildings designed following the principles of Modern Movement (MoMo) Architecture [28], and is therefore very homogeneous [29]. The typology features inherent bioclimatic assets often lost in contemporary dense developments: high surface-to-volume ratios and shallow floor plans that facilitate effective cross-ventilation and nocturnal heat dissipation. These passive design principles [30] offer a latent resilience potential that standard retrofitting protocols threaten to compromise.

1.2. Previous studies and approaches

Previous studies have characterised existing building stocks in European cities, noting their alarming ageing status and low energy efficiency inherent to highly outdated residential stock [31]. In particular, one research focused on pre-1945 buildings emphasises the high percentage of old housing still in use requiring urgent retrofitting actions, whilst highlighting that conventional thermal comfort standards developed for new climatized buildings may not adequately reflect actual occupant interactions, adaptive behaviours, and thermal perception [32]. Other studies focused on warm climates, assessing cooling demand [4], identifying it as an imminent problem in temperate and hot regions [33]. Several works [34–36] focused on challenges posed by the increasing frequency of heatwaves and the prediction of progressively shorter and warmer winters. Furthermore, some research [37] has also highlighted potential overheating resulting from standard-based and passive-house retrofitting as a problem requiring new adaptive approaches [38]. Moreover, while energy studies in residential buildings often focused on consumption demand [25,39], previous research [40] has also assessed the real performance of vulnerable households operating without HVAC systems or using them sporadically.

According to standards such as ASHRAE 55 [41] and EN 16798 [18] indoor adaptive comfort is a key factor affecting occupants’ well-being. In this respect, natural ventilation is a cost-effective and efficient strategy for maintaining thermal comfort [13] during most of the year in free-running systems [42,43]. This in turn has led to the literature highlighting passive strategies as solutions for preventing overheating while saving energy [44,45]. Whereas some recent research focuses on the real potential of these passive resources [43,46] applied in low-income houses, other studies are concentrating on real user behaviour in terms of energy benchmarks, a crucial issue when considering passive performance [47]. Studies suggest that energy retrofits can provide significant benefits from an energy, health, and economic standpoint [48], especially in obsolete buildings [49]. Moreover, recent focus has been observed on future conditions and long-term performance that can lead to different optimal designs [50,51]. In this context, the uncertainty of overheating in climate change scenarios is examined [52].

There are still challenges to be overcome in the comprehensive assessment of energy and thermal performance in buildings. These analyses usually concentrate on building energy modelling (BEM) [53], which requires climate data, generally obtained from rural weather stations. However, there is a degree of inaccuracy due to failure to include the UHI effect [54,55], potentially leading to underestimation. As a result, to mitigate UHI effects [56], recent studies are focusing on outdoor urban microclimate [57], searching for more efficient methods to address urban morphology and its corresponding microclimate impacts. Then, the outdoor climate can be mitigated, benefiting both urban outdoor conditions and building indoor performance through energy

exchanges [58]. Some studies focus on the characterisation of comfort outdoor parameters [59], while others have achieved significant heat reduction through effective urban passive mitigation strategies [60]. Several tools address the need for BEM climate data and the possible UHI underestimation by morphing rural climatic files, such as the recent Vertical City Weather Generator [61] and the Urban Weather Generator model [62]. This last urban canopy model is included in the Ladybug Tools suite for Grasshopper [63], which also performs parametric energy simulations [64] using EnergyPlus [65].

1.3. Research gap, scope and paper structure

Previous literature has already analysed the energy performance of low-income dwellings [47] and focused on increasing cooling demand, with different studies also assessing the impact of CC on the housing stock [66,67] and the resulting evolution of energy demand. The energy benefits of a standard-based retrofit have also been evaluated elsewhere [48]. However, a critical misalignment remains between current energy efficiency policies, predominantly focused on winter heating demand, and the accelerating cooling needs driven by climate change. Few studies have quantified the 'lock-in' risk of regulation-compliant retrofits in social housing, where the absence of active cooling transforms standard insulation measures into potential overheating traps under future projections. This particularly applies to the parts of the world which will experience the most drastic changes in their climatic boundary conditions.

This research aims to bridge this gap by introducing a novel approach based on four main pillars. Firstly, the main aim of the study is to assess thermal performance resilience, focusing on indoor comfort conditions within an evolved CC scenario following a current standard-based retrofit and evaluating the potential adaptability to CC that current retrofitting policies estimate for the near future. Secondly, this issue is approached with a diachronic perspective examining a representative case study throughout the evolution of climate during the expected lifespan of these buildings [68]. Several scenarios are analysed, from their construction in the mid-20th century to the climate forecasts in 2080, according to the CC IPCC projections [2]. Third, there is an increased potential impact and replicability of the study as the residential case study typology archetype selected is widespread throughout Europe. This case study focus allows the evaluation of potential adaptability to climate change for obsolete low-income residential developments which do not rely on HVAC systems. Finally, by considering the neighbourhood as a whole there is a comprehensive focus on the influence of the building's position, orientation, and height on thermal performance, analysing the effect of these factors on interactions with environmental conditions such as solar radiation, shading, and level of exposure. The main goal is, therefore, to assess how interventions promoted by current building codes can effectively enhance indoor conditions while saving energy in obsolete passive houses in the near future. At the same time, it also aims to evaluate possible negative effects or overheating situations in order to propose alternative solutions.

This article is structured into two main sections. The first of these focuses on presenting the case study and providing a detailed explanation of the methodology, while the second presents the results of the individual scenarios, followed by a comprehensive discussion. This is followed by a summary of the main conclusions of the study.

2. Materials and methodology

This section is divided into five parts. The first of these presents a characterisation of the specific case study. This is followed by an overview of different scenarios for analysis over time. The third part then details the method used to obtain the weather dataset for the individual scenarios. The fourth part details the numerical model for the building and simulations setups, including all options and assumptions. Finally, a description is offered of the building performance indicators used to

evaluate the impact of each scenario. A comprehensive methodology for energy and comfort analysis is presented, and the workflow is summarised in Fig. 1. A representative case study was selected and analysed as an archetypal MoMo mid-20th century design.

2.1. Materials: Case study description

The case study examines archetypal social housing buildings constructed in the mid-20th century as part of a residential complex following MoMo guidelines in Valencia, Spain (Fig. 2). This coastal city's climate is classified as *BSh* in the *Köppen-Geiger* system [69,70], with moderate winters, warm and humid summers, and few annual precipitations, all influenced by the Mediterranean Sea. According to recent studies [24], the Mediterranean area is one of the most affected by climate change and has already suffered the consequences in the last few years. In the summer of 2023, the maximum recorded dry bulb temperature ever [71] (46.8°C) was reached, while during the autumn of 2024, it suffered a severe flood caused by a cut-off low. This clearly shows the need to study climatic resilience and heat mitigation strategies, not just for the buildings in this area, but also for the entire Mediterranean basin.

The neighbourhood, with 614 dwellings, was built in 1962 as a low-income district [28,68] and even today still has a low mean income compared to the citywide average [72]. The research focuses on the linear buildings (Figs. 2 and 3), which represent 67% of the total district-built dwellings. These correspond to the linear block typology, a characteristic residential building form of mid-20th century European social housing developments. These buildings are four to five stories high, with between four and seven staircases, providing access to two dwellings per landing through a common vertical circulation core. The dwellings have façades on both sides, mostly with a north-south orientation to ensure cross ventilation. This enables natural lighting and ventilation in all main rooms, with main bedrooms and the living room facing the more favourable orientation and the kitchen and another bedroom on the opposite side. The most common unit of these buildings has three bedrooms, a kitchen, a living room, a bathroom, an entrance, and two terraces, making up a net floor area of 70 m². The original plan is represented in Fig. 2. See Appendix A0 for more images.

The uniformity of this typology across the neighbourhood, with only minor variations in number of bedrooms (ranging from 2 to 4), facilitates the representative analysis of the entire housing stock. From the total number of dwellings, a sample was selected to represent each of the distinct existing conditions (Fig. 3). Consequently, three dwellings were chosen per level: one at either end, and one in the middle. Next, three levels were selected based on exposure and boundary conditions: the ground floor, the middle level (1st floor), and the top floor (roof level). Additionally, two building orientations were considered for each design: one with a north-south façade orientation and the other with an east-west orientation. Thus, eighteen distinct dwellings were selected for analysis during the preliminary stage, representing all relevant variables in the neighbourhood. All these units have been modelled in 3D, including the urban context (built context and trees). The selected dwellings are detailed with their positions and identification codes in Fig. 3.

The original layout of the case study was quickly modified. The urban spaces added landscaping in public spaces, and the dwellings were customised by the occupants. This transformation included glazing the terraces, which were incorporated into the indoor usable area. Currently, 92% of the original terraces are enclosed and exterior mortar protection and new window materials have been added to the envelope. Moreover, the internal distribution was modified by the occupants.

2.2. Analysed scenarios

The thermal energy assessment is viewed in successive stages through a temporal evolution established as scenarios (SC). These

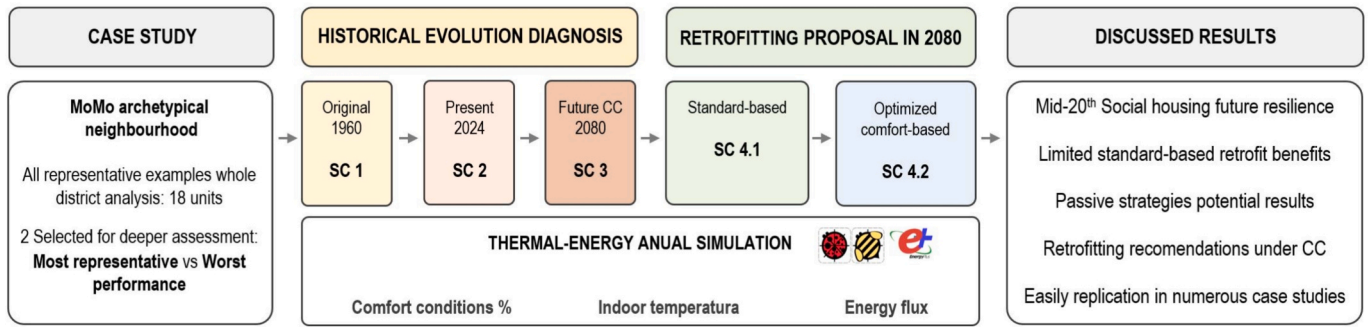


Fig. 1. Graphical representation of the methodology workflow with identification of analysis scenarios and performance indicators.



Fig. 2. Location of the case study area: City of Valencia in the eastern Mediterranean coast of Spain, case study district located in the coastal suburbs, north and south façades and typical dwelling plant.

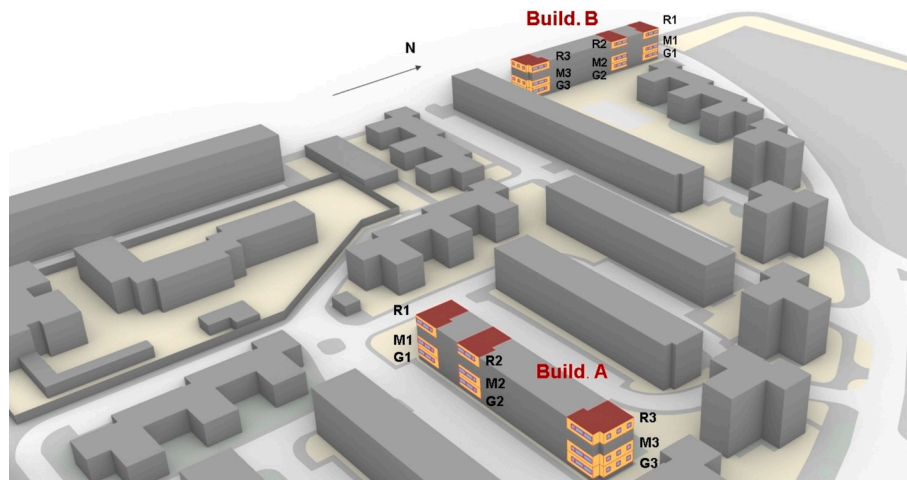


Fig. 3. Case study neighbourhood 3D model (trees have been eliminated just for visualisation purposes). Marked in orange, the 18 dwellings selected with their codes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

represent different conditions based on the temporal climate evolution brought about by CC, and on the evolution and possible improvements of the original constructions. The scenarios involve a time span of over a century: their historical evolution over the last 60 years, but also the future comfort conditions – 60 years from now – according to the worst CC predictions. In this last scenario, the level of comfort enhancement, CC resilience, and energy efficiency is assessed when the case study is standard-based versus passive cooling-based retrofit. The five scenarios proposed are summarised in [Table 1](#):

2.3. Climate data for different scenarios

Past, present, and future climate resilience of the case study is analysed using numerical simulations. To address the future scenario, this study employs the climate projections developed by the IPCC [2], which establish various possibilities based on emission trends and the severity of resulting mean temperature increases. Any translation of these future scenarios to a local climate involves uncertainties in final values, whilst BEM simulations require specific continuous hourly data. Therefore, this study adopts the most adverse scenario proposed by the IPCC, RCP8.5, as it represents the upper boundary of plausible expert projections. This approach ensures that results are assessed under maximum climate stress conditions, thereby interpreting findings as upper-bound overheating risk. Consequently, any future improvements in mitigation efforts would transform the assumed uncertainty into a safety margin for adaptation strategies.

To obtain the hourly climate data required for the BEM, EPW format files are sourced from the EnergyPlus database, which contains climate data collected in past years from local official meteorological stations. To morph these files into future RCP8.5 scenario conditions, the open-access Climate Change World Weather Generator (CCWorldWeatherGen 1.9) [73] was employed. This tool utilises the HadCM3 [74] global climate model under the RCP8.5 scenario and applies the morphing methodology developed by Jentsch et al. According to the tool's technical requirements [75], baseline EPW files must be derived from the 1961–1990 reference period to match the HadCM3 temporal framework, as using more recent baseline data would overestimate climate change impacts. Specifically for Valencia's climate, an IWECC (International Weather for Energy Calculation) file was employed, derived from up to eighteen years of hourly DATSAV3 [76] climate data archived at the National Climatic Data Center. The IWECC file contains data from 1980 to 1990, the earliest available dataset for this location. According to historical temperature records and relevant literature [1], there were minimal changes in the local climate between 1960 and 1980 [71], so that the 1980 s weather file is considered representative of the climate conditions of the 1960, being the baseline for the original scenario (SC1). This baseline file was then morphed using CCWorldWeatherGen 1.9 to generate conditions for 2024 (present scenario, SC2) and 2080 (future scenario, SC3 and SC4), aligned with IPCC RCP8.5 climate change projections. Annual thermal variations for each scenario are presented in Appendix A1.

Whilst CCWorldWeatherGen 1.9 [73] is one of the most widely

employed tools in the literature for morphing and generating future climate files [77,78], all future climate projections inherently carry uncertainties. Several authors have previously reported potential accuracy limitations of this tool when estimating climate parameters [77,79]. Nunes et al. [79] demonstrated that whilst dry-bulb temperature predictions achieve good accuracy, and relative humidity remains acceptable, solar radiation exhibits substantially higher errors. To quantify this uncertainty in the present study, the morphed file (from 1980) for the 2020 s (SC2) was validated against the most recent TMY file available for Valencia (TMYx 2009–2023). The validation yielded results consistent with previous literature [79]: temperature predictions demonstrated good performance (NMBE: 0.64%, CV(RMSE): 21.25%), relative humidity showed acceptable accuracy (NMBE: 4.04%, CV (RMSE): 31.47%), whilst solar radiation presented higher dispersion (NMBE: –7.21, CV(RMSE): 60.83%). These error metrics are presented in detail in Appendix A2. However, this study focuses on comparative analysis between scenarios, and the same morphing algorithms are applied consistently across all temporal scenarios (SC1-SC4), so the systematic bias remains constant. Consequently, while absolute temperature predictions carry inherent uncertainty, the relative performance deltas between scenarios are methodologically robust, allowing for valid comparative stress-testing.

The baseline and subsequently morphed weather files are representative of a weather station located on the city outskirts or rural areas with few surrounding buildings, therefore, the UHI in the city is not represented in the files. Therefore, the Urban Weather Generator software, UWG [62], was used for further morphing in order to include the UHI effect in the simulations to improve data accuracy. The UWG model is included in the Ladybug Tool *Dragonfly* [63], which allows weather morphing based on the geometry information of the urban setting modelled in Rhinoceros. It also needs inputs such as materials, terrain, traffic, building information, and vegetation in order to adapt the original EPW file from the outskirts of the city to an urban EPW file considering anthropogenic heat, vegetation, and building morphology. After running the UWG for past, present, and future scenarios, the results show an increasing UHI effect at night. A detailed comparison of original and morphed EPW is found in Appendix-A3.

2.4. Simulation tools and assumptions

This study is based on numerical building energy simulation using Ladybug Tools (LBT) for Grasshopper [63]. These tools link the 3D model built in the Rhinoceros interface [80] to the building energy simulation solver EnergyPlus [65]. While EnergyPlus is the most widely accepted and used BEM software in the literature, the use of Rhinoceros-Grasshopper first provides the finished 3D model of the case study, and the workflow on the graphical programming interface allows a parametric and fully customised simulation.

Each dwelling unit is modelled as a single thermal zone for several reasons. Firstly, stems from the substantial heterogeneity in interior layouts stemming from historical modifications, whose detailed reproduction in modelling is neither viable nor would contribute meaningfully

Table 1
Studied scenarios main features. In *italic* have been marked the main retrofitting actions.

Scenario	Building – urban status	Climate	Envelope	Solar rad. control	Nat. vent. management
SC1	Original	1960	Two-layer brick wall. Wood frame-single pane window. Aerated roof	None	Daily early morning + summer nights
SC2	Current status	2024	Two-layer brick wall + mortar. <i>Steel frame-doble pane window. Slightly isolated roof</i>	Current <i>urban trees</i> protection	Daily early morning + summer nights
SC3	Current status	2080 (RCP8.5)	Same as SC2	Same as SC2	Daily early morning + summer nights
SC4.1	Regulation-compliant insulated envelope	2080 (RCP8.5)	Two-layer <i>isolated wall</i> + clear mortar. PVC frame – <i>isolated low radiation glass. Isolated clear roof</i>	Same as SC2 + <i>windows shading element</i>	Daily early morning + summer nights
SC4.2	Ventilation optimisation + Fans	2080 (RCP8.5)	Same as SC4.1	Same as SC4.1	<i>Optimisation</i> based on temperature balance

insights about the archetype typology under study. Moreover, with eighteen dwellings evaluated across five scenarios, disaggregation into interior sub-spaces would result in an excessively high number of spaces to simulate and analyse. Finally, the study prioritises identifying performance trends attributable to envelope interventions, dwelling position, and climate evolution. This approach aligns with established practices in large-scale building studies and comparative assessments, where single-zone representations provide adequate accuracy for relative performance evaluation when appropriately contextualised [81]. However, specific limitations are explicitly acknowledged: this representation does not capture intra-dwelling thermal variability depending on orientation, solar exposure, and ventilation access. Consequently, the model may underestimate overheating peaks in unfavourably oriented spaces or overestimate night-time cooling effectiveness due to unrepresented thermal stratification. Despite these limitations regarding absolute temperature predictions, the relative performance trends identified in this study remain methodologically robust for informing envelope improvement strategies and climate adaptation planning.

The surrounding context is also modelled to reproduce the shading-reflective effect, while the adjacent surfaces of the dwellings are considered adiabatic. The software therefore only considers the thermal flux through the external envelope (outdoor floors, façades, windows, and roofs), and the effect of the reflected short-wave radiation [82] of the nearest urban environment: façades and floors. Moreover, urban trees are modelled with an albedo of 0.2 (default for vegetation) and a 35% of transparency, estimated by the existing foliage. The solar distribution is set as default by Ladybug-Honeybee, with full interior and exterior reflections.

In order to define the boundary conditions and constructive constraints on which the simulations are to be based, thermal loads and energy programs are set for the different scenarios, selecting typical values for the residential sector in this location. These start with a base program, an initial default characteristic from the LBT [63], in the Honeybee-Energy library. Loads and programs are based on standards of the US Department of Energy database [83], as well as on the most recent ASHRAE 90.1 Standards for sites and buildings [84]. Although these base programs contemplate all the loads for the simulation, some have been specifically assigned by the authors for greater accuracy (See Table 2). Building occupancy is calculated based on dwelling distribution, number of bedrooms, and typical average family size, which was higher in 1960. Lighting is estimated based on internal distribution and original installation, using incandescent lamps in SC1 (1960) and LEDs in other scenarios. Infiltration is assigned by default according to the envelope [83,84]: pre-1980 for SC1, 2, 3, and 2020 for SC4.1, and SC4.2. In SC 1, 2, 3 and 4.1, natural ventilation settings are based on typical occupant behaviour [47]: two hours of morning ventilation in winter (07:00–08:00) and extended nighttime ventilation in summer (23:00–09:00 h from June to September). However, SC4.2 introduces an optimised control logic adapted during the seasons (See Table 3). The summer optimisation refers to the conditional activation: By restricting window operation to periods where outdoor air temperature (OAT) is

Table 2
Program, internal loads and assumptions per each scenario.

Parameter	SC1	SC2	SC3	SC4.1 & SC4.2
LBT base program	Pre 1980 Midrise apartment	2004 Midrise apartment	2004 Midrise apartment	2020 Midrise apartment
Occupancy	0.083 pp/m ²	0.06 pp/m ²	0.06 pp/m ²	0.06 pp/m ²
Lighting	12 W/m ² (Incandescent bulbs)	5 W/m ² (LED)	5 W/m ² (LED)	5 W/m ² (LED)
Electric equips	5.4 W/m ²	6.7 W/m ²	6.7 W/m ²	6.7 W/m ²
Infiltration	0.001133 m ³ /s-m ²	0.001024 m ³ /s-m ²	0.001024 m ³ /s-m ²	0.000569 m ³ /s-m ²
Minimum ventilation	1.89 ACH	0.35 ACH	0.35 ACH	0.35 ACH
Natural ventilation	2 h in the morning + summer nights	2 h in the morning + summer nights	2 h in the morning + summer nights	2 h in the morning + summer nights
Use of Fans	No	No	No	No
				Optimiz. based on energy balance Yes (1.5 m/s)

Table 3
Natural ventilation control logic and scheduling.

Season	Months	Ventilation Period	Control Logic and Objectives
Cold	Nov–Mar	14:00–16:00	Fixed schedule during peak OAT to ensure typical air renovation while minimising heat loss.
Temperate	Apr, May, Oct	08:00–09:00 & 18:00–23:00	Morning flush and evening cooling to maintain comfort without significant thermal oscillations.
Warm	Jun–Sep	IF OAT < IOT	Condition-based: Ventilation is activated only when OAT is lower than IOT to maximise passive cooling and use thermal inertia to maintain comfort for as long as possible.

lower than indoor operative temperature (IOT), the model prevents unintended heat gains and ensures that the enthalpy of the indoor air is reduced whenever possible through passive means. Additionally, as part of passive strategies in SC4.2, air speed, crucial to thermal comfort, is optimally controlled with fans in summer by increasing it by 1.5 m/s following European Standards [18]. The standard and the literature [42] consider these devices as a passive system for adaptative comfort due to its negligible impact on energy consumption, while empirical studies have proved their high efficacy improving comfort [85].

The thermal conductivity properties for each construction layer are calculated according to an on-site survey supported by technical documentation of the original construction plans and details. These are shown in Appendix-A4. The envelope has been enhanced implementing energy retrofitting for SC4.1 and 4.2, built according to the current national standard [16]. Thus, the general thermal transmittance of opaque envelopes and windows has been reduced, as have the solar gains (See Table 2 and Appendix-A4).

A standardized comparative stress-testing methodology was adopted rather than a calibration to specific user data. Since the objective is to evaluate the relative resilience of the building envelope against climate forcing (2080 scenarios) and policy constraints, relying on normative occupancy profiles [47] is methodologically superior. This approach isolates the 'building physics' performance from the noise of stochastic user behaviour, providing a robust baseline for comparative policy analysis [86]. While absolute temperature values carry inherent uncertainty, the relative performance deltas between scenarios remain statistically valid for identifying overheating trends.

As this study highlights [86], normative-based energy calculation methods such as those based on international standards offer simplicity, transparency, robustness, and reproducibility, making them particularly suitable for systematic energy assessments and comparative retrofit evaluation. In this case, while monitoring individual dwellings could provide calibration data for specific units, such data would not be representative of the broader dwelling stock, given the inevitable

variability in user behaviour and occupancy patterns. Therefore, standard energy use behaviour based on well-established statistical studies [47] and official standards [11,18,82,84] are employed, ensuring reliable representation of typical conditions and enabling attribution of performance variations exclusively to controlled parametric changes (envelope interventions, dwelling position, climate scenarios) rather than to unquantified behavioural differences.

In view of the above, it should be noted that this normative approach prioritises comparative validity over absolute accuracy, with performance differences between scenarios remaining methodologically robust as systematic assumptions are applied consistently across all simulations. However, it constitutes a limitation that is discussed in the corresponding Limitations section.

2.5. Performance indicators

Given the research focus on the energy performance of free-running mode buildings, this assessment is based on indoor passive thermal comfort. To that end, the adaptive comfort model set out in EN 16798 [18] is used. This European standard defines comfort categories using the Predicted Mean Vote (PMV) [87] and the Predicted Percentage of Dissatisfied (PPD) [88]. For free-running buildings, EN 16798 employs an adaptive comfort approach that links IOT with OAT through empirically derived equations, considering the limit categories established directly from the PMV. Table 4 presents the main characteristics for EN 16798, calculating thermal comfort.

EN 16,798 stands out for its moving average method, which places greater emphasis on the conditions of previous days, contrasting with other standards such as ASHRAE 55 [41] used for adaptive comfort evaluation. Another notable aspect of EN 16798 is that it does not specify whether the meteorological data should be officially recorded or monitored on-site. This is significant as official meteorological stations are often located in the city outskirts, where the UHI effect is notably lower than in dense urban environments. Data on the outdoor running mean external temperature (θ_{rm}) and the IOT of the dwelling (θ_o) are required in order to implement the mathematical comfort model according to EN 16798. The adaptive model assumes that occupants in existing buildings without active climatization, such as the one analysed, adjust their expectations and behaviours based on outdoor climatic conditions, leading to greater tolerance of thermal fluctuations. Thus for the case study, the applicable category limits are Category III, (PPD < 15%, equivalent to ± 0.7 PMV in static conditions), which translates into an adaptive temperature band. For the present scenario for the case study in question, with standard clothing and metabolic rates, this can be translated into an approximate range of acceptable comfortable temperatures from + 2°C to -2.5°C of the neutral comfortable temperature. Comfort assessment is therefore based on the EN 16798 instant results, that states if IOT remains within this adaptive temperature band per each hour. These are then quantified and the duration hours per each condition are calculated. This metric provides a more realistic approximation to occupant adaptive behaviour and expectations.

Table 4
Key Characteristics for Comfort Calculation According to EN 16798 [18].

Category Limits	EN 16,798	
		I – PPD < 6%
	II – PPD < 10%	II – PMV < + 0.5
	III – PPD < 15%	III – PMV < + 0.7
	IV – PPD < 25%	IV – PMV < + 1.0
Acceptability Limits	$f(x) = 0.33 \theta_{rm} + 18.8$	
Outdoor thermal values	$f(x) = (1 - \alpha) \theta_{ed-1} + \alpha \theta_{rm-1}$	
Metabolic rate	1 – 1.3 met	
Clothing insulation	0.5 – 1.0 clo	
Application Range	Above 25°C artificially increased air velocity can be used to compensate for temperatures	

Based on the above, the research first assesses the comfort condition (warm discomfort, comfort or cold discomfort) of the case study, measuring the monthly and annual comfort percentage. This analysis is complemented with the study of the IOT and the thermal fluxes through the evolution of the different scenarios.

3. Results and discussion

This section presents the results of the studied scenarios. First, a general overview of all the dwellings is commented and two specific dwellings are selected for a more in-depth study. Their results of the historical evolution scenarios are then analysed, before going to offer an examination of the retrofitting scenario results presented. Finally, a general overview is discussed.

3.1. Results overview

An initial annual comfort analysis is carried out on the eighteen representative selected dwellings. Results are extracted for the first three scenarios: original (SC1), current (SC2), and future (SC3) conditions. The results are presented graphically, according to comfort condition and the total annual percentage of comfort hours (Fig. 4).

The evolution of comfort conditions across the three scenarios (Fig. 4) shows a gradual increase in temperatures and a slight rise in overheating. In the first scenario, cold and conditions of discomfort prevail due to low temperatures and the poor performance of the original building envelopes, with annual comfort levels of 50%-67%. While this could be considered unsatisfactory, the original design still provides comfort for about half of the year with no need for HVAC systems. The second scenario shows a minor improvement, with reduced winter discomfort, and an increase in annual comfort hours to between 55% and nearly 70%. The third scenario (2080 according to the IPCC [2]) indicates a moderate decline in comfort, with improved winter conditions due to reduced cold, but significantly worsened summer comfort due to prolonged and intensified hot hours.

Notable differences are observed depending on the position and orientation of the dwellings (see Fig. 4). In terms of orientation, Building B (with façades facing east/west) shows a slight decrease in comfort hours compared to Building A (façades facing north/south), especially during winter. The most notable differences are due to the level of the dwellings. The ground-floor dwellings (G) reflect the high thermal inertia of the ground, exhibiting worse comfort levels in the first two scenarios but better results in the third due to overheating and improvements in winter. Middle (M) and roof-level (R) dwellings display no significant differences, although roof-level dwellings experience a slight decline in comfort due to the increased climatic exposure of the façades. Additionally, within the same level, internal dwellings perform better than those at the ends, which also face greater climatic exposure.

Based on the results overview, two dwellings are selected for further analysis (bold in Fig. 4):

- **A_M2**: intermediate floor- internal location, representing 40% of all dwellings and the most common type in the neighbourhood.
- **B_R1**: top floor facing north, showing the worst comfort performance.

3.2. Evolution over time

The three initial scenarios are assessed as an evolving analysis over time, serving as a diagnostic for further retrofitting evaluation. For each scenario, the key thermal comfort results are summarised in a chart figure with the hourly comfort condition graph and the monthly mean OAT and IOT comparison. Table A3 in the appendix-A4 describes the envelope characteristics and construction thermal-conductivity properties for each scenario. Additional analytical figures are also included in the appendix-A5, supporting these results and discussion.

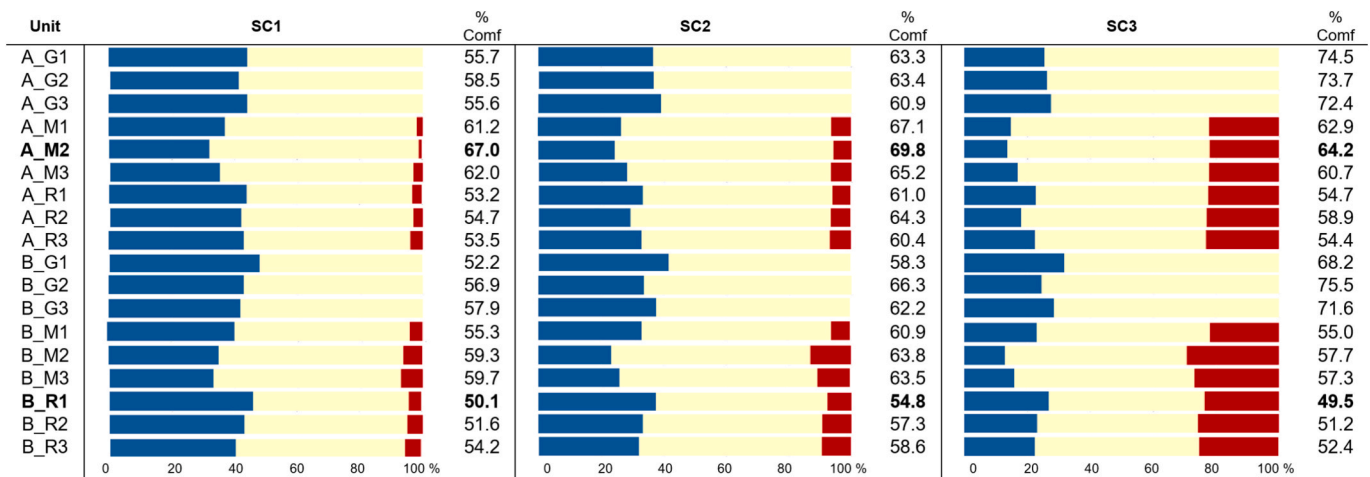


Fig. 4. Annual distribution of comfort conditions in scenarios 1 to 3 for the 18 dwellings selected. Each bar represents the annual percentage of comfort condition (blue = cold discomfort; yellow = comfort; red = hot discomfort). Each column of “% Comf” represents the total percentage of comfort hours per scenario and dwelling. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2.1. Original 1960 scenario (SC1) results

The main results for both dwellings during SC1 are summarised in Fig. 5. As shown in Fig. 5a, unit A_M2 performs significantly better in terms of comfort than B_R1 throughout the year, with 67% of annual comfort hours compared to 50% for B_R1. Both units achieve good comfort levels during the mid-seasons, but performance worsens in winter (See Appendix A5-a). This also aligns with Fig. 5b, where the IOT remains low during winter and temperate during the mid-seasons and summer. The impact of natural ventilation on IOT is also evident here. During most of the cold season IOT remains higher than OAT, but early morning ventilation causes a rapid cooling effect. This lowers the IOT, and in the case of B_R1, this cannot rise above the OAT again due to low energy gains. During summer, natural ventilation plays a key role in maintaining a temperate IOT. After a full day of heat gains, evening and nighttime ventilation help reduce the IOT to acceptable levels (Fig. 5b). The energy flux through the envelope has also been analysed (See Appendix A5-a). Although heat loss through windows is minimal, the energy flux through opaque envelope yields higher results, especially in B_R1, which has more exposed faces. Notable differences in solar gains are observed: A_M2 captures more solar energy in winter due to its south-facing orientation, while higher solar gains are observed in summer in B_R1. Additionally, B_R1 has greater sun exposure in the morning and evening due to its east-west orientation whereas solar gains for A_M2 are concentrated around midday. These factors, along with infiltrations, highlight the poor airtightness of the envelope surfaces in SC1.

3.2.2. Current 2024 scenario (SC2) results

The performance during SC2 reflects the current status of the dwellings as well as present weather conditions. Fig. 6a shows the comfort conditions throughout the year. The key difference compared to SC1 is noticeable in both units: while some cold discomfort is still experienced in winter and mid-seasons have several slightly cold nights (cold discomfort accounts for 24% of annual hours in A_M2 and 38% in B_R1), the rising temperatures from 1960 to 2024 have led to a decline in summer comfort, with an annual heat discomfort of approximately 6% in A_M2 and 8% in B_R1 (See Appendix A5-b). This trend is also evident in Fig. 6b, where temperature performance highlights two key aspects. First, the early morning ventilation during winter appears to be inefficient, rapidly cooling the indoor space without effectively maintaining comfort conditions. Second, during summer, the higher diurnal OAT causes discomfort during most of the day, pushing the IOT above comfortable levels. However, the drop in the nocturnal OAT, combined with natural ventilation, ensures sufficient cooling of the IOT, making

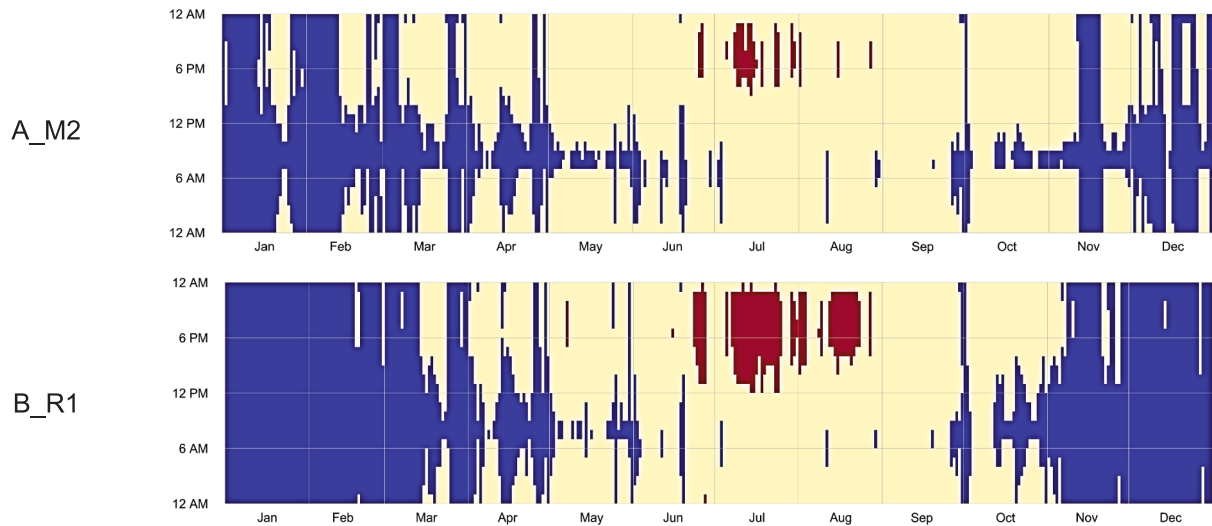
summer nights more comfortable. In terms of energy flux (see chart in Appendix A5-b), some minor improvement interventions were made in windows and roofs. However, the primary heat gains during summer continue to come from the opaque envelope and solar transmission. Conversely, ventilation and infiltration are the main cooling mechanisms during summer, but they contribute to heat loss in winter exacerbating the effects of energy conduction through the opaque envelope. Thus, these previous minor interventions alone cannot address the current climate conditions.

3.2.3. Current status in 2080 (SC3) results

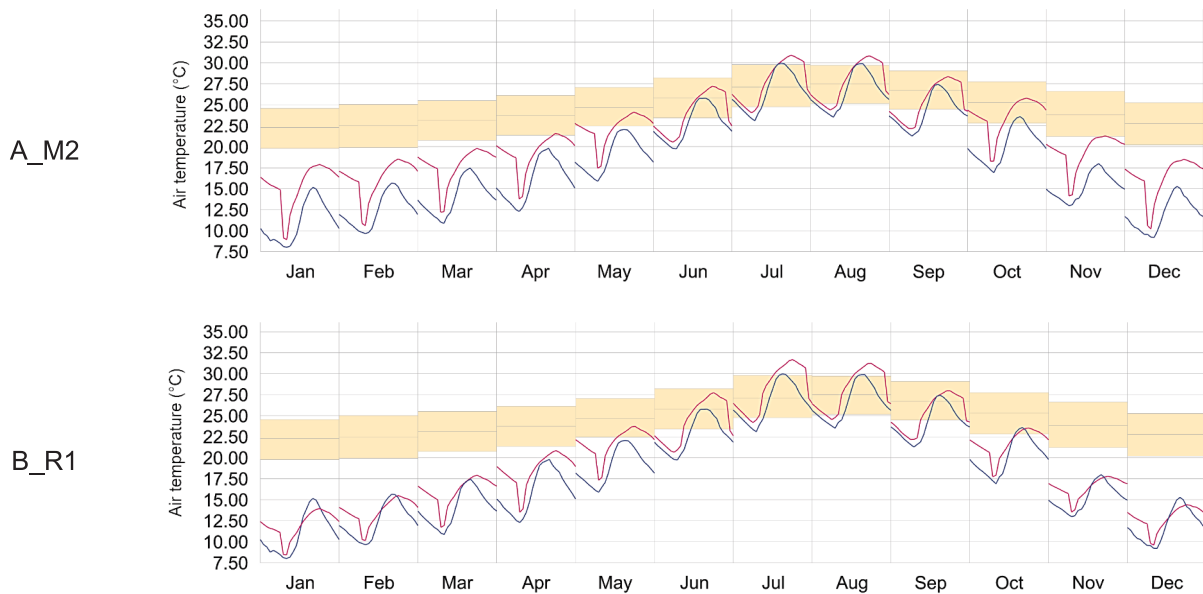
SC3 and the subsequent are subjected to the RCP8.5 projection scenario for the year 2080, the most adverse scenario anticipated by the IPCC. Therefore, all results presented in this and subsequent scenarios should be interpreted as the upper-bound of future heat exposure risk. Any future improvements in emission mitigation pathways would translate into less severe overheating outcomes than those presented here.

The most notable change in this scenario is the improvement in winter comfort (A_M2 has 14% of cold annual discomfort while B_R1 has 27%). In contrast, summer conditions have significantly worsened, including nighttime discomfort (Fig. 7a), in this case, A_M2 displays 22% of annual hot discomfort, which stands at 24% in B_R1. The general rise in OAT results in milder winters, but still with periods of cold discomfort. However, the concentration of hours of discomfort has mostly gone beyond the limits for humans (See Appendix A5-c). Although ventilation is still a critical cooling mechanism, it no longer suffices to reduce IOT below OAT. In addition, since the building operates as a free-running system, it is entirely dependent on OAT and any thermal mass effects. However, due to the poor thermal properties of the envelope, the IOT oscillates closely with the OAT (Fig. 7b), showing the poor conditions of the envelope (See Appendix A5-c). This scenario displays a significant energy exchange through the envelope, with the same causes as above, although with higher OAT its detrimental effects are exacerbated. 2080 climate still causes balance loss in winter with no controlled ventilation and infiltration, while summer temperatures and internal overheating reflect the pressing need for intervention.

These results provide a useful diagnosis to understand how the building will perform under future conditions and to identify the key problems to be resolved. The improvement of the building envelope to control energy fluxes, increase solar control, and develop a more rational approach to natural ventilation will be crucial for improving the performance of these types of constructions.



(a) Annual comfort condition according with EN 16798 [18], cold: blue, comfortable:yellow, hot: red.



(b) Mean air temperature per month: OAT: blue, IOT: red, and mean neutral indoor comfortable temperature (NICT) per month (yellow).

Fig. 5. Compared energy-comfort results of two cases study dwellings in SC1 (1960).

3.3. Future retrofitting proposals (SC4) results

Following the analysis, this section examines the results after the application of a passive improvement retrofitting intervention based on current standards. Firstly, it focuses on an intervention based on current regulations. Secondly, it proposes the implementation of adapted measures to optimise passive comfort. In this case, in order to compare the effectiveness of both interventions, the results are presented for scenarios 4.1 and 4.2, in parallel for each case study.

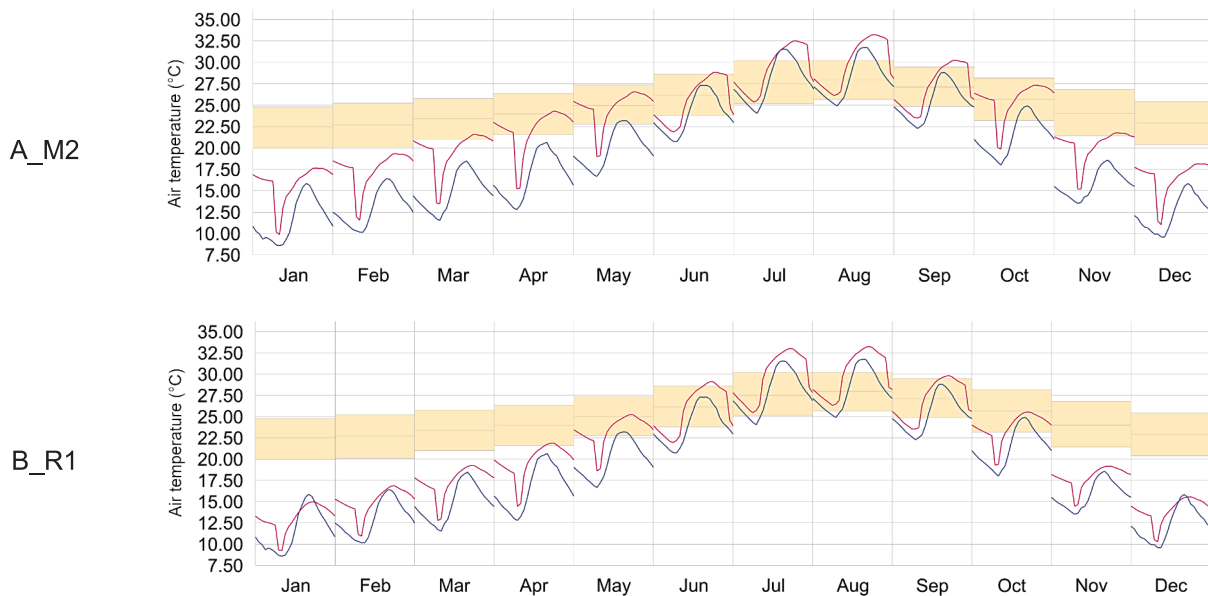
3.3.1. Current regulation-based retrofitting (SC4.1)

Focusing first on the comfort situation (Fig. 8a for unit A_M2 and Fig. 9a for unit B_R1), the measures adopted in SC4.1 have substantially improved winter conditions compared to SC3, although they are still poorer for B_R1. In contrast, summer conditions continue to be

unfavourable, and new periods of discomfort due to heat appear throughout the year. As a result, A_M2 has a total percentage of 75% annual comfort hours, while this figure stands at 63% for B_R1. This is caused by the overheating resulting from the addition of insulation and increased thermal inertia (See Appendix A5-d and A5-e for annual hour distribution), as well as inefficient ventilation. This can be seen in the comparative OAT and IOT chart for SC4.1 (Fig. 8b and 9b). The IOT oscillation shows that, although the increased inertia reduces and softens diurnal temperature peaks, the IOT has been buffered compared to the OAT. However, ventilation contributes to raising the IOT in summer, while also continuing to cause rapid and uncontrolled IOT drops in winter. Now, due to the improved airtightness, infiltrations have been reduced, although they are still much higher in B_R2 due to its larger envelope surface. Therefore, with a more airtight envelope and higher transmittance, ventilation becomes the primary energy flow



(a) Annual comfort condition according with EN 16798 [18], cold: blue, comfortable: yellow, hot: red.



(b) Mean air temperature per month: OAT: blue, IOT: red, and mean NICT per month (yellow).

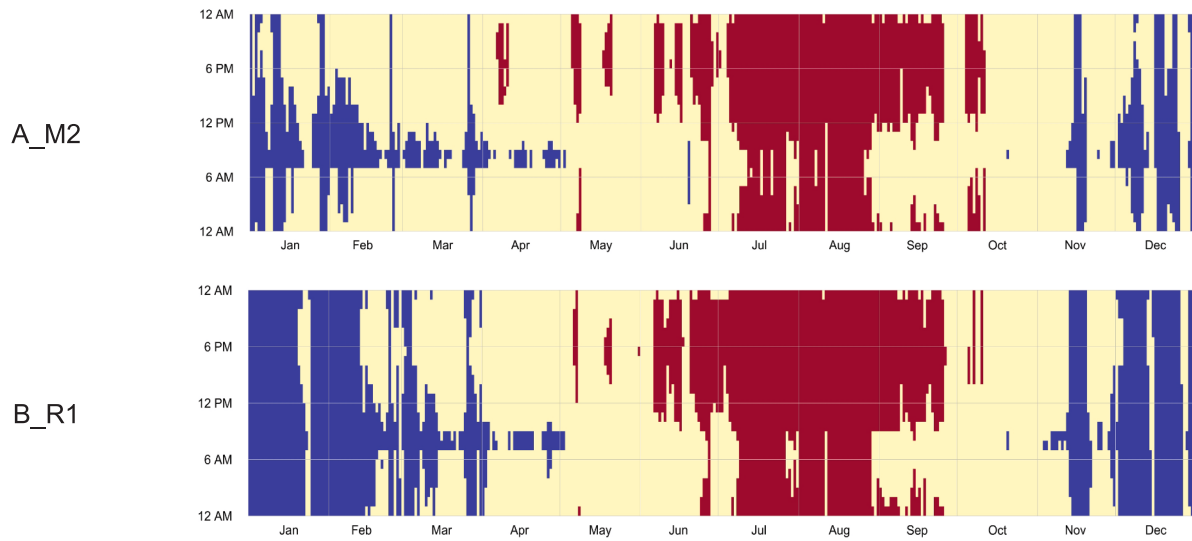
Fig. 6. Compared energy-comfort results of two cases study dwellings in SC2 (2024).

between the exterior and interior (See Appendix A5-d and A5-e for more detail). The regulation-based retrofitting has increased thermal transmittance, in turn, minimising the energy exchange. Likewise, the improvement in solar heat gain coefficient (SHGC) for glazing and the new solar protections have also limited direct solar radiation heating. It can therefore be stated that the intervention based on current regulations has been efficient in limiting energy exchanges with the exterior. However, the increased air tightness and insulation create a 'thermal entrapment' effect. Once solar or internal heat gains penetrate the dwelling, the highly insulated envelope inhibits radiative cooling at night, while the lack of managed ventilation prevents convective heat removal. This transforms the dwelling into a heat trap during prolonged warm spells.

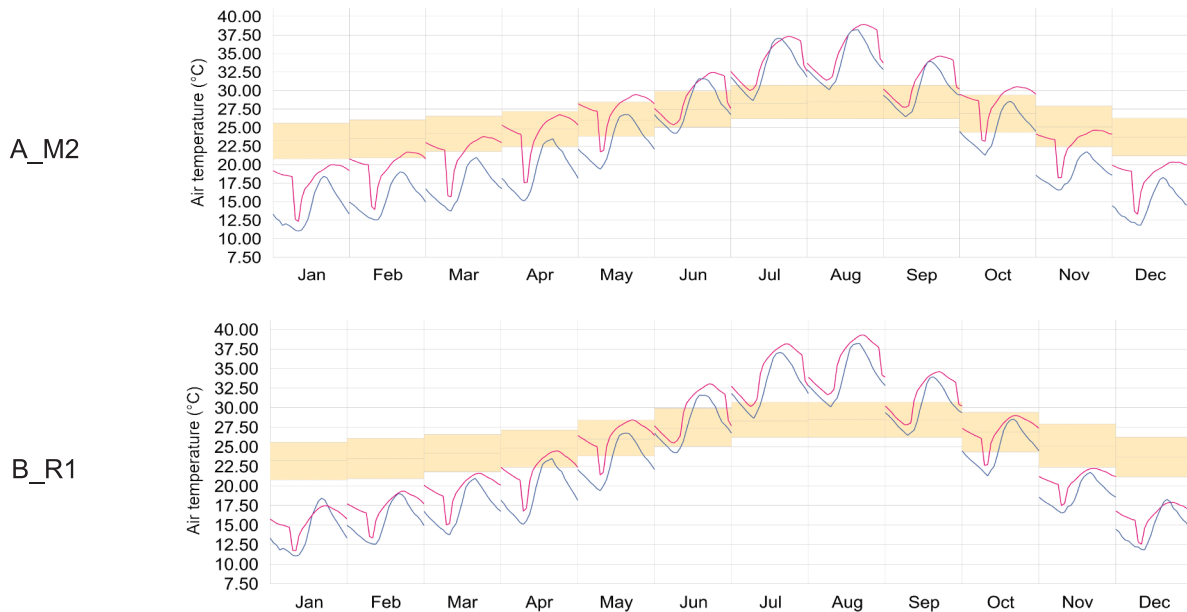
3.3.2. Optimised comfort improvement (SC4.2)

Based on the evolving multi-perspective analysis detailed above,

some aspects are crucial to ensuring improved retrofitting. Firstly, a rationalisation of natural ventilation must be carried out as this essential practice must be controlled and optimised to take full advantage of it during each season (See Table 3). Therefore, in winter, ventilation follows the typical brief openings periods, but now it is set during the OAT peaks, minimising decreases in IOT. This can be clearly seen in the temperature chart (Fig. 8b and 9b), where SC4.2 shows a lower imbalance in IOT. Moreover, in mild seasons, ventilation is set during a short refreshing boost in the morning, following typical practices, and during the late afternoon and evening, ensuring that IOT remains near the threshold within comfort limits. Meanwhile, during summer, ventilation is applied whenever OAT is below the IOT. Therefore, IOT follows OAT in parallel when the latter is within a pleasant range (Fig. 8b and 9b), while ventilation is paused and thermal inertia is utilised to keep fresh IOT within acceptable limits for as long as possible, even when external OAT is elevated. This is made possible by the already existing higher



(a) Annual comfort condition according with EN 16798 [18], cold: blue, comfortable: yellow, hot: red.



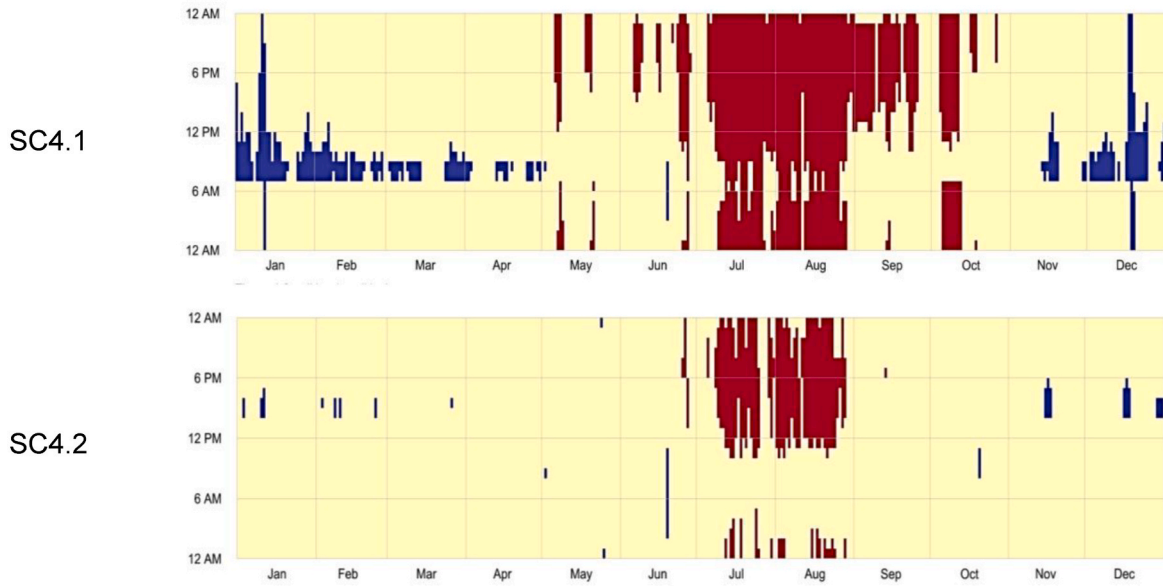
(b) Mean air temperature per month: OAT: blue, IOT: red, and mean NICT per month (yellow).

Fig. 7. Compared energy-comfort results of two cases study dwellings in SC3 (2080).

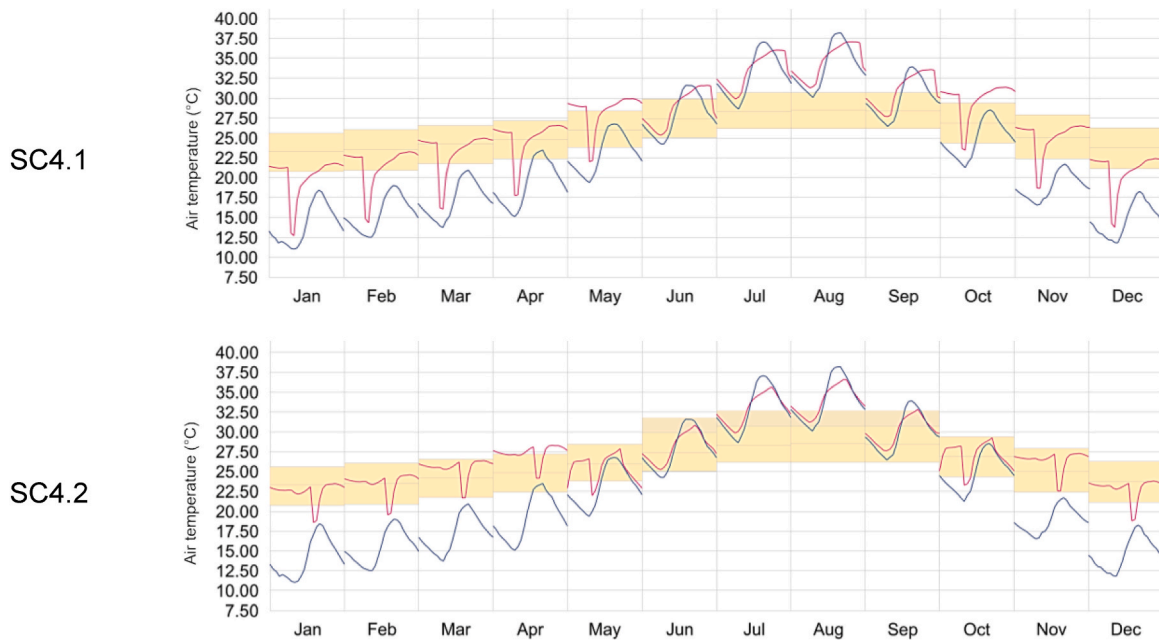
thermal inertia (See Appendix A5-d and A5-e).

Although ventilation optimisation improves daily temperature cycles, the rise of OAT due to CC often leads to uncontrolled increases in IOT. To address this, a hybrid low-energy strategy is proposed using ceiling fans. While not strictly passive, these devices operate with negligible energy intensity while significantly expanding the adaptive comfort polygon [42]. According to EN 16798 [18] and recent experimental studies [85], elevated air speeds increase the upper operative temperature threshold by up to 2-3°C. This results in more hours in

comfort conditions without active cooling systems. Comfort charts for SC4.2 (Fig. 8a and 9a) show clear improvements in both dwellings, with A_M2 achieving comfort conditions almost year-round, for 93% of annual hours, while B_R1, the least favourable unit, still displays a lower percentage of annual hours of comfort, 82%, but indicates better outcomes for the rest of dwellings.



(a) Annual comfort condition according with EN 16798 [18], cold: blue, comfortable: yellow, hot: red.



(b) Mean air temperature per month: OAT: blue, IOT: red, and mean NICT per month (yellow).

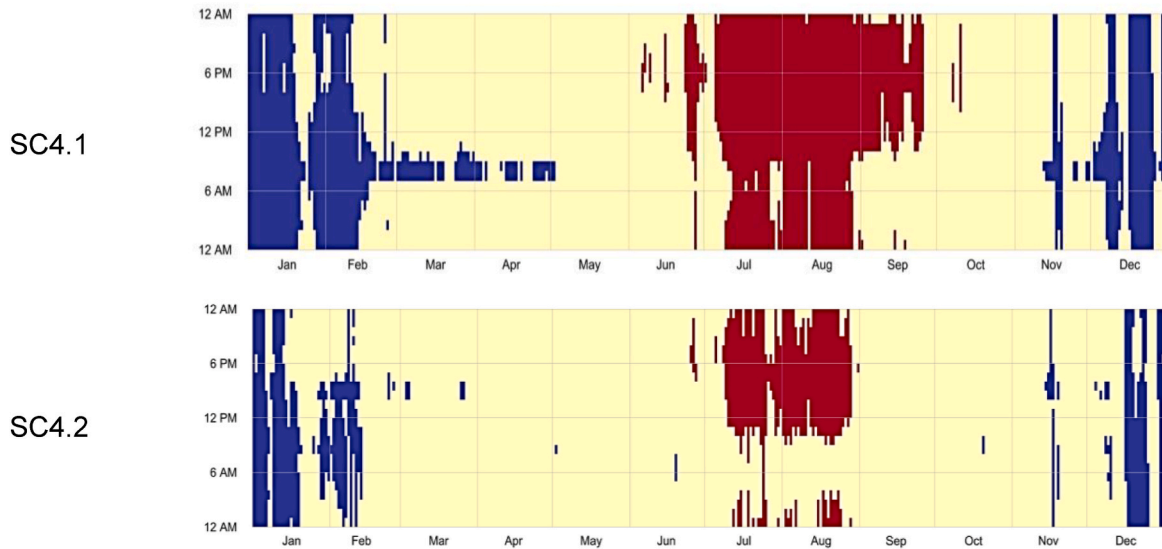
Fig. 8. Compared energy-comfort results of A_M2 case study in SC4.1 vs SC4.2 (improvements in 2080).

3.4. Discussion

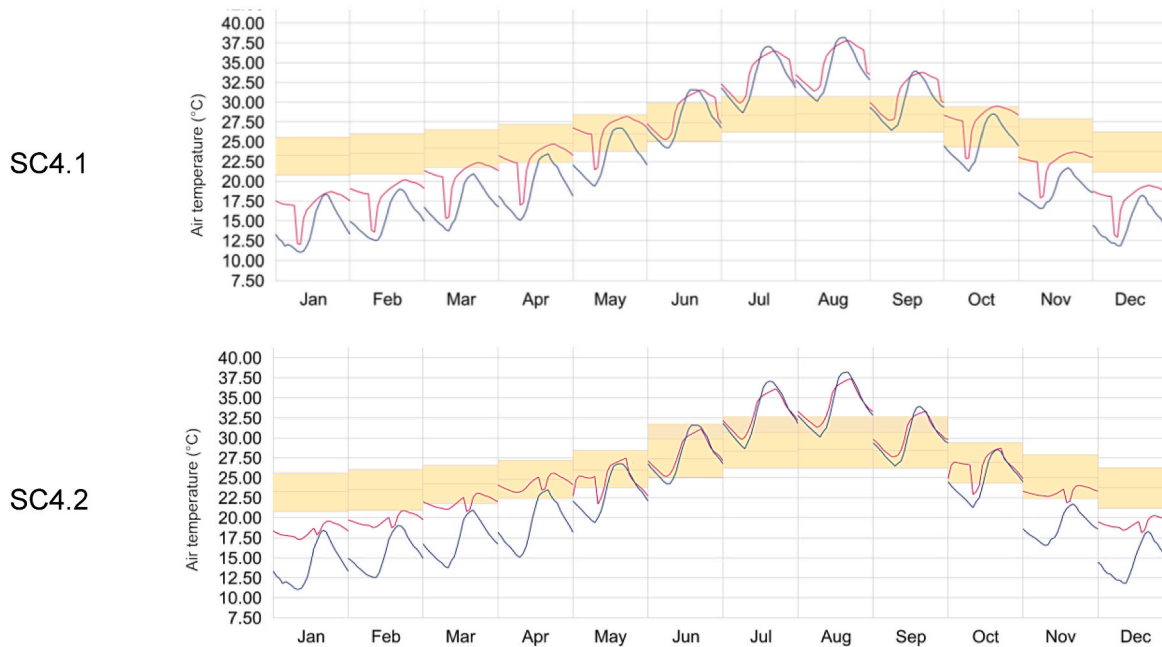
The findings presented in this study are based on a normative modelling approach [86] employing standardised occupancy profiles [47] and internal gains from established standards and statistical databases [11,18,82,84]. This methodology may introduce uncertainty in absolute predicted values, which may vary in occupied dwellings depending on actual user behaviour and operational patterns. However, the relative performance trends between scenarios, dwelling positions, and climate conditions remain methodologically robust. Consequently, the principal conclusions regarding the effectiveness of passive strategies and the inefficacy of regulation-based interventions under future climate scenarios are substantiated by the comparative analysis

framework employed.

The evolution over time analysis across scenarios SC1, SC2, and SC3, as summarised in Fig. 10, reveals key insights into the building's performance. In SC1, despite low energy efficiency and poor winter comfort (around 10% comfort hours), the building performs well in mild climates, achieving 80% of comfort hours from May to October, validating the MoMo architecture principles in the particular case of this temperate climate. The design's double orientation allows cross-ventilation and sunlight exposure, but lack of insulation and thermal inertia cause severe winter discomfort, with percentages near zero and IOT below 18°C. As the climate changes in SC2 and SC3, winter conditions slightly improve, but summer comfort deteriorates significantly, with IOT at 30-40°C throughout the day. According to Table 5, buildings from the 1960



(a) Annual comfort condition according with EN 16798 [18], cold: blue, comfortable: yellow, hot: red.



(b) Mean air temperature per month: OAT: blue, IOT: red, and mean NICT per month (yellow).

Fig. 9. Compared energy-comfort results of B_R1 case study in SC4.1 vs SC4.2 (improvements in 2080).

s will achieve an average of 61.9% comfort hours per year by 2080, demonstrating the partial effectiveness of the original design but also the need for improvements to address discomfort hours.

The analysis provides a comprehensive diagnosis of the case study's performance, extrapolated to these archetypal buildings, highlighting key issues and necessary measures. A major problem is the lack of insulation and thermal inertia, causing IOT to fluctuate with OAT, leading to poor winter comfort and difficulty in maintaining acceptable IOT in summer despite ventilation. Effective solar control and rationalised ventilation management are crucial. Orientation-specific issues were identified, and traditional solar control methods for south-facing facades were ineffective for east- or west-facing facades. Additionally, orientation, placement, and exposure in the building significantly impact performance, as differences between A_M2 and B_R1 and results

in Fig. 4 have shown.

The regulation-based retrofitting (SC4.1) reveals a counterproductive 'thermos effect' under future climate conditions. While the intervention successfully decouples the dwelling from winter cold (increasing comfort by 30%), it unintentionally traps internal heat gains during the extended summer of the 2080 scenario. The standard retrofit not only fails to mitigate overheating but exacerbates it compared to the non-insulated scenario in specific peak periods, reducing August comfort hours by nearly 20 percentage points (Fig. 11). New insulation limited maximum IOT to 37.5°C during summer (Figs. 8 and 9), but thermal comfort did not improve due to overheating from increased thermal inertia. Based on the average results across all dwellings, Table 5 shows how cold discomfort conditions have improved from 22% to almost 9% of total annual hours, while comfortable hours improved

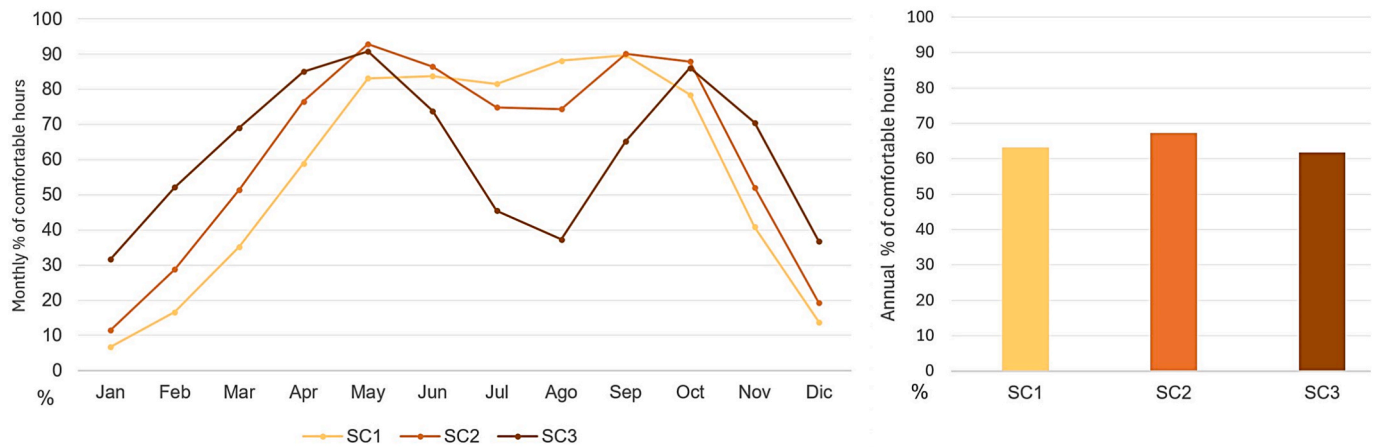


Fig. 10. Mean comfort hours of all 18 analysed dwellings assessed through the temporal scenarios, first monthly (left), and then annually (right).

Table 5

Summary of annual comfort condition results for the 18 dwelling per scenario, in %.

Comfort condition (%)	SC1	SC2	SC3	SC4.1	SC4.2	SC No-UHI
Cold	40.7	32.5	22.1	8.9	2.7	4.0
Comfort	56.6	62.3	61.9	74.4	92.0	93.7
Hot	2.7	5.2	16.0	16.7	5.4	2.2

from 62% to 74%. Despite this improvement, the summer worsening seen previously has increased hot discomfort, on average, by 0.7 percentage points, demonstrating the limited or even negative effectiveness of standard-based measures for warm climates. European energy standards [8,16,18], with envelope and insulation mainly focused on cold winter climates, overlook summer conditions, which are increasing in length and frequency due to climate change [2,36]. These standards assume that mechanical HVAC systems are used in buildings [25,39], but many southern European buildings, especially low-income ones, operate passively [47], leading to summer overheating (Fig. 11). This highlights the limited and counterproductive nature of widely imposed measures and standards, which may worsen conditions in increasingly warm climates [3] due to their failure to adapt to regional reality.

Therefore, a passive-adapted solution is proposed to better address the previous issue. A substantial improvement in IOT control is achieved by rationalising and optimising ventilation, reducing average daily maximum temperatures by 1–1.5°C during July and August (Figs. 8 and

9). Additionally, the use of fans results in much more acceptable comfort conditions, as seen previously [42]. Although electric fans consume electricity, they are considered a passive cooling strategy in building energy performance standards and scientific literature [18,85]. This classification is justified by their negligible energy impact compared to mechanical cooling systems. A typical ceiling fan consumes approximately 60 W, whereas a standard split air conditioning unit for a residential room (15–20 m²) typically requires 700–800 W of electrical power. Consequently, ceiling fans consume less than 10% of the energy demanded by active mechanical cooling systems while still providing thermal comfort improvement through air movement in temperate to warm conditions. In these conditions, SC4.2 achieves an average annual comfort level of 92% (Fig. 11). These results, compared with 62% of SC3 and 74% of SC4.1 (Table 5) represents an annual improvement of nearly 30 and 20 percentage points respectively. As shown in Table 5, hot discomfort decreased from 16.7% in SC4.1, to 5.4% in SC4.2. This improvement is further detailed in Fig. 11, which clearly demonstrate an improvement of up to 45 percentage points in comfort hours during August for the optimised scenario. This success is partly due to the original MoMo health-focused design [12,13,30]. Moreover, given the widespread presence of this archetype across Europe [28], this methodology, improvement, and resulting positive outcomes are impactful and easily replicable for many outdated case studies.

Despite the overall good results obtained in SC4.2, the 5.4% of annual hours, and a considerable percentage of summer hours still fall outside comfort conditions (Fig. 8a, 9a, 11 and Table 5), requiring active

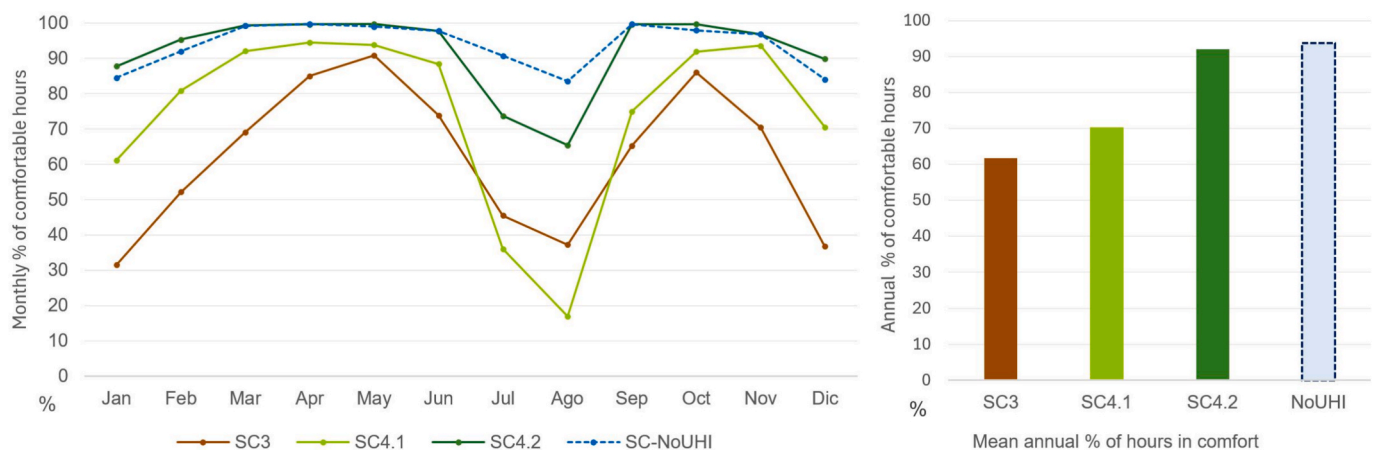


Fig. 11. Mean comfort hours of the 18 analysed dwellings assessed in the 2080 scenarios, comparing the current status and the diverse strategies applied. First monthly (left), and then annually (right).

systems or risking occupant discomfort and health [21]. Current research and literature offer limited additional passive solutions, with options like passive evaporative-cooling systems [89] or phase change materials [90], but these remain complex and unaffordable for many. Another alternative, planned urban space interventions to reduce temperatures and mitigate the UHI effect, could improve outdoor comfort [59] and reduce OAT and IOT. Studies show a 1.5°C reduction in OAT just from passive urban strategies [60]. In this regard, this research proposes to assess the hypothetical effect of a scenario that removes the UHI effect (SC.NoUHI), repeating SC4.2 but using a rural EPW file that excludes UHI effect. Preliminary results are promising, with SC.NoUHI achieving nearly 20 percentage-point increases in summer comfort, reaching 85% of passive comfort hours in August (Fig. 11) and reducing hot discomfort from 5.4% to 2.2% of annual hours, reaching a final 93.7% of total comfortable hours, (Table 5). These findings highlight the need for further research to address existing building improvement limitations.

The passive improvement proposed to complement standard-based ones involves minimal energy consumption. Proper energy rehabilitation, fans, solar control and rational ventilation can significantly improve living conditions and save money, while common natural ventilation practices [47] often lead to thermal imbalances. However, users need to learn how to manage these home passive resources, and authorities and public organisations must raise awareness in order to disseminate and explain them. Therefore, success could be dependent on smart home-systems providing clear indications based on real-time OAT and IOT data. The implementation of low-cost monitoring devices systems can bridge the gap between building physics and occupant behaviour. By providing real-time environmental feedback (e.g., alerts when OAT < IOT), these interfaces empower users to activate passive cooling strategies precisely when thermodynamically efficient, maximizing the adaptive potential of the dwelling. Incorporating such dynamics into building regulations and standards can improve quality of life and economic savings for society without significant costs.

3.5. Study limitations and further research

The urban and architectural typology of the case study represents a widely prevalent archetype throughout Europe; however, this research has been conducted in a warm Mediterranean climate. Further studies should address analyses in other climate zones, such as arid, temperate, and cold climates, to compare and contrast findings and assess the transferability of conclusions across different climatic contexts.

Future climate projections are subject to inherent uncertainties stemming from both scenario selection and downscaling methodology. This study employs the RCP8.5 emissions pathway, representing the most severe climate trajectory projected by the IPCC, providing a worst-case reference against which actual climate evolution may prove less extreme if emission reduction efforts succeed. Moreover, climate downscaling tools inevitably introduce uncertainties into future projections. Although the accuracy of the CCWorldWeatherGen 1.9 tool has been quantified in Appendix A2, these uncertainties constitute a limitation that must be acknowledged. Specifically, temperature shows reliable accuracy, relative humidity has acceptable accuracy, whilst solar radiation shows some uncertainties.

A significant methodological limitation is the absence of calibration to measured performance data from the analysed dwellings. Actual thermal conditions in occupied dwellings will inevitably deviate from model predictions due to diverse occupant behaviours, interior modifications, and operational patterns not captured by standardised assumptions. This limitation particularly affects the absolute validity of predicted comfort percentages and temperature values for individual dwellings. The study's design as controlled parametric scenarios, where only specific variables are modified in each case (climate conditions, envelope properties, dwelling position), requires isolating these targeted effects from the confounding influence of occupant variability across

multiple dwelling typologies. Conversely, calibrating accessible dwellings would compromise the generalisability required for archetype-based comparative analysis. Therefore, whilst absolute values carry inherent uncertainty, the relative performance trends and comparative differences between scenarios, which constitute the study's principal conclusions, remain methodologically valid.

Additionally, dwellings were modelled as a single thermal zone, following previous methodologies [81], meaning internal divisions and door operations were not considered. This simplification may underestimate peak temperatures in rooms with south-west orientations or restricted cross-ventilation, particularly during extreme heat events. The extent of this underestimation depends on dwelling-specific factors, including internal layout, door management, and occupant behaviour. Conversely, single-zone modelling may overestimate the effectiveness of night-time cooling, which relies on specific opening configurations, vertical airflow, and thermal stratification. A more detailed assessment of ventilation fluxes would require multi-zone or CFD modelling to evaluate internal distribution and cooling potential more precisely. Furthermore, specific results and the improvements obtained have depended largely on natural cross-ventilation. This is strongly linked to the architectural design of the case study (double façade and cross ventilation), which has enhanced the passive results. Further research should explore other typologies with less ventilation capacity.

Finally, this work has focused on indoor comfort conditions, categorising them as comfortable or uncomfortable. However, it has not graded or quantified the degree of comfort or discomfort within the established rigid margins. It is also important to note that as this study focuses on passive free running buildings, so that the results could not be extrapolated to actively climatized spaces. Therefore, future approaches can focus on mixed scenarios and translate the results into quantifiable terms of energy consumption reduction needed to counter discomfort situations.

4. Conclusions

This study proposes the resilience evaluation of a standard-based retrofit for a representative case of 20th-century social housing against future overheating due to CC. A scenario-based analysis methodology, considering the case study temporal evolution, has been developed, providing a valuable preliminary diagnosis of the main problems these buildings are expected to face in the near future. The major shortcomings identified include lack of insulation, low thermal inertia, no solar protection, uncontrolled ventilation, and infiltrations. However, despite these issues, the buildings also demonstrate a capacity for potential environmental adaptation, thanks to the original MoMo design.

The projected results from the standard-based retrofit indicate the limited effectiveness of current standard approaches for passive buildings in warm climates. While these measures improve winter comfort by up to 30 points, their lack of adaptation to warm climates may reduce summer comfort by up to 20 points compared to pre-intervention conditions, resulting in only a 9-point increase in mean annual comfortable hours. In response, this study proposes a complementary passive and adaptive improvement, where rationalised natural ventilation and the use of fans could significantly enhance summer conditions, potentially increasing comfort hours by 40 points over the standard-based retrofit, reaching approximately 90% annual comfort hours. Additionally, this research explores how mitigating UHI effects through urban interventions could improve indoor comfort, suggesting a potential increase of 15–20 points in summer comfort hours. These findings suggest the need to revise current standards and norms to effectively address future overheating scenarios and the scarcity of research on the real effects of urban interventions on indoor comfort. Consequently, this study argues that European directives must urgently evolve from a 'heating-dominated' logic to a 'resilience-first' framework. Mandating high-insulation retrofits in social housing without simultaneous requirements for adaptive ventilation strategies is not merely inefficient; it

is a vector for future energy poverty and health risks.

In conclusion, implementing measures not solely based on generalist standards but grounded in scientific research on local climate and its future overheated projections, can offer a good opportunity to enhance the comfort of residents in outdated housing, while substantially reducing energy costs. These additional low-cost improvements, potentially applicable with accessible smart devices and user awareness, can be integrated into the numerous rehabilitation efforts already underway across Europe. The methodology and positive results presented, applied to an architectural archetype which is widely prevalent in Europe, suggest increased impact and replicability potential. As climate change projections continue to exacerbate environmental and social challenges, these adaptive, passive strategies beyond current standards are crucial for fostering more resilient, sustainable communities. The more widespread adoption of these approaches can have a lasting, positive impact on society, aligning with global efforts to address both climate and social inequalities.

CRedit authorship contribution statement

Javier Sola-Caraballo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Investigation, Formal analysis, Data curation. **Victoria Patricia López-Cabeza:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation. **Eduardo Diz-Mellado:** Visualization, Validation, Investigation, Formal analysis. **Carlos Rivera-Gomez:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Carmen Galan-Marin:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

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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Appendix A. Supplementary data

Supplementary data to this article including plans, images, and simulation data of the case study can be found online at <https://doi.org/10.1016/j.enbuild.2026.117673>.

Data availability

Data will be made available on request.

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