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Mitigating Overheating Risks for Modern Flats in London Due to Climate Change

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Abstract: With the increase in global temperatures, a significant threat of overheating has been reported due to more frequent and severe heatwaves in the UK housing stock. This research analyzes dwellings' physical attributes through overheating assessments and their adaptation for modern flats in London in the current (2022) and anticipated (2050) weather. According to preliminary research, Southeast and London in England, mid-terraced, and flats (especially built post 2012), among other archetypes, were discovered to be the most susceptible to overheating in the UK. This study employed a case study of a 2015 modern flat located in a high-risk overheating zone in London to understand the building's overheating exposure. A range of Dynamic Thermal Simulations (DTS) was conducted using EnergyPlus with reference to case studies in order to assess the performance of passive cooling mitigation strategies (PCMS) on peak summer days (15 July) as well as during the summer against CIBSE Guide A and ASHARE 55. Reduced window area and LoE triple glazing were identified as excellent mitigation prototypes, in which solar gains through exterior glazing were reduced by 85.5% due to triple glazing. Zone sensible cooling was reduced by 52%, which minimized CO_2 emissions. It was also identified that the final retrofit model passed CIBSE Guide A by achieving a temperature threshold of 20 °C to 25 °C during the summer months, whereas it failed to accomplish the ASHARE 55 criteria (20–24 °C). The outcome of this study justifies the necessity of tested PCMS and advises UK policymakers on how to foster resilient housing plans to overcome overheating issues.

Keywords: overheating; climate change; passive cooling mitigation strategy; modern flat; EnergyPlus; thermal comfort; London

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1. Introduction

Since the UK government is scaling up its efforts towards net zero, resilient higher adaptation goals should be implemented against heatwaves. The UK's average surface temperature has increased by 1.2 °C since the pre-industrial era (1850–1900) [1]. As per UKCP18, which is largely in connection with prior predictions of UKCP09 [2], by the end of the 21st century, the UK climate will continue to warm, and the sea levels will continue to increase. Given the current weather, there is a moderate concern in the Midlands and Wales, and the risk is particularly high in the Southeast of England, where London is the hotspot. There is currently little risk to Scotland, Northern Ireland, and Northern England [3].

A dwelling exceeding 24 °C of OT can disrupt sleep quality and cause discomfort. CIBSE TM59 recommends that peak bedroom temperatures should not exceed a threshold of 26 °C [4], which can be referred to as overheating. Practically, the air temperature is utilized to assess overheating by measuring humidity, absence of airflow, radiant heat, and duration of heat exposure for the region [5]. These periods of unusually hot weather in the summer are classified as heatwaves [6].

The UK witnessed record-breaking heat on 18 and 19 July 2022, with temperatures over 40 °C in London. As per Zachariah [7], these days were announced as red alerts (heatwaves), so rare with a 1 in 100 chance that they were statistically impossible before the Industrial Revolution. The Level 4 heat-health alert "national emergency" was declared by the UK Health Security Agency. The extreme heat caused an increase in hospital admissions, numerous fires, and serious disruptions in public transit [8]. If efforts are not made to tackle global warming, parts of the UK could theoretically experience an average temperature of 40 °C in July 2050, as predicted by the Met Office [9]. But then, there will also be individual weather events like today, where heatwaves could reach 45 °C, or even become closer to 50 °C, in 2050 [9].

According to the statistics of UK housing stock and its energy performance, in 2020, 46% of the stock had the highest EPC band A to C, as opposed to 14% in 2010, whereas only 11% of the stock was categorized in band E to G in 2020, which was 39% in 2010, as shown in Figure 1 [10]. Therefore, it can be concluded that during the last decade, the energy performance of UK dwellings has significantly improved due to the utilization of sustainable building elements and HVAC systems, which led to higher EPC bands.

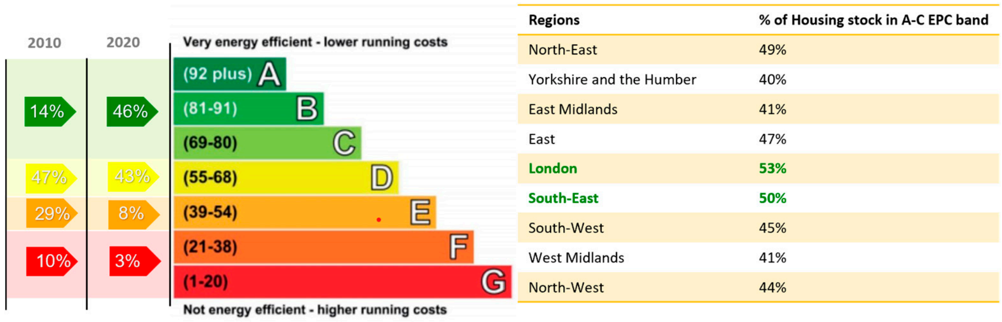


Figure 1. The increase in energy efficiency of UK housing stock between 2010 and 2020 [10].

According to the census of 2021 [11], households with the highest median energy efficiency score were identified in London (53%) and the Southeast (50%) compared to all other regions in England. London has a lower number of homes with F or G bands and the highest number of homes with an EER (energy efficiency ratio) of A or B. This indicates that one of the most overheating-prone regions (London) experiences a high level of internal heat gains during the summer despite having the highest EPC ratings due to climate change and location. Consequently, adaptive strategies and mitigation measures should be implemented to alleviate the discomfort of the occupants.

In terms of internal heat gain, the old dwellings somewhat perform better compared to modern structures due to the lower air infiltration rate employed, as per Approved Document Part F-Ventilation [12]. But overheating episodes were still reported in old constructions. A substantial amount of secondary data was discovered highlighting retrofit overheating mitigation measures for traditional housing stock (1900–2000) that effectively improved thermal comfort. However, limited data were found for high-EPC-rated modern flats (constructed after 2012) in terms of overheating adaptation. They are greatly vulnerable to overheating due to their high level of airtightness [12].

The aim of this study is to assess the overheating conditions in modern flats with the EPC bands A, B, and C in London and test relevant PCMS for the current climate and a 2050s 90% high-emission weather scenario during summer, with an emphasis on the extreme summer month of July. This is achieved by developing dynamic thermal modelling (DTM) of a modern flat and examining the extent of improvement in internal thermal comfort against CIBSE Guide A and ASHARE 55, 2017 by performing sensitivity analysis on various PCMS. The discovered set of PCMS may become a toolkit for experts (retrofit consultants, manufacturers, architects, designers, etc.), which can be executed from the design stage as well as employed in the retrofitting of UK housing stock. The following objectives are formulated to accomplish the aim:

- to discover and analyze existing literature on UK housing stock in terms of overheating exposure during the summer due to climate change and its mitigating solutions,
- to determine the OT exceeding the habitable temperature (25 °C) and examine PCMS,

- to achieve energy-efficient combinations of PCMS for UK domestic dwellings that will eliminate overheating risks in the present and future climatic probabilities.

2. Context and Background Knowledge

This climate change scenario and its percussions in the future in terms of overheating exposure in the UK housing stock were discussed. British standards providing an internal housing threshold temperature for overheating analysis were identified. Major factors responsible for internal heat gains were explained thoroughly. The examined PCMS were reviewed from the secondary literature. Highly durable and efficient PCMS were recognized and further evaluated in this study.

The research gap was distinguished from the analysis of current literature, which facilitated the authors' construction of methodology.

2.1. Climate Change Causes Overheating in the UK Housing Stock

The UK's Climate Change Risk Assessment (CCRA3) took into account emission scenarios as of mid-2021. The emission scenario RCP2.6 targets keeping global temperatures below 2 °C, while RCP6.0 fits within the present policy compatibility, showing a 4 °C increase at the end of the 21st century [9,13]. Adopting COP26 concepts into practice globally, RCP2.6 might be accomplished by 2100. Climate Action Tracker, however, voiced reservations about how realistic it would be to achieve the COP26 targets of reducing emissions by 2030, thereby placing a burden on the carbon budget for 1.5 °C [14]. The UK building regulations and policies have addressed climate change by prioritizing adaptation to colder winters while paying minimal attention to overheating problems in modern structures.

According to official statistics from the UK Valuation Office Agency [15], terraced houses represent 26.3% of all housing stock in England and Wales, followed by semi-detached houses (23.8%) and flats (23.2%). The research, which concentrates on areas vulnerable to overheating, indicates that flats comprise the majority of housing stock in London (55%), while the Southeast region has a more evenly distributed mixture of terraced houses (24%), flats (23%), and semi-detached houses (21%) [15]. The size, layout, and construction of a house affect the ways it reacts to heat. Typical UK archetypes are shown in Figure 2, each with unique sizes and geometric characteristics that influence overheating [3].

Figure 2. Classification of the Housing Stock, UK (created by author through Adobe Photoshop); derived from [3].

A qualitative study and experimental results on categorized housing stock demonstrate that the threat of overheating differs by house type. Due to their wider floor space, detached houses have the lowest risk, followed by semi-detached and end-terraced houses [3]. Mid-terraced houses suffer a larger risk because of their smaller size, while contemporary flats are the most vulnerable. Modern apartments with full-height glass and restricted ventilation alternatives are aggravated by the excessive air tightness imposed by Approved Document Part F [12], particularly in those built after 2000. Top floors are especially prone to overheating since hot air rises quicker than cool air and has less possibility for cross-ventilation owing to their limited windows [3]. The study focuses on modern apartments due to their predominance in London (55%), possibly providing mitigation prototypes for experts to address overheating problems in 55% of London's flats and 23.2% of dwellings (flats) in England and Wales overall.

Based on the English Housing Survey 2020–2021 [16], 8% of English homes experienced excessive heat in at least one room, with a 40% rise in overheating in living areas and bedrooms since 2018, once anticipated for the 2050s [17]. Flats and little houses in London and the Southeast were particularly vulnerable. Only 2% of English houses recorded utilizing air conditioning, whereas 50% utilized portable fans [18]. Due to hot, impure urban areas, increased air conditioner usage in the UK strains electricity supply and burdens the impoverished with prices. Furthermore, the discharge of heat waste from air coolers exacerbates the consequences of urban heat islands [19,20].

2.2. British Standards for Comparative Overheating Analysis

Different definitions of overheating are presently used to evaluate a property's overheating risk in the UK, during both new construction and retrofitting. Table 1 shows the comparison of UK standards in relation to overheating.

Table 1. Comparison of UK standards in terms of overheating.

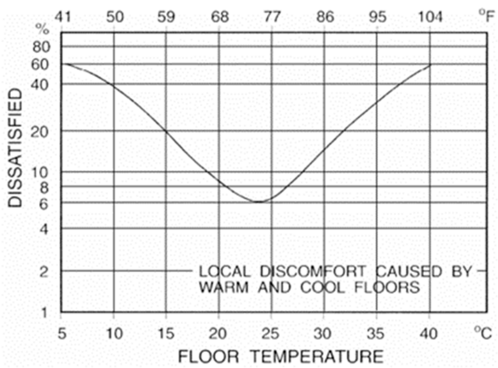
Standard	Synopsis	Concise Explanation	Scope
SAP Appendix P [21]	Assessment of a dwelling with an overheating risk in the summer. Does not provide cooling needs, does not affect SAP rating or CO_2 emissions, and is non-integral	Assessment method for a Threshold Temperature: 20.5–22.0 °C low risk, 22.0–23.5 °C medium risk, ≥23.5 °C high risk	To evaluate and compare dwelling (both existing and new) energy performance
ASHRAE 55 [22]	Describes thermal comfort to explain acceptable levels of internal thermal temperature for occupants	Based on occupant activities, clothing insulation levels, ventilation, air speed, humidity, acceptable air temperature change, and OTs are identified. Optimal comfortable OT ranges between 20 °C and 24 °C.  DB utilizes EnergyPlus report outputs, which use ASHARE 55-2010 to validate occupant thermal comfort with reference to outside temperature	To identify appropriate thermal comfort levels for occupants under a wide range of conditions

Table 1. *Cont.*

Standard	Synopsis	Concise Explanation	Scope
CIBSE Guide A [23]	Provides benchmark summer temperatures and overheating criteria	The adaptive approach to comfort, CIBSE, considers a range of OTs in which acceptable indoor conditions are related to outside conditions	To assist in the identification of various factors of overheating and guidance for mitigation
CIBSE TM59 [4]	Standard methodology to predict overheating risks for domestic building designs (new build or major refurbishment)	Two requirements are listed in CIBSE TM59: Criteria A for living rooms, kitchens, and bedrooms is as follows: During the months of May to September, the percentage of occupied hours where the operating temperature is 1 Kelvin or higher than the comfort temperature should not exceed 3%. Criteria B for bedrooms only: The OT in a bedroom from 10 p.m. to 7 a.m. should not exceed 26 °C for more than 1% of the annual hours to offer comfort (CIBSE indicates "guarantee comfort"). Overall, 33 or more hours over 26 °C are reported as a failure since 1% of the yearly hours between 10 p.m. and 7 a.m. for bedrooms is 32 h. The acceptable summer indoor design operating temperature for non-air-conditioned dwellings is 25 °C.	Dynamic thermal modelling of new and old residential structures under various conditions
CIBSE TM52 BS EN 15251: 2007 (European Standard) [24]	Indoor environmental parameters for building energy performance design and assessment address internal air quality, thermal environment, lighting, and acoustics. Provides guidelines for indoor conditions where occupant's comfort would not be compromised in the name of energy savings	Acceptable temperature range for free-running buildings and of PMV for mechanically ventilated buildings. Acceptable temperature of category I lies within ± 2 K, so the optimum temperature is considered between 24 °C and 2 °C	To recommend stable and adaptive criteria for thermal comfort assessment of all types of buildings

CIBSE Guide A and the ASHARE 55 method are utilized to predict OT, as the EnergyPlus dataset already possesses this benchmark within the software.

2.3. Accountable Factors for Overheating

The authors divided overheating factors into three parts: subjective heating sources, sociological factors, and the elements of dwelling that disrupt indoor air quality as shown in Figure 3.

2.3.1. External Air Temperature

The "Urban Heat Island Effect" (UHIE) is caused by variables such as industrial activity, big structures, and minimal green space, resulting in greater temperatures in highly populated metropolitan regions such as London [19]. Even in less densely populated urban zones with some vegetation, temperatures may still be roughly 2 °C higher than in rural areas, making night-time cooling difficult.

2.3.2. Internal Heat Gains

Human metabolism produces heat based on the type of activity and is proportionate to the amount of air inhaled (breathing). A sedentary adult not performing physical activity, for example, is expected to produce 58 W of heat per square meter of the skin's surface, or one metabolic unit (met) [25]. The lighting, electrical equipment, and services (boiler, thermostat, computer, gas stove, refrigerator) utilized through electricity are also converted into heat.

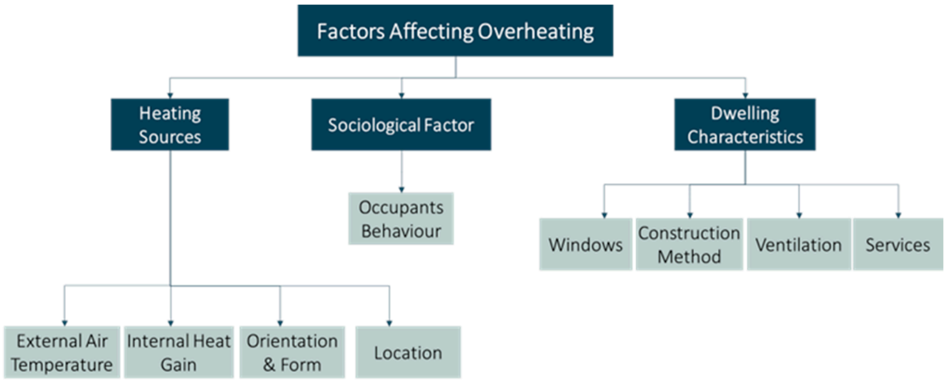


Figure 3. Overheating causing factors.

2.3.3. Orientation and Form

The ARUP panel [3] discovered that living areas facing west are the most likely to overheat, subsequently followed by those facing south, east, and north. In England, both ancient and modern mid-terraced structures frequently overlook orientation in design and construction, making certain properties more prone to overheating [5]. Apartments may have one side that is more prone to overheating than the other.

The Good Homes Alliance (GHA) [26] discovered 84 incidents of overheated residences using a survey that included environmental health officers, housing providers, residents, and consultants. In total, 59 of the 84 instances were flats (23 converted and 36 purpose built), mostly pre-1919 or post-2000 construction, implying that purpose-built flats in the UK tend to be more prone to overheating than those of other categories (Figure 4).

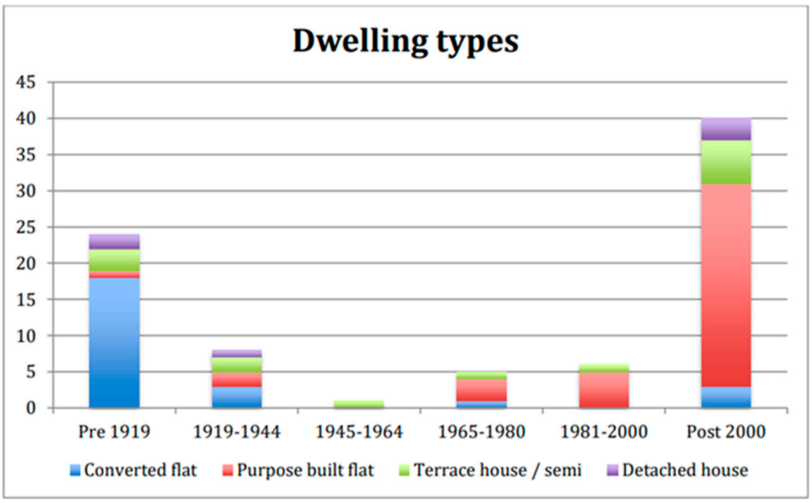


Figure 4. Classification of 84 Dwelling types suffering from overheating [26].

2.3.4. Location

People in urban areas like London may be reluctant to open windows due to extreme air pollution, noise, and security [5]. Among 58 dwellings, the highest number of overheated dwellings (32) was located in the urban areas, followed by 19 and 7 dwellings in suburbs and rural areas, as shown in Figure 5.

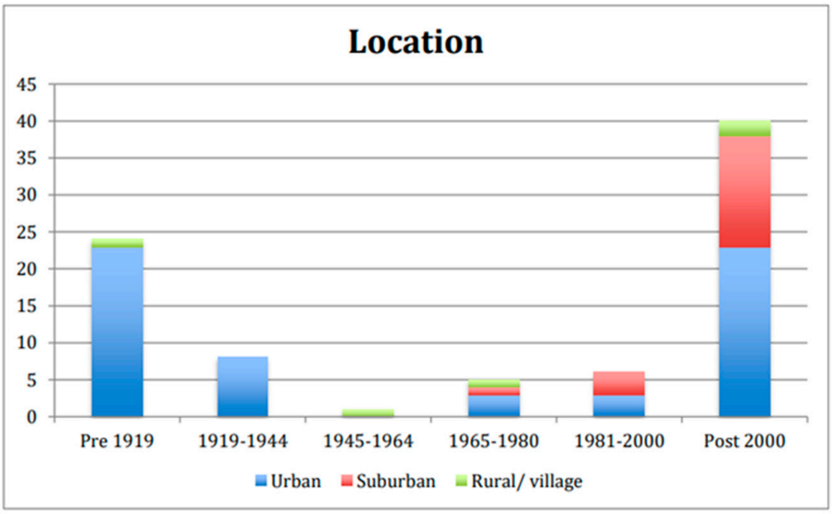


Figure 5. Distribution of 84 dwellings experiencing overheating as per location [26].

2.3.5. Windows

Any glazing with a large surface area accumulates solar gain, except north-facing windows. Homes in the UK usually lack window shading, which can result in excessive solar gain [27]. The heat from the radiation that is not reflected by blinds or curtains enters the room and heats the air in the room. Without window shade, solar energy is internally absorbed, and the heat is then gradually released back into the air of the space [5].

2.3.6. Construction Method

According to the English Housing Survey (EHS) [16], occupants in homes with insulated cavity walls and steel, concrete, or wooden frames have higher overheating issues compared to those in solid, uninsulated structures. Overheating rates in timber and steel frame structures are 18% and 17%, respectively [16]. Wall insulation, on the other hand, can minimize overheating in detached, end-terrace, and semi-detached houses with large outer wall areas, but has little effect on flats and mid-terrace structures with fewer external walls, according to ARUP's sensitivity assessments [3]. The efficacy of wall insulation differs based on location and climate, with that in Manchester being more effective than that in London. According to GHA's findings [26], uninsulated solid brickwork or stone masonry structures have the greatest overheating levels (31 homes out of 84), as opposed to insulated cavity brick/block and dwellings made of concrete, wood, SIPs, or steel (Figure 6).

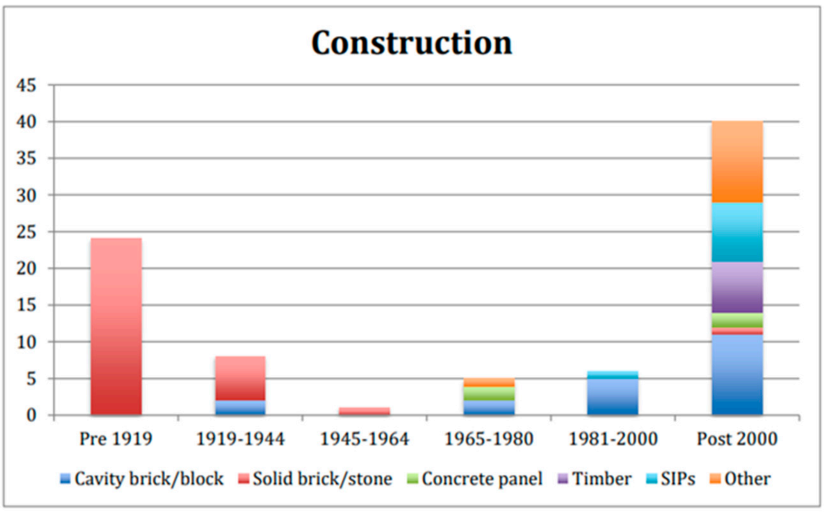


Figure 6. Construction types causing overheating [26].

According to Fosas et al. [28], insulation can contribute up to 5% of the overall overheating response in the UK homes, and increasing insulation levels may not always result in lower interior temperatures when window operation is restricted for safety purposes.

ARUP [3] and Fosas et al. [28] concluded that the influence of insulation on overheating is less significant when compared to glazing ratio, climate, location, building orientation, shading, and ventilation. External insulation serves an insignificant role in resolving overheating, particularly in new apartments, but when paired with other variables, it can help minimize the problem.

2.3.7. Ventilation

UK Part L building regulations [29] implied air permeability to be less than 10 $m^3/(h.m^2)$ at 50 Pa for domestic housing stock, highlighting the significance of regulated ventilation [30]. Mechanical ventilation with heat recovery (MVHR) is prevalent and required when a household's infiltration rate is less than 5 $m^3/(h.m^2)$; however, problems might emerge due to insufficient setup, training, and monitoring [31]. But it is widely used in Passivhaus and other well-insulated dwellings [32]. Surprisingly, Figure 7 shows that 42 homes with overheating rely on natural ventilation, demonstrating that simply opening windows is not sufficient. To reduce overheating, effective ventilation systems must incorporate design aspects such as window type, size, orientation, g-value, and night purge cooling capacities. Furthermore, post-2000 houses with specialized mechanical ventilation systems, as shown in Figure 7 [26], suffer heat-related concerns owing to installation, maintenance, or user control issues.

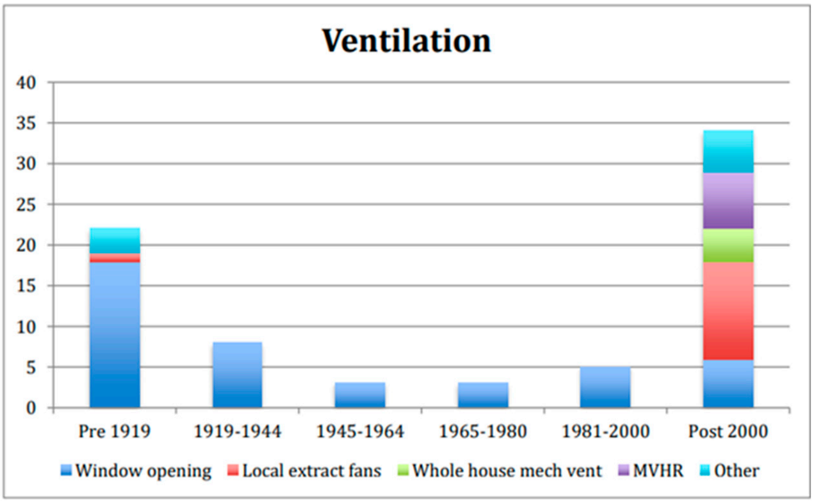


Figure 7. Overheating problems occurring in means of ventilation systems [26].

2.3.8. Services

It was crucial to take additional heat gains from community pipes into account when estimating the risk of overheating in flats that have a communal heating system. The usage of communal heating systems raised overheating risks due to heat loss from inadequate DHW pipes that are distributed through flats and corridors [3]. Uncontrollable underfloor heating that is malfunctioning may also cause major concern. Service voids for ventilation and pipes for drainage, electricity, water, and gas should be addressed to lower overheating.

2.3.9. Occupant Behavior

Houses with higher occupancy rates, such as those with elderly, disabled, or unemployed residents, were more susceptible to overheating because they were "in use" for an increased number of hours on a daily basis. Occupant activity can both increase and decrease the danger of overheating. Examples include window opening patterns, appliance use, and spatial layout. The use of heat-rejecting equipment often might potentially cause overheating. The risk of heat gain is higher when a bedroom is located in a hotter zone of the house, such as a south-facing space with glass windows. Bedrooms have lower thresholds for warming than living rooms [33].

2.4. Passive Cooling and Overheating Mitigation Strategies

Effective window design solutions are discussed to prevent internal heat gains from windows. Ventilation strategies and construction methods are highlighted, along with an additional non-passive method (Figure 8).

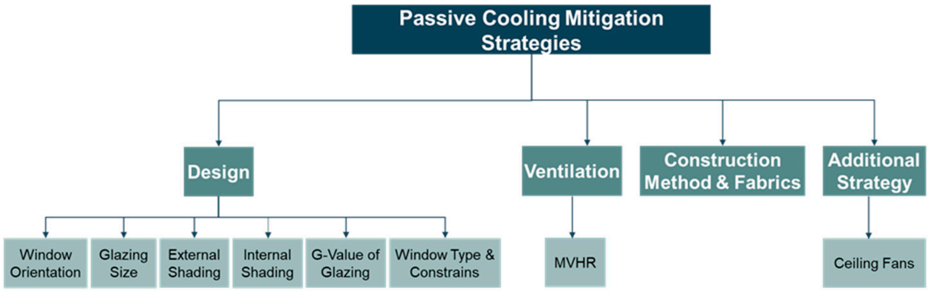


Figure 8. Accentuated parameters as mitigation strategies.

2.4.1. Window Orientation

In order to optimize solar benefits in winter and reduce overheating in summer, buildings should preferably be positioned north–south with maximum window coverage on the north façade to achieve daylight and a 15–25% glass area on the south façade. Orienting a residence north–south is not always practical. When developing openings for houses with an east–west orientation, extra attention should be paid to glazing areas and shading devices to address lower-angle sun radiation, which is usual at the start and end of the day in summer. Shading solutions like overhangs, louvres, external blinds, or shutters should be employed [34].

Approved Document O [35] has provided Window to Floor Ratios (WFR) for high and moderate overheating risk regions in the UK. Rooms of dwellings with and without cross-ventilation should not exceed the maximum glazing areas mentioned in Tables 2 and 3 below.

2.4.2. Glazing Size

Achieving excellent daylighting should be balanced against glazing size and placement. Vertical windows from floor to ceiling lose heat and create gains while being inefficient in increasing daylighting. For the same amount of window area, horizontal glazing offers more daylighting (Figure 9). With a larger sill height, it is also simpler to maximize the openable surfaces for passive cooling on horizontal windows [34].

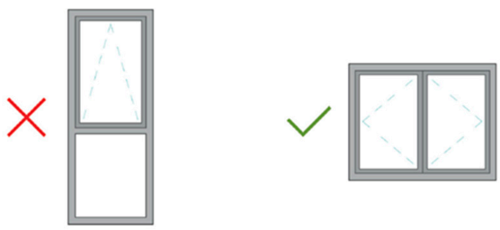


Figure 9. Glazing aspect and openable areas [34].

Table 2. Limiting solar gains for parts of buildings with cross-ventilation [35].

	High Risk Location		Moderate Risk Location	
Largest glazed façade Orientalin	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)
North	15	37	18	37
East	18	37	18	37
South	15	22	15	30
West	18	37	11	22

Table 3. Limiting solar gains for parts of buildings without cross-ventilation [35].

	High Risk Location		Moderate Risk Location	
Largest glazed façade Orientalin	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)	Maximum area of glazing (% floor area)	Maximum area of glazing in the most glazed room (% floor area of room)
North	15	26	18	26
East	11	18	18	26
South	11	11	15	15
West	11	18	11	11

2.4.3. Window Type and Constraints

The free-flowing, openable surface is determined by the window's size and opening technique. Tilted and top-hung windows have significantly smaller opening areas than side-hung windows, whereas inward-opening windows allow for exterior shutters and insect netting [34]. Porritt et al. [36] discovered that bottom-hinged windows decrease overheating by 11%, while top-hinged and side-hinged alternatives minimize it by 19% and 26%, respectively (Figure 10).

Figure 10. Types of windows [36].

2.4.4. External Shading

Overhangs and brise soleil are most suitable for south-facing windows to protect them from the high-level summer sun while not blocking the weak winter sun [34]. But, since the sun has a comparatively low altitude as it moves to the northwest in the mid- to late afternoon of summer, applying the same method to a west elevation would be less effective [37]. Moreover, the fixed shade or overhang should subtend a 60° angle to the bottom border of the glass, as shown in Figure 11 [34], where it is employed on the south windows. Vertical louvers and shutters are more suitable for northwest windows [37]. Deployable shading, like shutters, blinds, or awnings, is efficient where fixed shading is inapplicable. Automatic operation can be added where the shading device and window are not accessible [34].

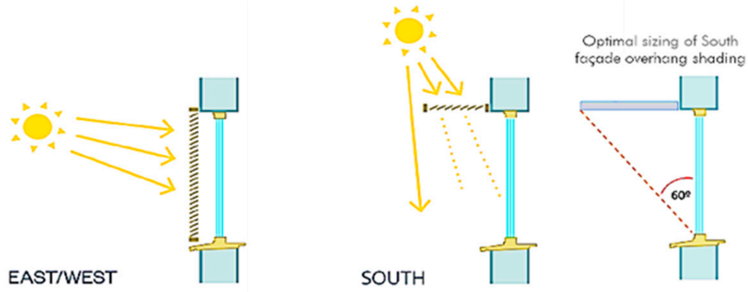


Figure 11. Shading strategies as per orientation [35] (created by author through Adobe Photoshop).

2.4.5. Internal Shading

If external shading is unattainable, internal shading can be considered, but it is less efficient. While internal shading can only limit solar gain by a maximum of 40%, external shading can lower it by 80–100% [34]. Depending on the behavior of the occupants, internal shading may limit cross-ventilation. For best results, it is worth placing white or reflective blinds behind the window, which would reflect the sun's radiation back out through the glass.

2.4.6. g-Value of Glazing

Solar gain can be minimized by glazing types with a lower g-value. The reduction in overheating risk needs to be balanced against the reduced winter sun light. A lower g-value also influences the quality of the vistas and the amount of daylighting throughout the year [34]. Adaptation of lower g-value glazing, particularly for overheating-prone locations, can be an efficient strategy.

2.4.7. Ventilation

Homes in the UK typically have 0.5 air changes per hour (ACH); however, mechanical systems may raise that number by 25–50%. With conventional systems, it is difficult to double ventilation to 1 ACH. No mechanical system can achieve this without being specifically constructed. Purge ventilation is at least four times as high or eight times the average, but it demands wide-opening windows. Sustainable ventilation should be passive and not rely on fuel. Therefore, the best passive ventilation technique would be night purge ventilation, since it achieves cooling overnight during the summer.

2.4.8. MVHR

When it is warm both indoors and outside, a smarter MVHR system detects it and activate "Summer Bypass Mode" [38]. These filters enter the fresh air and exhale warm, humid air. Yet, even in the boost mode, a typical Passivhaus MVHR system only generates approximately 0.5 ACH, providing barely any cooling, no more than opening windows [34]. A larger MVHR unit for more cooling is not practical due to restrictions imposed by larger duct diameters, higher unit costs, high energy consumption, and operational noise. Summer bypass is not mentioned in the UK BRs document F-Ventilation [12]. Consequently, the author would not be employing the MVHR unit as a modification tool.

2.4.9. Construction Methods and Fabric Interactions to Prevent Overheating

Lee and Steemers [39] evaluated the overheating of a historic mid-terraced house in London under four contexts (insulated/uninsulated cavity masonry, insulated/uninsulated timber frame masonry) with natural ventilation and internal blinds. Insulated timber framing performed worse than cavity masonry; insulation made overheating worse in a south-facing bedroom that was only used at night. Although solar blinds and opening windows reduced temperatures, they were not practical owing to security issues. According to Gupta and Cregg [40] research, exterior insulation was the most efficient, whereas internal insulation was the least effective and likely to cause severe heat gains. Thus, combining PCMS with effective external insulation would prevent overheating.

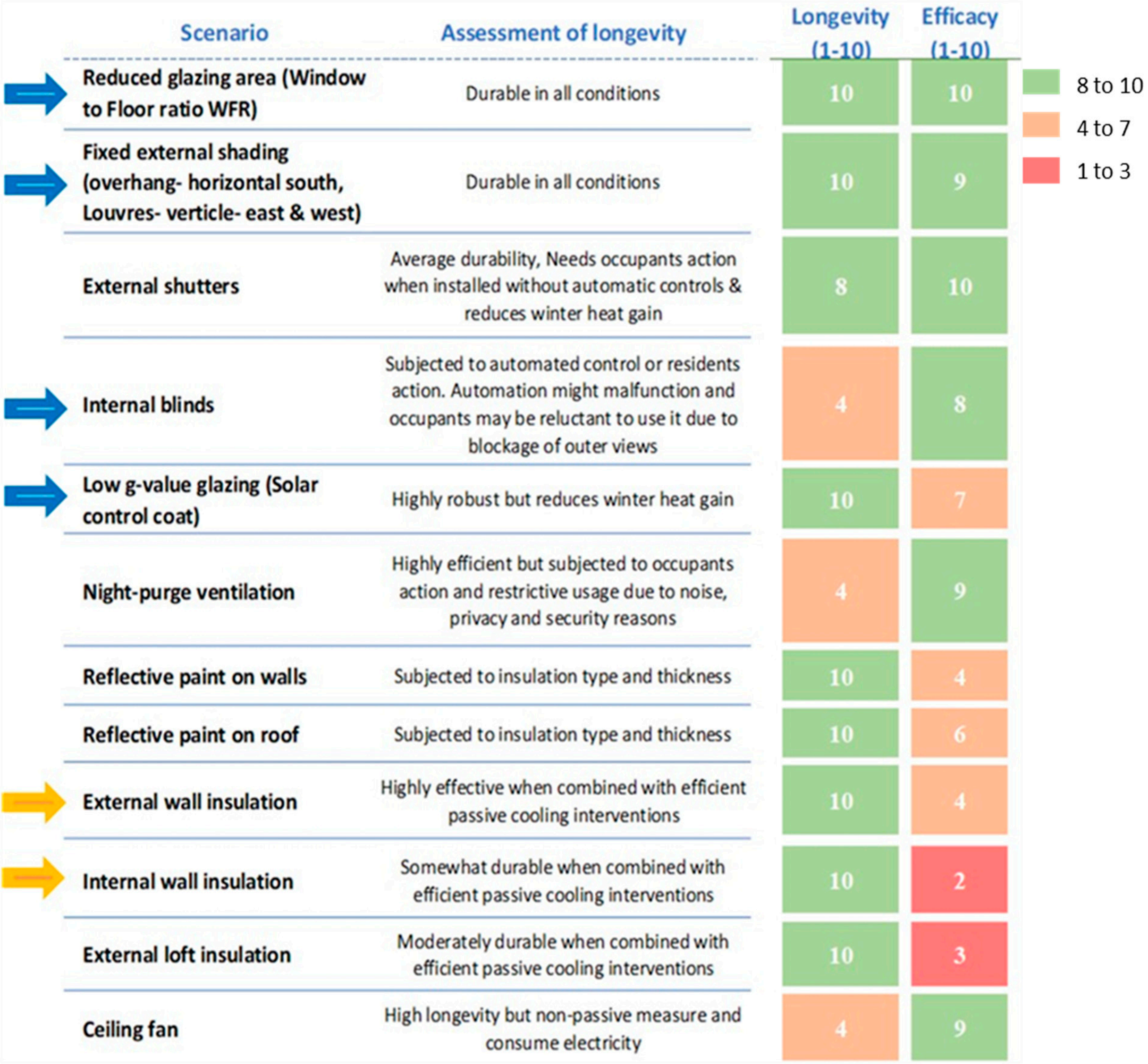
2.4.10. Additional Strategy: Ceiling Fans

Although ceiling fans do not attain factual cooling, they can result in a perceived temperature decline of 2–3 °C and are hence useful in sustaining comfort levels where a low degree of overheating is recorded [3]. Designers should install fans at 2.5 m or more of ceiling height for a suitable amount of airflow [5].

2.5. Discussion of Combined PCMS and Their Results as Per Climate Change

Dynamic thermal simulations (DTS) were performed by several researchers, including Wright and Venskunas [27], Morten [41], and Li et al. [42]. They studied the possible influence of future warming temperatures on overheating in conventional English dwellings. They examined potential mitigation strategies under high- and medium-emission scenarios from the present, 2030s, 2050s, and 2080s. External sun shade and natural ventilation, particularly at night, were the most effective overheating mitigation techniques, lowering overheating by around 50%. Morten [41] underlined the importance of outside drapes and automated shutters in mitigating future climate change. External shutters were shown to be the most effective method, followed by low g-value windows in living areas by ARUP's Bouhi et al. [3], but ceiling fans were an equally beneficial low-energy method compared to active cooling. Li et al.'s [42] simulation results revealed that solar control devices reduced median degree hours by 54%, external shutters, low g-value windows, and night purge ventilation decreased heat gain by 96%, 86%, and 89%, respectively, while internal curtains and roller blinds lowered heat gain by 57% and 50%, respectively.

Figure 12 highlights the ranking of PCMS as per longevity and efficacy after thoroughly analyzing the secondary literature. The blue tick measures were applied and tested on the dynamic thermal model of a selected case study (a modern flat in London), while the yellow tick measures already existed in the base model.



Scenario	Assessment of longevity	Longevity (1-10)	Efficacy (1-10)
Reduced glazing area (Window to Floor ratio WFR)	Durable in all conditions	10	10
Fixed external shading (overhang- horizontal south, Louvres- verticle- east & west)	Durable in all conditions	10	9
External shutters	Average durability, Needs occupants action when installed without automatic controls & reduces winter heat gain	8	10
Internal blinds	Subjected to automated control or residents action. Automation might malfunction and occupants may be reluctant to use it due to blockage of outer views	4	8
Low g-value glazing (Solar control coat)	Highly robust but reduces winter heat gain	10	7
Night-purge ventilation	Highly efficient but subjected to occupants action and restrictive usage due to noise, privacy and security reasons	4	9
Reflective paint on walls	Subjected to insulation type and thickness	10	4
Reflective paint on roof	Subjected to insulation type and thickness	10	6
External wall insulation	Highly effective when combined with efficient passive cooling interventions	10	4
Internal wall insulation	Somewhat durable when combined with efficient passive cooling interventions	10	2
External loft insulation	Moderately durable when combined with efficient passive cooling interventions	10	3
Ceiling fan	High longevity but non-passive measure and consume electricity	4	9

Figure 12. Synopsis of longevity and efficacy of mitigation strategies.

3. Methodology

3.1. Research Method

In this research, literature data collection was completed in a sequential multi-phase design approach by initially analyzing the problem of overheating in the UK housing stock due to climate change using the qualitative method, then identifying statistical data for the affected UK archetypes (apartments and mid-terraced houses) using the quantitative method, and finally emphasizing British overheating benchmarks along with factors causing overheating and its mitigation solutions using the qualitative method. To encompass a practical evaluation of the performance of the PCMS under overheating events, a range of dynamic thermal simulations (DTS) were performed using the EnergyPlus interface.

A substantial amount of secondary data was discovered highlighting retrofit overheating mitigation measures for old construction (1900s–2000s), which effectively improved thermal comfort. However, limited data were found mentioning mitigation steps for modern structures (constructed after 2010), especially those with a high EPC band, because they are greatly vulnerable to overheating due to their high level of airtightness. Since the ratio of modern purpose-built flats is the highest amongst other archetypes in London, it was worth evaluating for overheating risks. Moreover, London exclusively occupies 55% of flats among other archetypes and is a peak region experiencing overheating problems. Therefore, this study focuses on identifying mitigation solutions for modern flats in London.

To accomplish the aim, a case study of a modern flat from London (natural setting) was conducted to understand overheating exposure in current and 2050s UK weather in summer. The simulations were performed quantitatively by studying the actual conditions of the flat during the summer via a descriptive and evaluative research design. Effective strategies obtained from the simulation results became a prototype for the overheating-prone zones (London and Southeast) that can be implemented in the high-EPC UK housing stock. The methodological steps to attain the aim were divided into two phases, as shown in Figure 13.

Phase 1 (Overheating Analysis): The selected case study of a modern flat was assumably 3D-modelled in DB and monitored at each design step, incorporating location, weather, zones, occupancy hours, building fabric, and the HVAC system. Construction systems (U-values for walls, floors, doors, and windows) were employed as per the UK Building Regulations 2010 (Approved Document Part L [16]). Both the current and 2050 weather conditions were used to determine the flat's risks (number of hours over 25 °C).

Phase 2 (Performance of Retrofit Mitigation Strategies): The emphasis was placed on highly susceptible rooms (living rooms and bedrooms) in this phase. The OT for the base model was identified through thermal simulations. PCMS (refer to Figure 13) were applied step by step, compared, and examined in terms of internal thermal comfort under both climatic probabilities: the present and 2050. Lastly, the toolkit of the most efficient PCMS was discovered, which eliminated overheating in susceptible rooms by decreasing the number of hours exceeding 25 °C.

3.2. DesignBuilder (DB)

DB [43] was employed to perform thermal simulations with the EnergyPlus simulation engine, allowing advanced DTS at sub-hourly timesteps. This assessed the effect of integrated PCMS in different zones, such as living rooms, bedrooms, etc., on overheating, as well as tested solar gains on surfaces and their surface temperatures, internal temperature distribution, and passive performance [43]. DB is extensively used for the evaluation of building energy performance for both commercial and research purposes in the UK, and room level is used to measure temperatures.

Future Weather Data

To execute building simulations in terms of future climate change, percentiles provide a technique to explain various probability assumptions [43]. The worst-case scenario in a high emission might be above the 90th percentile, while the best-case scenario in a low emission might be the 10th percentile. For instance, if the 90th percentile prediction forecasts a 6 °C temperature increase by 2050, then there is a 90% chance that the real temperature increase will be lesser. The mean value is represented by the 50th percentile projection, which indicates an equal possibility of the temperature climbing above or below this range [44,45]. CIBSE offers the following emission scenarios for use in dynamic building simulations:

- 2020s: High emissions scenario (10th, 50th, 90th percentile),
- 2050s: Medium: 10th, 50th, 90th,
- 2050s: High: 10th, 50th, 90th.

DB provides thermal comfort by simulating results through operative temperature, which represents a thermal comfort index to assess occupant perceptions. These internal temperatures are achieved in accordance with the outside dry-bulb temperature (ODBT). In interpretation, the internal temperature changes as the ODBT fluctuates. Therefore, the average current climate's and 2050′s outside dry-bulb temperatures in DB are adopted with medium (50%) and high (90%) weather scenarios (Figure 14) shown in Table 4 to analyze overheating conditions.

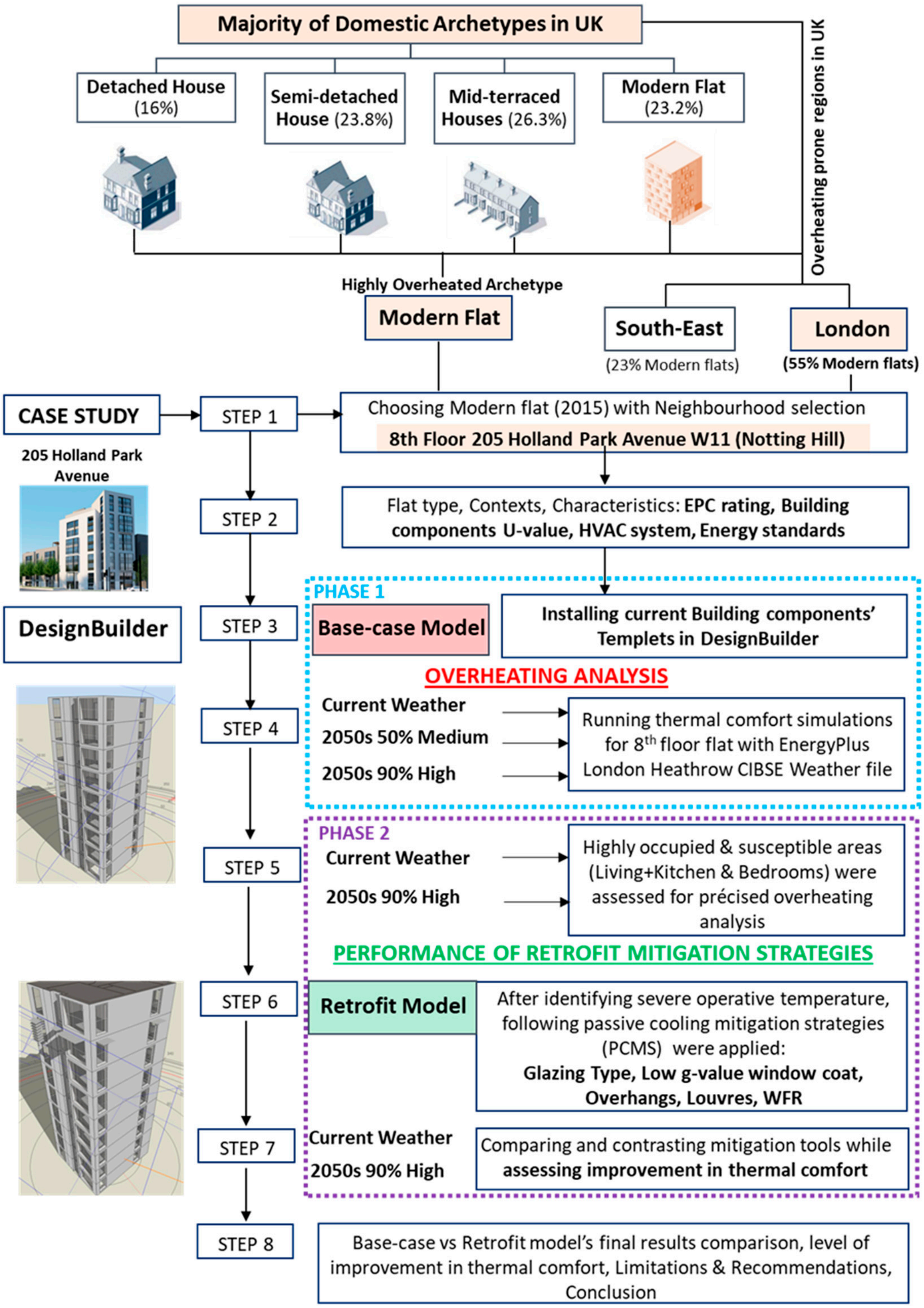


Figure 13. Research Framework.

Table 4. Overheating threshold of climate projections for London; derived from [27,40].

Current Climate	2050 Medium 50% Probability	2050 Medium 90% Probability
27.0–28.2 °C	27.3–29.7 °C	28.2–31.2 °C

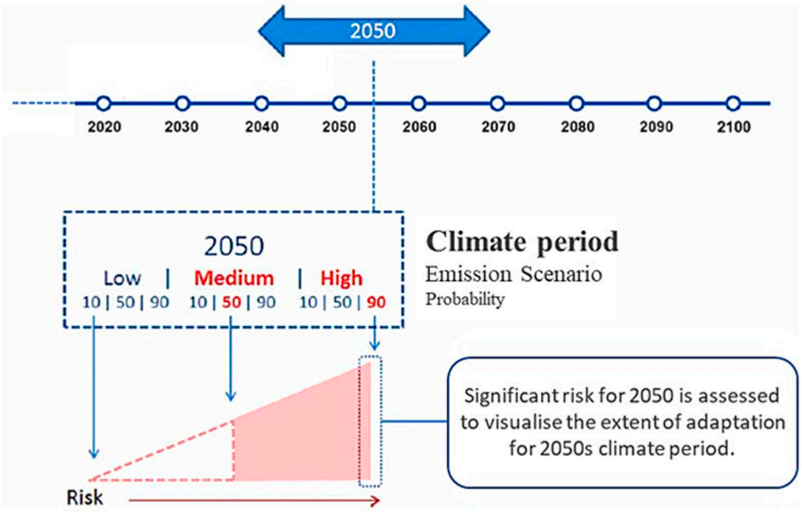


Figure 14. The probabilistic range tested for 2050s climate period illustrates significant risk; derived from [40].

Wright and Venskunas [27] generated a chart highlighting a high-emission (90%) scenario for 14 regions in the UK as per 2018 RCP 8.5 compared to UKCP09 and UKCP18. With reference to this chart, the 2050s' DSY was assumed to be a medium (50%)-emission scenario that increased by 1 °C and a high (90%)-emission scenario that increased by 2 °C according to UKCP18, as shown in Figure 15. The ODBT for the current climate was 28 °C in DB. Hence, in order to conduct overheating simulations in the 2050s in DB, according to the Wright and Venskunas [27] temperature fluctuation graph (Figure 15), ODBT was raised by 1 °C by assuming 29 °C for the 50th percentile medium-emission scenario. Similarly, a 30 °C ODBT was assumed for the 90th percentile high-emission scenario by raising the temperature by 2 °C.

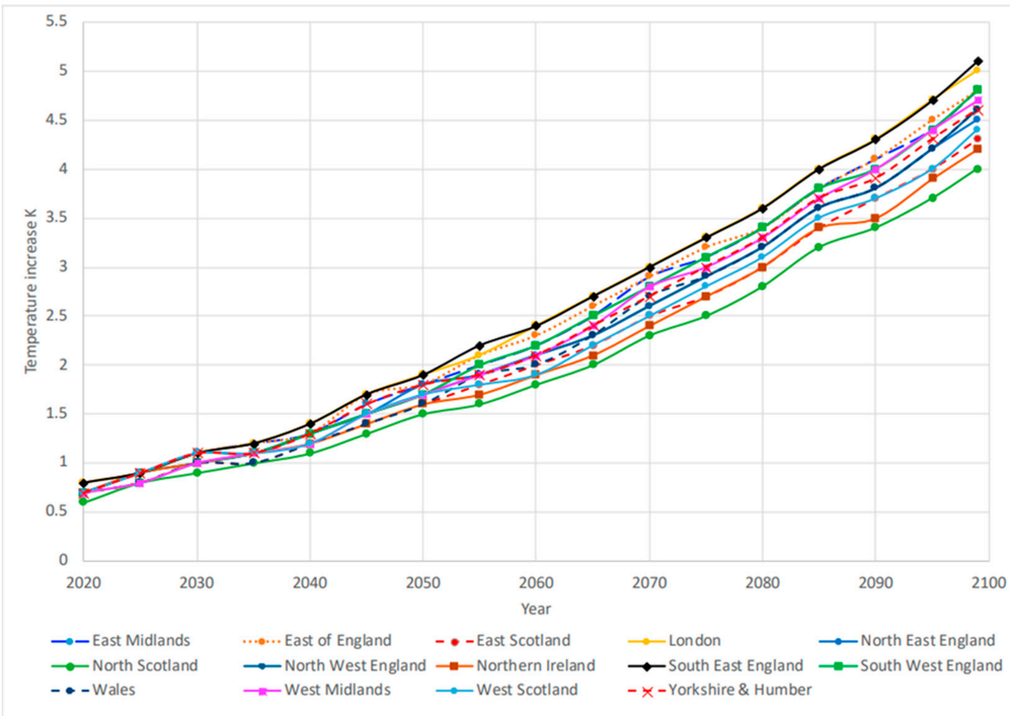


Figure 15. Temperature fluctuations from 1981-2000 baseline, for 2018 RCP 8.5, according to scenario UKCP09 and UKCP18 high-emission scenarios for 14 regions of UK [27].

4. Case Study

To reduce overheating caused by heat waves, the UK government released overheating mitigation Approved Document Part O [35]. The majority of British dwellings were categorized in document Part O [35] as having a moderate risk of overheating, with several high-risk regions, notably central and suburban London. The document imposed stronger regulations in high-risk areas. In order to collect extensive information and understand the ways in which the building components and HVAC systems were adopted in UK modern flats, an apartment on Holland Park Avenue, London W11 constructed in 2015 with an EPC rating of B was selected as a case study. The postcode (W11) is characterized as a high-risk zone in London (refer to Appendix C, Table C1 from Approved Document Part O [35]). DTM was developed with the guidance of this case study to acquire realistic and plausible simulation outputs in DB.

The property is located near central London at the junction of Holland Park and Holland Road in the urban area (Figure 16) and exposed to the A3220 primary road with a roundabout intersection [46]. As per the Road Traffic Statistics UK [47], A3220 is a Class A principal road in an urban area, which can be noisy and overcrowded. It can be indicated that people living there may not be able to open their windows due to loud noise and security reasons. The dense, solid structures near the flat may release heat, warm up the area by a few degrees, especially at night, and create UHIE.

Figure 16. Aerial view of 205 Holland Park Avenue [48].

The apartments on all floors were identical in design and layout. A southwest-cornered eighth-floor flat was chosen as a case study because the top floors are highly prone to overheating, as derived from the literature review [3]. The reasons for selecting this flat were its location, orientation of the living and kitchen (southwest) with a higher glazing ratio, 2015 construction, B-EPC rating, and building fabric and HVAC systems adapted from the new UK Energy Standards of 2010 and partly 2013 [49].

Part L1 2013 principles were also implemented after the property's inauguration in April 2013, which was expected to deliver a 25% improvement in energy efficiency compared to Part L1 2010. The development exceeds the requirements of the London Plan 2011 target by approximately 4% and those of the Part L 2010 target by approximately 29% [49]. This indicates that the property might be susceptible to overheating due to tighter energy standards with a 3 $m^3/h.m^2$ air-infiltration rate, which may not allow air penetration. The base case model was created in DB by adopting similar element specifications from Tables 5 and 6, and the planning layout from Figure 17 to accomplish the aim of the study.

Table 5. Apartment characteristics [49].

Address	Holland Park Avenue, London W11
County	Great London
Construction completion	2015
EPC rating	B (87)
Property type	Mixed-use development: 5 linked pavilions, 4–10 stories, 41 residential apartments
Selected apartment	8th floor, 2-bedroom flat
Apartment orientation	Southwest-facing living room with modern kitchen. Provision of 2 bathrooms
Floor to ceiling height (m)	3
Apartment floor area (m^2)	97.8
Heating system	Combined heat and power (CHP) with underfloor heating
Air permeability	q50 = 3 $m^3/h.m^2$
Ventilation system	Mechanical extract ventilation (MEV)—extract fans in the open kitchen and bathrooms
Demographics	Rental apartments allowed 4–5 occupants for a 2-bedroom suite
Energy standards	2010 UK building regulations, partially adopted part L1 2013

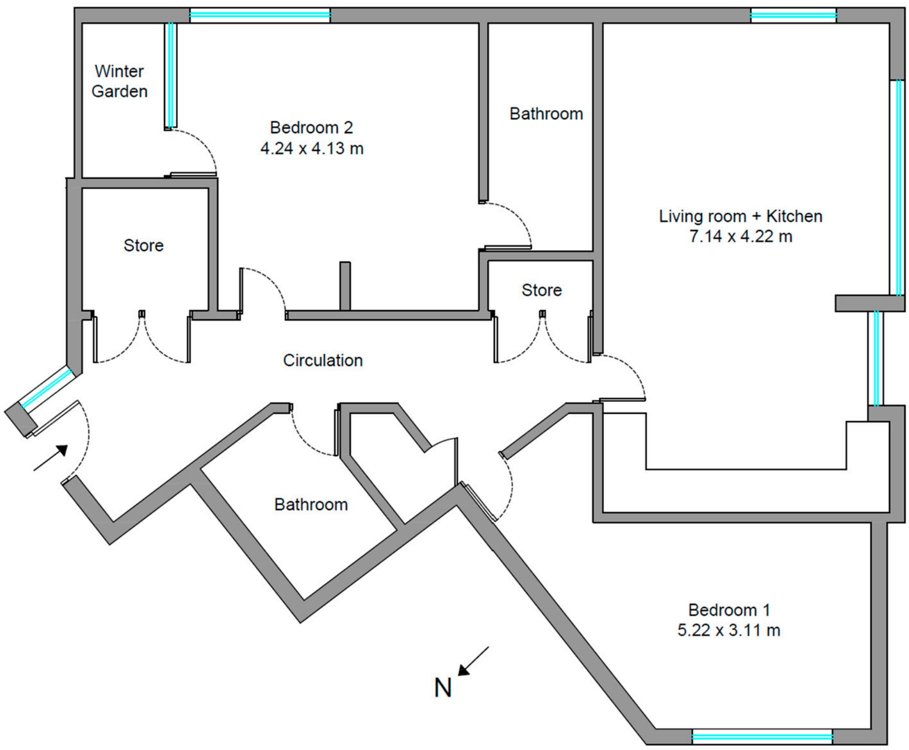


Figure 17. Eighth floor plan (drafted by the author); derived from [46].

Table 6. U-values of building components [49].

Building Components	U-Value (W/(m^2.K))
External Wall	0.20
Floor	0.19
Roof	0.15
Windows (Double glazed)	1.78
Doors	1.50

Phase 1: Base Case Model Configurations in DB

The property of the case study was located in a 4.5-mile radius of central London and 13 miles from London Heathrow Airport. Therefore, London Heathrow was chosen in the location template of DB for a precise evaluation, as shown in Figure 18. The base case model was developed as per the assumptions from the case study, which is shown in Figures 16 and 19.

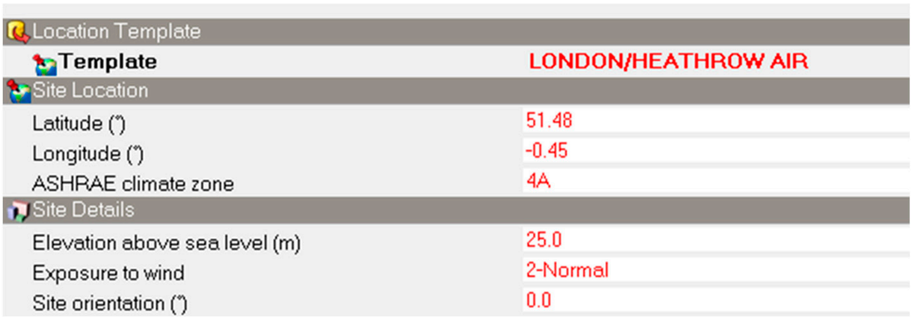
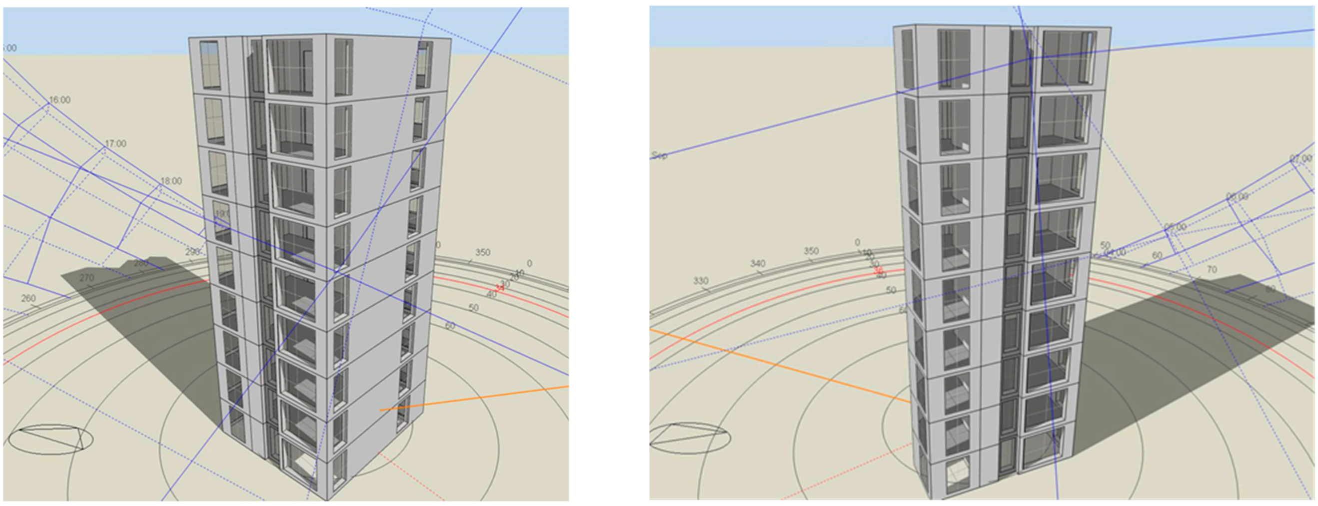


Figure 18. Location Template.



(**a**) (**b**)

Figure 19. DesignBuilder Base Model of a flat assumed from case study: (**a**) view from the southwest; (**b**) view from the southeast.

According to the UK housing standards [50], the occupancy rate of a domestic dwelling with two bedrooms varies from two to four members. It is assumed that the flat is occupied by three people, including a single parent with a child. Therefore, the building is presumed to be occupied for 20 h (2 p.m.–11 a.m.) on working days and 22 h on weekends, as shown in Table 7.

Table 7. Flat occupancy details.

Occupants	Occupants Living Pattern	Occupancy Ratio
Pensioners	A pensioner couple at home most of the day	08.00–20.00 Living room
		22.00–06.00 Bedroom 1
Single Parent	A working adult with a child going to school	14.00–18.00 Living room
		20.00–06.00 Bedroom 2

Since the electronic appliance also contributes to internal heat gains, the equipment schedule was added in DB to keep the overheating assessment accuracy intact. It was assumed that Bedroom 1 and the living room have televisions and are utilized for 5 h (Monday to Saturday) (Table 8). Kitchen appliances come under the catering schedule. It is believed to be operated for 5 h every day. The activity template was selected according to internal area's utilization of CIBSE TM59, as shown in Figure 20. A substantial amount of daylighting was shown inside the flat at different times on 15 July 2022, according to the sun path (Figure 21).

Table 8. Activity Template set in DB.

Space	Floor Area	Occupancy (People/m^2)	Activity (m)	Summer Clothing (clo)	Equipment (W/m^2)	Schedule of Equipment
Living room, Kitchen	29	0.0188	1	0.65	TV 3.55	TV 5 h (Mon to Sat)
					Stove, Oven, Microwave 30	Catering 5 h (Mon to Sun)
Bedroom 1	16.23	0.0229	1	0.55	3.55	5 h (Mon to Sat)
Bedroom 2	17.46	0.0229	1	0.55	-	
Circulation	12	0.0155	0.9	0.65	-	

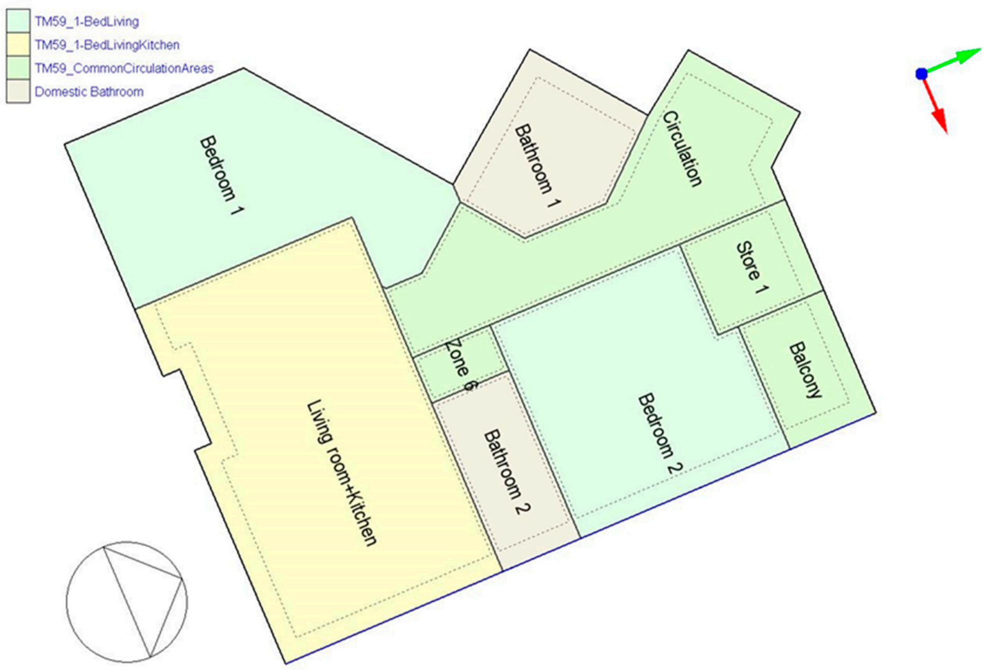


Figure 20. Base model of an 8th floor flat with the activity template.

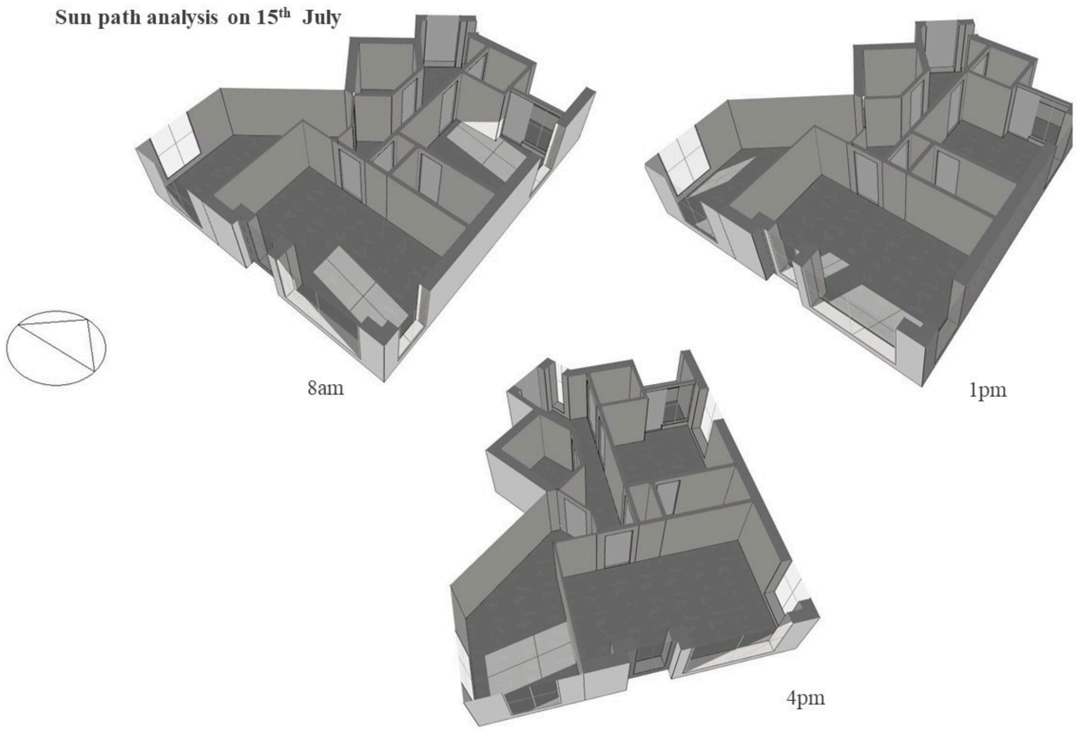


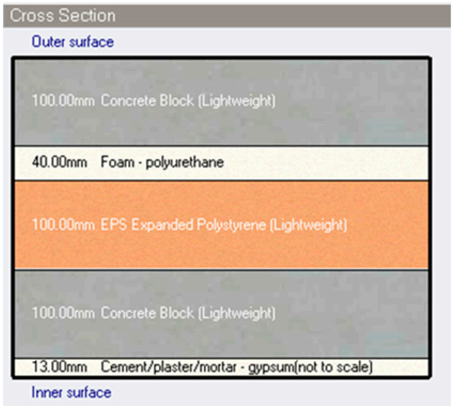
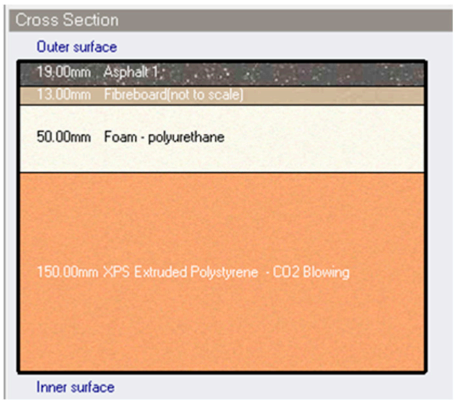
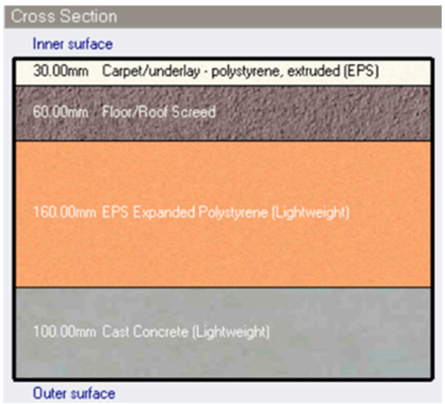
Figure 21. 8th Floor Base model in DesignBuilder: internal 3D layout with sun path analysis at different times on 15th July.

The energy-efficient building construction components are illustrated in Table 9 as a lightweight structure with U-values from Table 6.

Double-glazed windows were chosen for the base model as per Table 5. Overall, a 25% glazing with a top-hung outward opening was presumed (refer to Figure 10) (an approximately 70% openable ratio), which may provide some cross-ventilation when opened. While the surrounding area of the property was overcrowded with vehicles and people, a 25% openable glazing and a 75% fixed glazing (which cannot be operated by occupants) may moderately reduce noise pollution. Therefore, night purge ventilation can be recommended as one of the passive cooling solutions.

Moreover, a southwest façade with a 46% window-to-floor ratio (WFR) was assumed as per the case study as shown in Table 10. This was approximately twice the ratio presented in Part O [35]. Therefore, acceptable WFR was proposed after considering Part O guidelines (Tables 2 and 3) without compromising the daylight factor because low daylight may affect wellbeing. The reduced window sizes may be considered a mitigation strategy if required. Table 10 shows the window sizes installed in the base model.

Table 9. Construction Template.

	Construction Layers	**U-Value ($W/m^2.K$)**
External walls		0.20
Flat roof		0.15
Floor		0.19
Glazing (Double-Glazed windows)	UPVC window frame	1.80

Part L 2010 ventilation system was selected in the HVAC template (Figure 22), meeting the high-level requirements of building regulations Part L1 2010 and 2013 (Table 5). The air infiltration rate of mechanical ventilation was kept at 3 ACH. The heating system was kept as default, and mechanical cooling for summer was scheduled for May to September for 4 h from mid-day (12.00–16.00 h) and kept off during winter as shown in Figure 23.

Table 10. Window design details of Base model with proposed WFR.

Model Zones	Window Size (m)	Floor Area (m^2)	Orientation	Window to Floor Ratio (WFR) in %	Acceptable WFR as Per Part 'O'
Living room	2.5 × 3	29	SW	46%	22%
	2.5 × 1		SE		
Kitchen	2.5 × 1.30		SW		
Bedroom 1	2.5 × 1.50	16.23	SW	46%	25%
	2.5 × 1.50		NW		
Bedroom 2	2.5 × 1.50	17.46	SE	35%	27%
Bedroom 2 (Balcony)	2.5 × 1.15		NE		

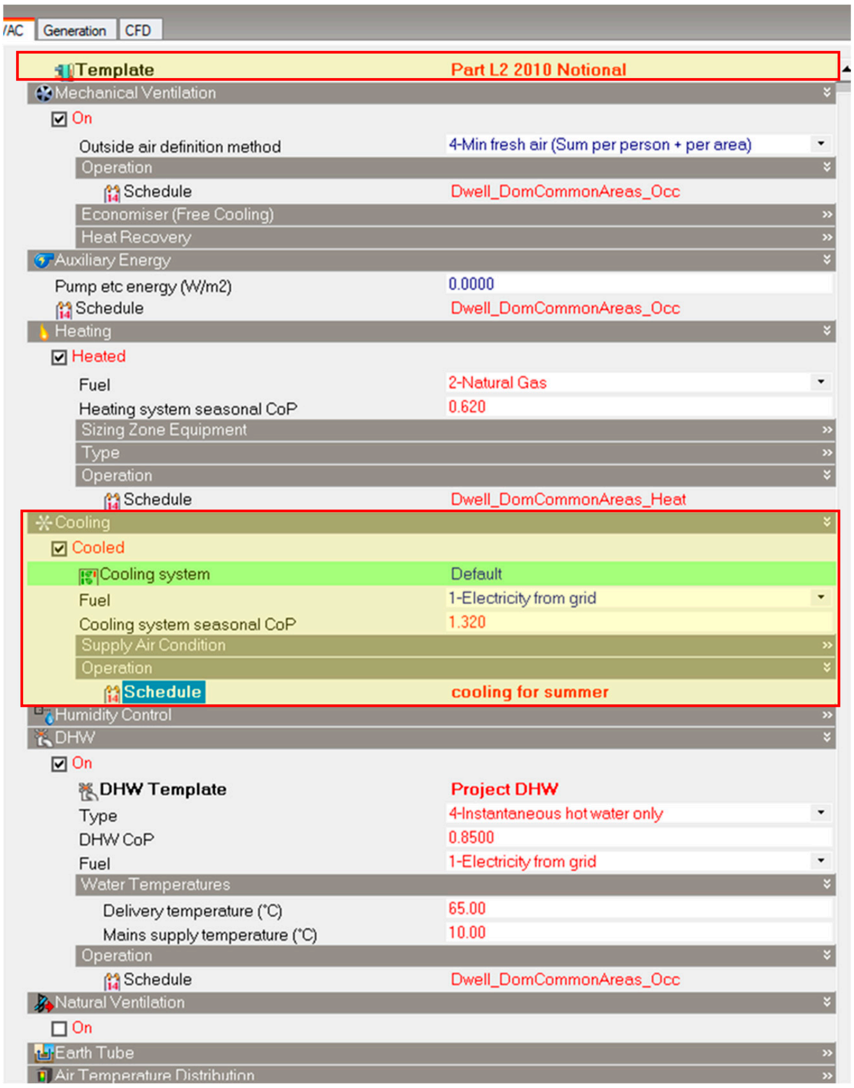


Figure 22. HVAC Template.

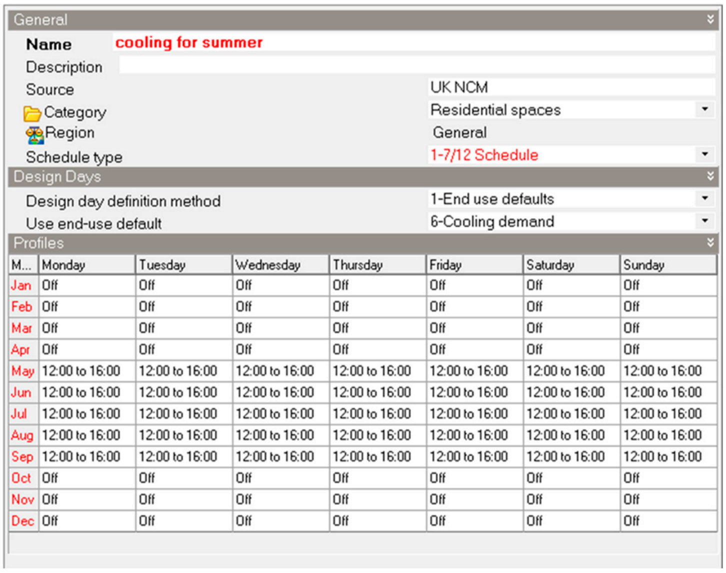


Figure 23. Schedule for summer cooling according to property design.

5. Results

5.1. Phase 1: Base Model (Flat 8) Overheating Analysis (15th July)

5.1.1. Current Climate

A range of DTS was conducted for the peak summer day (15 July) to analyze overheating conditions with reference to heatwave occurrences. When ODBT reached its highest level of 28.20 °C at 14:00 h, the OT began to rise despite providing mechanical cooling. The house retained a temperature between 26.51 °C and 31.34 °C for the whole day, and the temperature was at 30.17–31.34 °C for 2 h (12.00–14.00 h). This condition is dangerous for the wellbeing of the occupants because they were spending 20 h a day inside. Domestic dwelling should maintain a 21–25 °C habitable temperature as per CIBSE Guide A [23] and ASHARE-55 [22] during the summertime.

The primary factor identified for internal overheating was solar gains through exterior windows because they can directly penetrate through the external glazing, while the other factors, namely walls, ceilings, floors, partitions, and general lighting at night, were negligible. The solar gains in Flat 8 started to increase OT from 5.00–6.00 h in the morning by 3.04 kW until 18.00 h in the evening. Moreover, energy consumption for zone sensible cooling began at 6.00 h and reached its peak during mid-day, consuming 5.96–5.57 kW from 12.00 to 14.00 h.

5.1.2. 2050s Climate

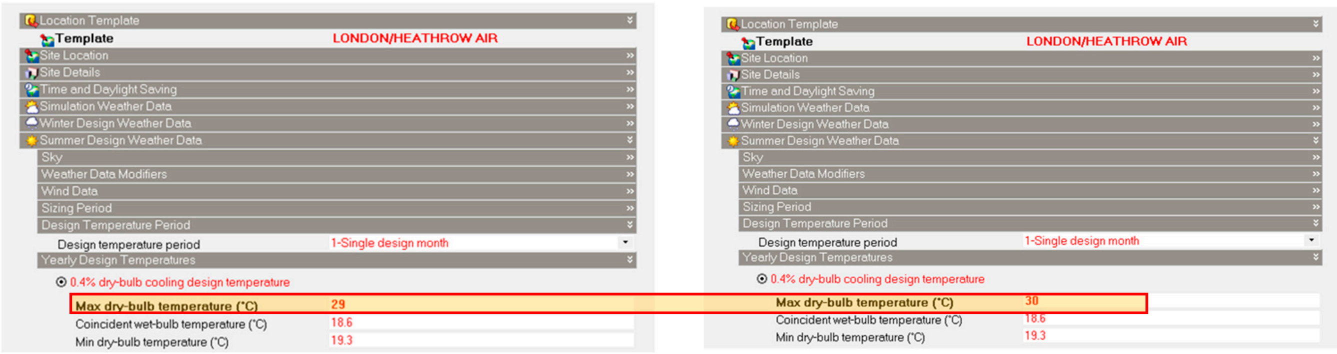
- 50% medium-emission scenario

A 29 °C ODBT was added for the 2050s 50th percentile medium-emission scenario, shown in Figure 24, which is 1 °C higher than the current climate. The house remained between 27.74 °C and 31.16 °C for the whole day, and 30.13 °C and 1.16 °C OT were recorded for 2 h (10.00–12.00 h), similar to the current climate, but here, the flat experienced a larger frequency of 27.89–28.72 °C OT throughout the day, which was 1.3 °C lower for the 2022 climate.

- 90% high-emission scenario

A 30 °C ODBT was added for the 90th percentile (%) high-emission scenario in DB (2 °C higher than 2022). The overheating analysis for this scenario was similar to the 50% medium-emission scenario, with only 0.20–0.30 °C fluctuations. Therefore, in further study, the performance of PCMS was evaluated for a 90% high-emission scenario.

For a precise overheating assessment, OT will be analyzed for highly susceptible areas (living rooms and bedrooms) for both climates in further study because these rooms have massive glazing areas and a higher occupancy ratio.



(**a**) (**b**)

Figure 24. Outside dry bulb temperature for 2050s climate; (**a**) 50% medium-emission scenario, (**b**) 90% medium-emission scenario.

5.2. Phase 2: Overheating Analysis of the Living and Kitchen and Bedrooms (15 July)

5.2.1. Current Climate

Compared to the whole flat, the living room and kitchen had the highest internal heat gains due to massive window coverage in the southwest (WFR: 46; refer to Table 10), which was clearly reflected in the simulation results. A range of 28.66–29.89 °C of OT (1 °C higher than the whole flat's OT) was reported throughout the day because of solar gains through exterior windows. Similarly, Bedroom 1, also oriented in the southwest (WFR: 46%) with most coverage in the west, showed peak heat gains of 30.13 °C OT at 18:00 h, ranging from 28.77 °C to 30.13 °C all day long. While Bedroom 2, located in the southeast (WFR: 35%), experienced lower heat gains (27.66–29.81 °C all day) in comparison but higher according to CIBSE Guide A and ASHARE 55 (24–25 °C).

5.2.2. 2050s 90% High-Emission Scenario

Starting from 8.00 h and lasting until 16.00 h, the living room and kitchen experienced severe OT of 29.59–33.24 °C. Similarly, Bedrooms 1 and 2 suffered from a dangerous environment where OT ranged from 28.72 °C to 30.80 °C and 28.95 °C to 31.83 °C, respectively. The frequency of more than 30 °C of internal temperature was noticeably higher in the 2050s (a 90% higher scenario) compared to 2022.

5.3. Phase 2: Retrofit Model-Performance of PCMS

Since all the rooms reported severe temperatures of 28–33 °C for both climates, no single tool can mitigate overheating, but the combination of durable and effective PCMS may eliminate overheating. Methods of PCMS were applied, compared, and analyzed.

The following PCMS were employed in the living room, kitchen, and Bedroom 1 and 2 areas as per orientation and necessity:

1. Triple glazing installation.
2. Low g-value window coating.
3. 1 m overhangs.
4. Louvers.
5. Windowto-floor ratio (WFR): The ratio of glazing (windows, skylights, etc.) divided by the total floor area of a particular room. Ideal WFR should be adapted as per Approved Document O (refer to Tables 2 and 3) to limit solar gains for parts of buildings to accommodate thermal comfort in the summer.

Double-glazed windows were replaced by triple-glazed low-emissivity (LoE) 13 mm air-filled glazing with a U-value of 1.10 W/m^2.K. A solar control LoE coating was applied to the outermost plane of the window. High-reflective LoE transmittance shade (internal blinds) was also provided in the internal facade of the opening, as shown in Figure 25, which can be operated by occupants as per their comfort and needs.

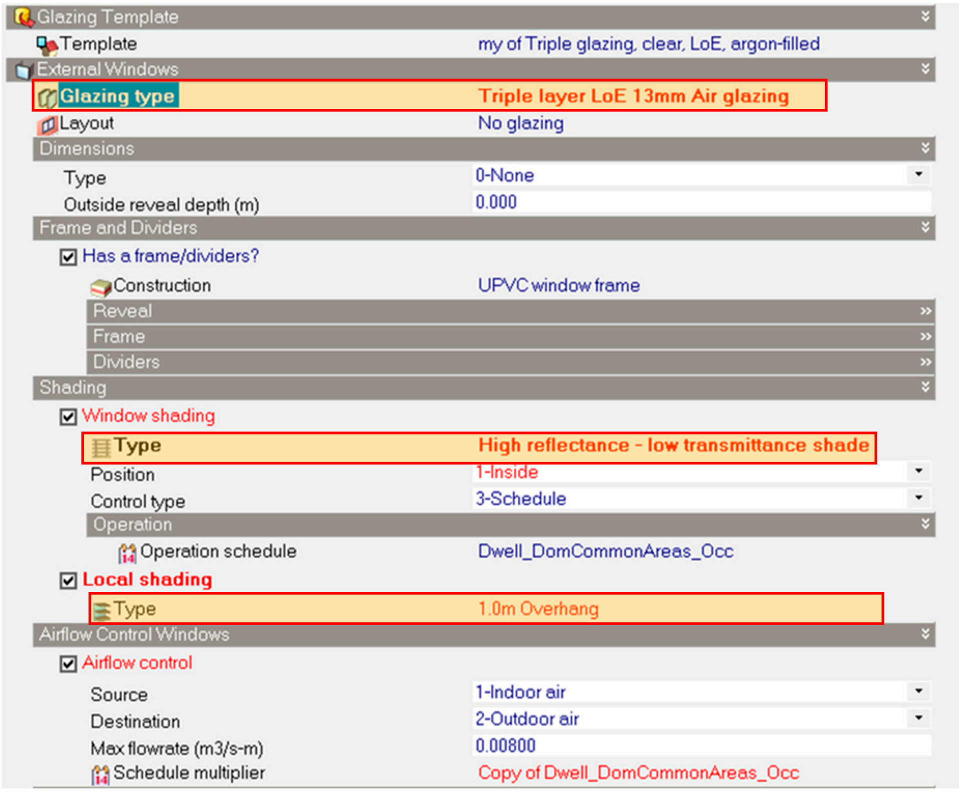


Figure 25. Modified opening template.

5.3.1. Current Climate: Performance of 1 to 4 PCMS

- Living room and kitchen:

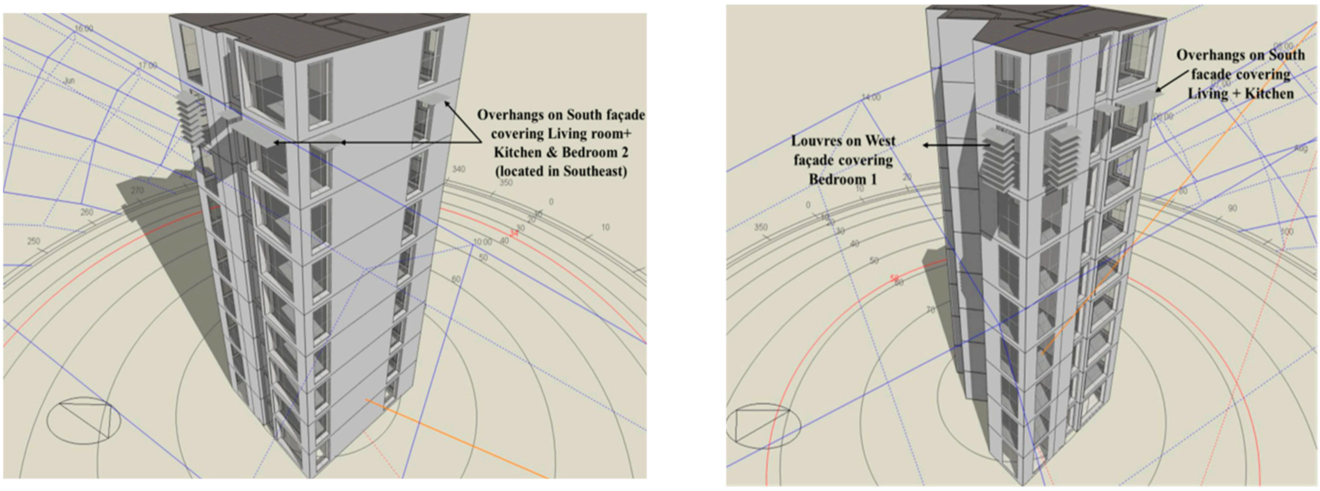
As the overhang shading was ideal for the south façade because of the high-angle sun, 1 m projected overhangs (refer to Figure 26 were provided on the glazing, which was covering the living room and kitchen in the southwest. After the adaptation of the above-mentioned PCMS, the thermal comfort in the living and kitchen areas was significantly improved, with the peak OT reduced by 1 °C from 29.89 °C to 28.67 °C at 10.00 h compared to the base model. However, the range of 27.00 °C to 28.67 °C OT was still not the habitable temperature threshold for the occupants, and other PCMS should be studied. The solar gains through exterior glazing were reduced by 96.5% (0.07 kW at 12:00 h in the retrofit model, which was 2 kW in the base model at 12:00 h).

- Bedroom 1:

Since Bedroom 1 was oriented in the west, 1 m externally projected louvres with an eight-blade configuration were provided, as shown in Figure 26b. The extreme OT was remarkably reduced by 1.4 °C, from 30.13 °C at 18:00 h in the base model to 28.74 °C in the retrofit model. One of the reasons for the thermal improvement was the massive reduction in solar gains from exterior windows.

- Bedroom 2:

The orientation of Bedroom 2 glazing was southeast, so 1 m of projected overhang was provided, which improved thermal comfort in the retrofit model by dropping 1 °C from the base model (from 29.81 °C to 28.84 °C at 10.00 h).



(**a**) (**b**)

Figure 26. Shading device implementation to Flat 8: (**a**) 1 m projected overhangs applied on southeast windows covering living room, kitchen and Bedroom 2, (**b**) louvers applied on west windows covering Bedroom 1.

5.3.2. 2050s 90% High-Emission Scenario: Performance of 1 to 4 PCMS

After applying 1 to 4 PCMS to the retrofit model under the 2050s 90% high climate scenario, the model showed a noteworthy 2–3 °C reduction in the internal rooms. The model was experiencing a 29.59–33.24 °C OT in the living room and the kitchen from 8:00 to 16:00 h, which was lowered approximately by 3 °C and dropped to 28–29 °C. Likewise, thermal comfort in Bedrooms 1 and 2 was improved by 2 °C.

To conclude, significant improvement was reported in the retrofit model containing 1-4 PCMS, which was operated solely through openings. Since the rooms did not achieve temperature thresholds as per CIBSE Guide A and ASHARE 55, other guaranteed overheating mitigation tools, such as the window-to-floor ratio (WFR), will be combined by adopting an acceptable WFR as per Table 11. The final OT obtained will be compared with the habitable temperature threshold (24–25 °C).

Table 11. Window size comparison for the Base model and the retrofit (Green) model.

Model Zones	Window Size (m) (Base Model)	Proposed Window Size (m) as per Acceptable WFR (Retrofit Model)	Floor Area (m^2)	Orientation	Window to Floor Ratio (WFR) in %	Acceptable WFR as per Part 'O'
Living room	2.5 × 3	2 × 1.50	29	SW	46%	22%
	2.5 × 1	1.5 × 1		SE		
Kitchen	2.5 × 1.33	2 × 1		SW		
Bedroom 1	2.5 × 1.50	2 × 1	16.23	SW	46%	25%
	2.5 × 1.50	2 × 1		NW		
Bedroom 2	2.5 × 1.50	2 × 1.30	17.46	SE	35%	27%
Bedroom 2 (Balcony)	2.5 × 1.15	2 × 1		NE		

- Window to Floor Ratio (WFR)

Modified sizes were provided for windows in the final retrofit model. Table 10 demonstrates proposed window sizes according to acceptable WFR, highlighted in green for the retrofit model. The final retrofit model is shown in Figure 27, where window sizes can be compared from the flats on different floors.

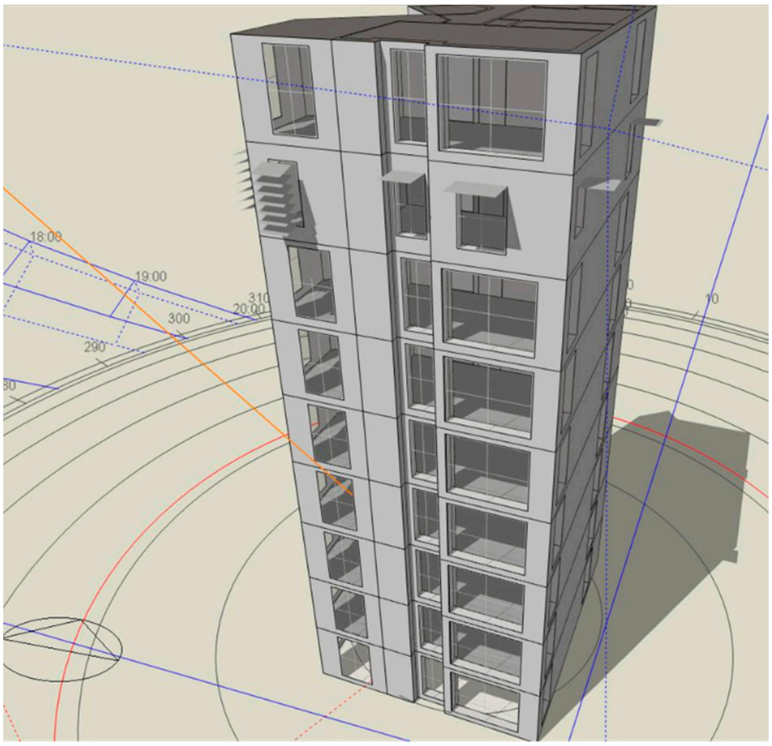


Figure 27. Final retrofit model (8th floor) after installing proposed windows sizes.

5.4. Final Retrofit Model Performance (Living, Kitchen and Bedrooms) on 15 July

5.4.1. Current Climate

The OT in the living room and kitchen was reduced by 0.7 °C from 28.72 °C to 28.0 °C, and daytime thermal comfort was improved after installing the proposed window sizes. Similarly, in Bedrooms 1 and 2, the thermal comfort was improved by OT reducing 1 °C throughout the day.

Table 12 highlights the comparison of temperature drops for all the rooms from the base model to the final retrofit model after applying all the mitigation measures for both climates. To conclude, OT was significantly reduced in all the rooms in the final retrofit model, with the living room and kitchen dropping 1.7 °C, Bedroom 1 dropping the most at 2.4 °C, and Bedroom 2 dropping 2 °C.

Table 12. Comparison of OT from the Base model to the retrofit model.

Operative Temperatures (OT) after Implementing PCMS: 15 July 2022						
	Base Model OT	**Retrofit Model OT after Implementing 1 to 4 PCMS**	**Drop in OT**	**OT after Applying Acceptable WFR**	**Drop in OT**	**Total Drop in OT**
Living room + Kitchen	28.2–29.9 °C	27.0–28.6 °C	1 °C	26.3–28.0 °C	0.7 °C	**1.7 °C**
Bedroom 1	27.7– 30.1 °C	26.8–28.7 °C	1.4 °C	26.2–27.8 °C	1 °C	**2.4 °C**
Bedroom 2	27.1–29.8 °C	26.7–28.2 °C	1 °C	26.2–27.9 °C	1 °C	**2 °C**

5.4.2. 2050s 90% High-Emission Scenario

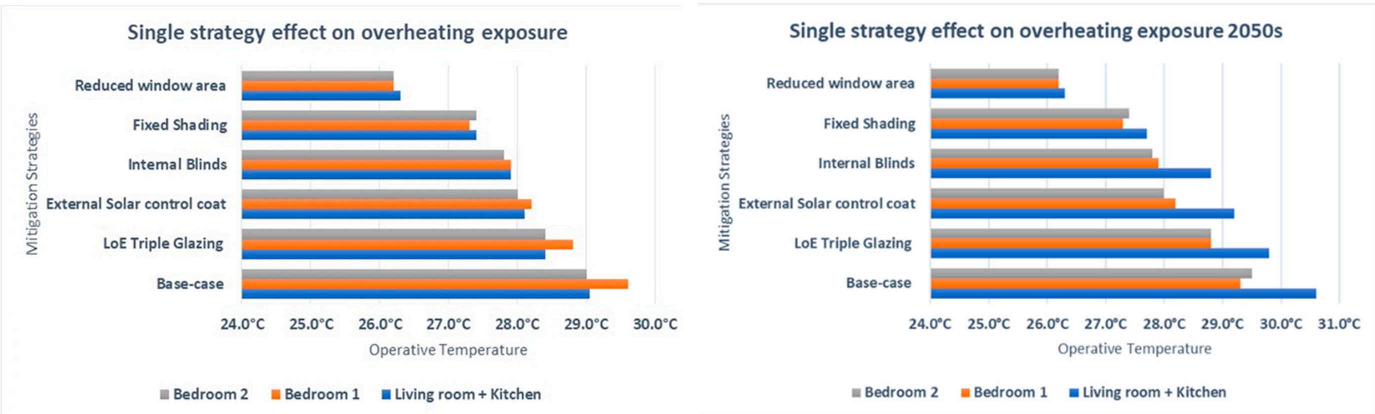
In the final retrofit model of 2050, the OT was further reduced by 1.6 °C in the living room and kitchen and by 1 °C and 1.7 °C in Bedrooms 1 and 2, respectively.

All the PCMS performed exceptionally well for 2050′s 90% high-emission scenario compared to the current climate since the OT dropped by 4.6 °C in total in the living room and kitchen, whereas it merely dropped by 1.7 °C in 2022, as compared in Table 13. Similarly, more degrees were dropped in Bedrooms 1 and 2 in 2050 compared to 2022. Therefore, it indicates that the set of PCMS will perform remarkably well in future climates to minimize internal heat gains.

Table 13. Comparison of overall reduction in OT in 2050 and current climate.

	Operative Temperatures (OT) after Implementing PCMS: 15 July 2050						2022
	Base Model OT	**Retrofit Model OT after Implementing 1 to 4 PCMS**	**Drop in OT**	**OT after Applying Acceptable WFR**	**Drop in OT**	**Total Drop in OT 2050**	**Total Drop in OT 2022**
Living room + Kitchen	27.4–33.24 °C	26.5–29.7 °C	3 °C	26.3–28.1 °C	1.6 °C	**4.6 °C**	**1.7 °C**
Bedroom 1	28.0–30.8 °C	26.7–28.9 °C	2 °C	26.3–28.0 °C	1 °C	**3 °C**	**2.4 °C**
Bedroom 2	27.1–31.8 °C	26.3–29.7 °C	2 °C	26.4–8.0 °C	1.7 °C	**3.7 °C**	**2 °C**

In terms of single PCMS performance, the window-to-floor ratio (WFR) attained the largest temperature fall, as depicted in Figure 28. In 2022, the living room and the kitchen experienced a 1 °C improvement, while in 2050, they improved by 1.6 °C. The second-best technique, LoE triple glazing, reduced temperatures by around 0.5 °C and 1 °C for the climates of 2022 and 2050, respectively. It also considerably increased the thermal comfort in Bedrooms 1 and 2. When combined, other methods like fixed shading, internal blinds, and sun control coating decreased temperatures by around 0.5–0.7 °C for 2022 and by 1–1.8 °C for 2050 in all rooms.



(**a**) (**b**)

Figure 28. Comparison of individual PCMS performance: (**a**) in current climate; (**b**) in 2050s climate.

5.5. Phase 2: Final Retrofit Model Performance (Flat 8) on 15th July

After applying 1 to 5 PCMS, the whole Block 8 (eighth floor flat) dropped 4 °C overall, ranging from 26.75 °C to 31.34 °C in the base model to falling under 26.24 °C to 27.67 °C in the final retrofit model on 15 July. Moreover, solar gains through exterior glazing were reduced by 85.5% (now 0.55 kW at 10:00 h, which was 3.79 kW in the base model). Similarly, energy consumed by zone sensible cooling was decreased by 52% (in the final retrofit model, 2.85 kW at mid-day compared to 5.96 kW in the base model).

5.6. Final Retrofit Model: Performance of Flat 8 throughout the Summer (May to September)

Overheating was experienced throughout the summer, not only during the summer peak month (July). The OT exceeded 25 °C to 28 °C, started in June, and continued like that until September.

The simulation results showed that the OT was ranging from 22 °C to 28 °C in the base model from May to September, remarkably decreasing by 2 °C and falling to 20 °C to 25.9 °C in the final retrofit model because of the implementation of PCMS. Therefore, it can be identified that the flat achieved OT below 24 °C throughout the summer (except in July and August, where OT ranged between 25 °C and 26 °C). According to CIBSE Guide A, it did not attain the ASHARE 55 comfort temperature threshold (20–24 °C) as shown in Figure 29. Therefore, it can be validated that after implementing 1–5 PCMS, the final retrofit model achieved standardized internal thermal comfort in the summer according to the UK overheating benchmark (CIBSE Guide A).

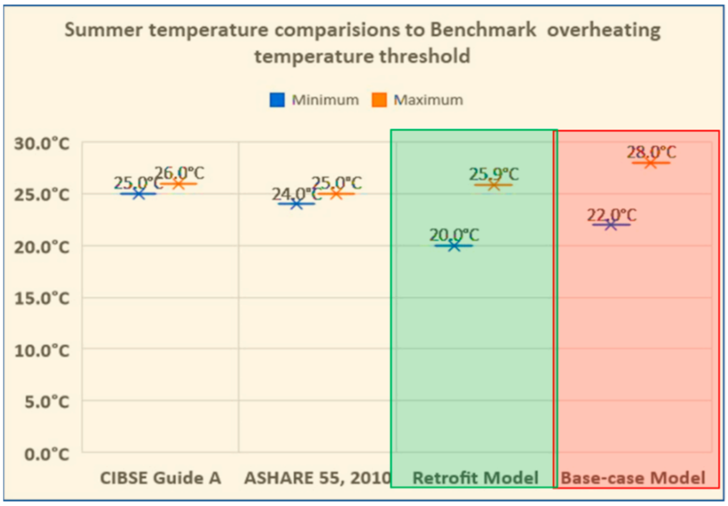


Figure 29. Comparison of Base and Retrofit Temperature thresholds to benchmark standards.

6. Discussion

This study contributed major improvements to the knowledge regarding overheating exposure in contemporary British flats and their PCMS. The necessity of tackling the principal drivers of overheating is one of the key findings that construction professionals and policymakers may benefit from. This entails using proper window designs that consider aspects such as glazing type, window-to-floor ratio (WFR), low g-value glass, and shading devices to reduce internal heat gains. Notably, the use of retrofit window solutions resulted in a 52% decrease in energy usage for zone sensitive cooling, resulting in considerable cost savings and lower CO_2 emissions.

Given the scarcity of the literature on overheating issues in modern high-EPC-rated flats and their PCMS, the findings of this study clearly delivered critical knowledge of overheating contributors with a practical examination that improves internal thermal comfort by approximately 66% during summer-inclusive heatwave occurrences in the present. All PCMS excelled in terms of future climatic probability, improving internal thermal comfort by 92%.

The recommendations from the research and probable future research areas that would be worthwhile to study could be summed up as follows:

- Since living rooms and bedrooms still have a 26–28 °C OT despite the adaptation of PCMS for 2050's 90% high weather scenario, a table/ceiling fan operating for 2–3 h does not consume huge amounts of electricity compared to air conditioning but aids in cool air circulation by reducing 2 °C to 3 °C of OT, which should be employed in the near future.

- Strategies that require no occupant involvement can facilitate more consistency (fixed objects, automatic controls) for future scenarios.
- The study will be further expanded by assessing indoor air quality against outdoor air pollutants like NO_2 and PM_5, the concentrations of which are higher in urban surroundings in the context of London.
- To gather a factual assessment of overheating episodes in terms of occupant comfort and responsive behaviour, a survey should be conducted among the occupants living in overheating-prone regions. It may provide in-depth knowledge of sociological aspects that can be combined with secondary literature findings and simulation results.
- The current study encompasses overheating mitigation strategies through window design and technologies. A detailed DTS can be performed to reduce energy consumption and CO_2.

Limitations

Although night purge ventilation is an excellent measure to let fresh, cold air in, the outside temperature should be lower than inside.

There were a few constraints in the DB software that restricted the retrofit model from obtaining the temperature threshold of ASHARE 55.

- External shutters were one of the best PCMS; similarly, solar re-elective external paint was an option on walls and roofs (refer to Figure 12). DB did not facilitate such applications. Moreover, types of windows (side-hung, top-hung, sliding, casement windows, etc.) were not included in the DB, in which retrofitting fixed windows (discussed in Section 2.4) to side-hung windows would have assisted in improving thermal comfort by proposing 2 h of night purge ventilation during extreme summer months. These solutions may have helped the author achieve the temperature threshold of ASHARE 55 (24–25 °C) for the final retrofit model.
- Results can provide estimated knowledge of the performance of PCMS. For example, to attain maximum benefit from reducing internal heat gains, overhangs should be provided to cut down on solar radiation on the south façade, as the sun angle is significantly high. But, in DB, shading devices can be applied according to the spaces (for example, a living room, a bedroom, etc.), not the orientation, which limits the potential for accuracy.

7. Conclusions

The background study incorporated overheating issues during the summer in UK housing stock due to climate change. Particularly apartments and mid-terraced homes are highly susceptible to overheating, with the southeast and London identified as overheating-prone regions. Modern apartments with excellent EPC ratings are overlooked by researchers in terms of overheating and adaptation tools, while similar literature was discovered in large amounts for older mid-terraced, detached, and semi-detached houses. Overheating events have expanded in modern apartments as a result of increased airtightness in housing as per the new UK Building Regulations.

To address heatwaves, this study primarily assessed overheating and adaptation strategies during peak summer months and heatwave occurrence months for susceptible areas (living areas and bedrooms) along with the whole summer (May–September) against CIBSE Guide A and ASHARE 55. A flat at Holland Park Avenue W11 was analyzed as a case study to understand the building components and HVAC systems that fulfilled Steps 1 and 2 as per Figure 13. To accomplish Phase 1 (Steps 3 and 4), DTM was developed as a base case model in DB to perform overheating analysis for 2022 and 2050. OT was found to be 5 °C higher in Flat 8 compared to CIBSE (25–26 °C) in 2022 and 6 °C in the 2050 climate. Since the flat was occupied for 20 to 22 h a day by an elderly couple and a single parent, this condition was threatening to the occupants. After initiating Phase 2 (Step 5), since the flat had 46% of the glazing area in living areas and Bedroom 1 and 35% in Bedroom 2, OT was 1–2 °C greater in rooms compared to the other areas of the flat. Solar gains through windows were the primary responsible source, so the authors adopted a window design approach to minimize overheating issues. The following PCMS were simulated in DB (Step 6):

1. Triple glazing installation.
2. Low g-value window coating.
3. 1m overhangs.
4. Louvers.
5. Window to floor ratio (WFR).

After the implementation of 1 to 4 PCMS, solar gains through windows were remarkably reduced by 96.5%, but relatively high OT (27 °C to 28.6 °C) was still reported in all rooms. Therefore, the fifth PCMS was applied by incorporating modified, smaller-sized windows (refer to Table 10). As a result, the window to floor ratio outperformed all the other PCMS, followed by LoE triple glazing. However, the OT for the final retrofit model ranged from 26.2 °C to 28.0 °C on 15th July, but it still lacked the ability to achieve habitable OT as per CIBSE (25–26 °C) or ASHARE 55 (24–25 °C).

The improvement in indoor environment of the final retrofit model was remarkable after employing all PCMS compared to the base model, as it dropped overall from 1.7 °C to 2.4 °C in the 2022 climate and from 3.0 °C to 4.6 °C in 2050 in all rooms.

A major reason for high OT despite applying PCMS was the selection of the peak summer month (15 July) to address heatwaves. The other reason was the high-risk overheating location (London). Simulation results proved the hypothesis that London is the most susceptible region for overheating in the UK due to climate change. The final retrofit model achieved an average of 20–25.9 °C OT as per CIBSE Guide A for all summer months.

Reduced window area and LoE triple glazing were identified as the most excellent PCMS. The performance of all strategies was 60% better in the 2050s climate compared to the 2022s climate, which also decreased energy consumption for both climates by 52%, resulting in lower CO_2 emissions. Thus, positive simulation results for 1 to 5 PCMS completed Phase 2 by accomplishing the aim of the study. If these PCMS were adopted in the current flats (50% of total housing stock) of London of southeast England and (23% of total housing stock), it would guarantee an improvement in thermal comfort. It is also applicable to any type of housing stock experiencing overheating issues in the UK.

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Abbreviations

ACH	Air Changes per Hour
ASHARE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CCC	Climate Change Committee
CCRA3	UK's 3rd Climate Change Risk Assessment
CIBSE	Chartered Institution of Building Services Engineers
DB	DesignBuilder
DCLG	Department for Communities and Local Government SAP- Standard Assessment Procedure
DEFRA	Department for Environment, Food & Rural Affairs
DLUHC	Department for Levelling Up, Housing and Communities
Dynamic thermal modelling (DTM)	A process of building modelling that forecasts the internal conditions and energy requirements of a building at short time intervals utilizing weather data and building attributes.
Dynamic thermal simulation (DTS)	employs a 3D model of a building to simulate its thermal performance hour by hour.
EPC	Energy Performance Certificate
EER	Energy Efficiency Ratio
EHS	English Housing Survey
GHA	Good Homes Alliance
g-value	a measure of solar heat (infrared radiation) permitted in through a particular part of a building.
HOC	House of Commons
Low-E (LoE)	An extent of emissivity, the attributes of a material to radiate thermal energy. Low-E glazing is a thin, practically colorless metallic coating that absorbs a short-wave heat radiation while still allowing most of the natural light to pass freely through the window.
OT	Operative Temperature
PCMS	Passive cooling mitigation strategy
TM59	Design methodology for the assessment of overheating risk in homes (2017)
TM52	The limits of thermal comfort: Avoiding overheating in European buildings
UKGBC	United Kingdom Green Building Council
UKCP09	UK Climate Projections 2009
UKCP18	UK Climate Projections 2018
UHIE	Urban Heat Island Effect

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