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Effects of Retrofit Strategies on Thermal Comfort and Energy Performance in Social Housing for Current and Future Weather Scenarios

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Abstract: With growing concerns over energy and heat-related mortality/morbidity rates, enhancing building performances is key to improving the health and well-being of building occupants while reducing CO_2 emissions, in line with the UK Government's Net-Zero targets. This study investigates the impacts of different retrofitting scenarios on overheating risk and energy performance in social housing for current and future climate conditions. Dynamic thermal simulations were carried out using Design Summer Year (DSY) weather files in DesignBuilder software for selected case study buildings. Winter performance was analysed using the Predicted Mean Vote (PMV) index, while summer results were assessed according to the Chartered Institution of Building Services Engineers Technical Memorandum 59 (CIBSE TM59) guidelines. The findings revealed that bedrooms, especially those facing south, were at high risk of overheating. Factors such as building construction, the number of exposed surfaces, and window area influenced the risks. External wall insulation outperformed internal wall insulation in improving summer comfort. In the winter, Passivhaus standards with natural ventilation ensured thermal comfort across all zones, with a 41–53% reduction in heating energy consumption under current weather conditions. The risk of overheating and associated health issues significantly increased for the future weather scenarios. Further investigation into ventilation strategies, occupant behaviour, and passive design is required to mitigate overheating risks while reducing energy consumption in buildings.

Keywords: thermal comfort; overheating; passive design; social housing; energy performance

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1. Introduction

Climate change has significantly accelerated retrofit initiatives to improve indoor environmental quality in buildings and hence improve energy performances while reducing the risk of ill health due to exposure to excessive heat and poor air quality. Under the current climate scenarios, there is a high risk of home overheating in London, and if climate change adaptation measures are not considered, occupants' exposure to excessive interior air temperatures is likely to worsen in the future [1]. Scientific evidence suggests that our climate is changing primarily as a result of human activities, particularly due to the release of greenhouse gas emissions into the atmosphere, which has recently reached unprecedented levels [2]. The frequency, duration, and intensity of heatwaves are expected to rise globally [3], even to a greater level than initially estimated [4]. According to the UK Climate Change Projections 2009 (UKCP09), all UK regions are predicted to get warmer, particularly in the summer [5], with many homes from the southeast of England to the north of Scotland exposed to acute overheating during the summer [6]. Under the Medium emissions scenario (compared to the baseline period between 1961 and 1990), the highest rise in summer mean temperatures will occur in South England, at an average of 4.2 °C by the end of the century [5]. In London, it is expected that by the middle of the century, day-time temperature will surpass 32 °C half of the time during the summer [7].

Moreover, a strong relationship exists between mortality risk and elevated temperatures at the population level, as evidenced by the heatwaves in England during the summer of 2022, which led to 2985 reported deaths [8], a significantly higher number than any figures since 2003 [9], particularly amongst older people [1,10]. Hence, without adequate climate adaptation and mitigation strategies, heat-related mortality rates could triple by 2050 [7]. Preventing heat-related mortality (and its associated socio-economic outcomes) is therefore a major priority in the UK and Europe [11–13]. In cities like London, the risk of overheating is exacerbated by the Urban Heat Island (UHI) effect [14]. The UK is the first country in the world to introduce a long-term legally binding framework to mitigate climate change. According to the Climate Change Act of 2008, UK emissions must reduce by 80% by 2050, compared to 1990's baseline levels [15].

New building regulations have led to more airtight and well-insulated building envelopes which may in turn increase the risk of poor indoor environmental quality, including overheating, if not coupled with suitable passive cooling strategies [16–20]. Previous research suggests that 20% of UK homes are experiencing indoor overheating [21–23]. Frequent interior overheating may lead to poor adaptation strategies, such as mechanical cooling systems, which could further increase CO_2 emissions and contribute to climate change [24]. Therefore, improving building performance using passive design solutions, such as natural ventilation, remains the best approach to simultaneously addressing overheating, comfort, energy efficiency, and health [18–20,25].

Dwelling typology [26–28], building fabric, and the age of construction [23,28] are some of the key factors contributing to the risk of overheating. Evidence suggests that homes built during the 1960s and 1970s [1] and post 1995 [29] tend to be the hottest. Moreover, flats, particularly those on the top floors [22,26,30], terraced houses [22,31], properties occupied by elderly residents [32,33], and bedrooms in comparison to living rooms [29] have been highlighted as the most exposed to the risk of overheating and the negative impact on occupants' health. While single-glazed windows and uninsulated walls in existing homes contribute to significant heat loss [34], some residential buildings which had undergone "systemic retrofit" interventions to enhance their thermal performance in the winter are now experiencing overheating problems in the summer [35]. Additionally, homes with high insulation levels and airtightness designed to save energy, whether newly constructed or retrofitted, are more vulnerable to summer overheating than those with lower insulation levels [36]. Moreover, homes built to Passivhaus standards (arguably the most energy-efficient standard for homes) may be most vulnerable, owing to the use of superinsulation, particularly in warmer climates [32,37].

To reduce the adverse impacts on occupants' well-being and health, the Committee on Climate Change (CCC) Adaptation Sub-Committee has recommended actions to limit overheating in buildings [38,39]. Yet, despite efforts to address the risk of overheating and its health-related outcomes, the issue is still largely unreported in the literature [40], particularly in flats and terraced homes [41].

To this end, this study assesses the effects of two energy-efficient retrofitting scenarios on energy performance and on winter/summer thermal comfort for current and future 2050 weather conditions in two problematic properties located in southeast England, namely, a top-floor flat and an end-of-terrace social house, using CIBSE weather data. The aim is to develop future-proof retrofit strategies that improve not only energy performance but also thermal comfort in residential buildings.

2. Materials and Methods

2.1. Research Methodology

This study explores how various building construction factors, including the U-values of walls, roofs, floors, and windows, airtightness, and the position of wall insulation (whether internal or external), may affect summer/winter thermal comfort and heating energy consumption in the winter. A series of simulations were conducted to achieve the research objectives, as shown in Figure 1. The first set of simulations was undertaken to assess thermal performance for the current situation, "the base case", in both case study properties using DesignBuilder software v7.2.0.032. The second set included the creation of two retrofit scenarios [42,43] based on the UK's Approved Document L for existing dwellings [44] and Passivhaus standards [45,46], where the performance of both internal and external wall insulation was investigated under both current and future climate scenarios. Owing to the volume of simulated data, the DesignBuilder Results Viewer 4.0 application (a separate program used to display EnergyPlus results) was used to export the result charts [47].

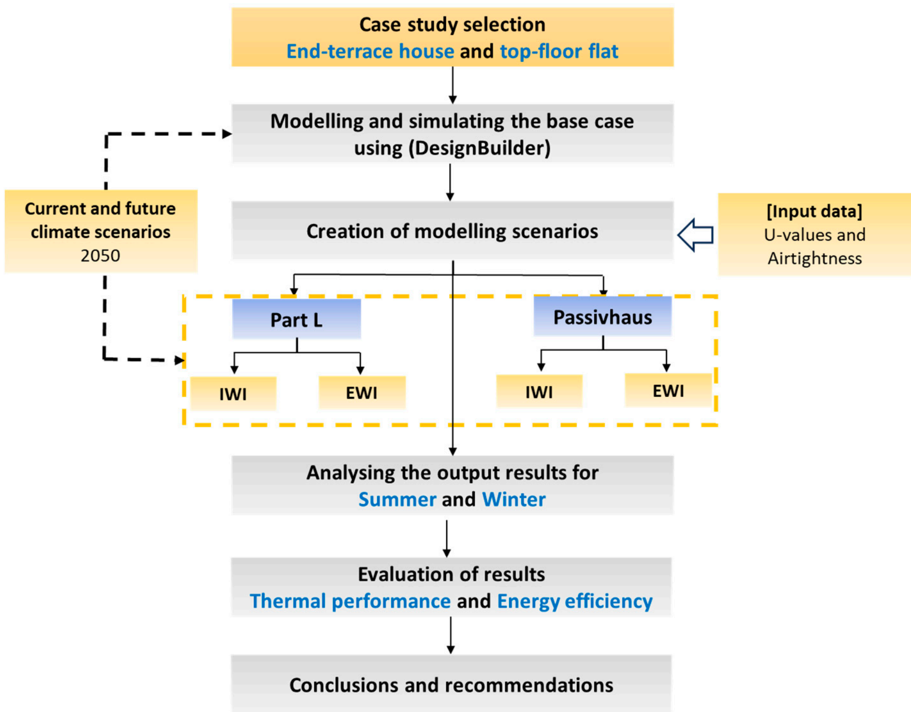


Figure 1. Research methodology.

2.2. DesignBuilder Software

DesignBuilder is an advanced software tool capable of providing detailed environmental performance data, including thermal comfort, carbon emissions, and energy consumption at varying time intervals. It operates with EnergyPlus, a robust simulation engine, delivering advanced dynamic thermal simulation at sub-hourly timesteps [46]. This software adopts TM59 templates, a standardised method from CIBSE, to predict overheating risk in residential building designs [48].

2.3. Simulation Settings and Analysis

An assessment of overheating risk during the summer was carried out and analysed according to "the adaptive thermal comfort of the Chartered Institution of Building Services Engineers (CIBSE) TM59: Design methodology for the assessment of overheating risk in homes" [49,50]. The simulation was performed using the CIBSE Design Summer Year (DSY) weather files for London, which represent the most suitable single continuous year of weather data utilised for the evaluation of overheating in buildings [51]. The summer simulation was performed from May to September following CIBSE and TM59 design methodologies, indicating when the model passed or failed the tests. Passing means that the results of kitchens, living rooms, and bedrooms should not exceed 3% of the occupied hours (Criterion A from May to September). For bedrooms only, the operative temperature in the bedroom between 10 p.m. and 7 a.m. should not rise above 26 °C for more than 1% of the hours in a year to ensure comfort during sleeping hours [49,50]. For the internal gains (occupancy, equipment, heat gain, and heating), occupancy schedules, and natural ventilation, TM59 profiles were adopted [49], where windows would open when the room temperature exceeded 22 °C during occupied hours.

For winter assessments, the Predicted Mean Vote index (PMV) was adopted following the comfort scales [52]. It is important to highlight that the comfort range typically falls within ±0.5. However, in this study, we followed a more flexible approach based on the TM52 Bedford comfort scale, which suggests that a range between −1 and +1 is also perceived as comfortable [52]. Winter simulations were performed from October to March, representing the winter season [53], and windows were set to be closed. Heating set points and clothing levels for all the zones followed CIBSE Guide A [49] (i.e., dwellings' living rooms at 22–23 °C, with bedrooms and kitchens at 17–19 °C). All the reported results are for the occupied periods.

2.4. Case Study and Building Simulation Modelling

In accordance with the literature [22,26,30,31], the case study properties were selected based on potential overheating risk, and a top-floor flat and a terraced house located in southeast England were chosen from a pool of typical case study buildings provided by the project partners, including a diverse range of occupation patterns, such as elderly occupants, young occupants, and families. The thermal performance of the selected properties was investigated to provide a more in-depth understanding of improved building elements for both summer and winter conditions.

The first case study building is a two-storey, end-of-terrace house with three exposed external surfaces, situated in southeast England (see Figure 2). It accommodates a family of three. The house was constructed between the 1930s and 1940s with solid brick walls and double-glazed windows installed in 2002 or later. Due to limited information about the construction details, typical specifications for 1940s building materials were used to develop the simulation model [54]. The typical U-values for houses from the 1930s and 1940s were applied as follows: 2.3 W/(m^2K) for the roof, 1.2 W/(m^2K) for internal floors, 1.7 W/(m^2K) for external walls, and 2.8 W/(m^2K) for glazing [55], as shown in Table 1, and a solar heat gain coefficient (SHGC) value of 0.763. The existing party wall was considered adiabatic (Figure 2b).

Figure 2. (**a**) The case study house; (**b**) a 3D model of the case study house; (**c**) ground-floor plan; (**d**) first-floor plan.

Table 1. The assigned airtightness and U-values for the case study scenarios [44–46,55].

3D Model Simulation Scenarios		**U-Values W/(m²K)**				**Airtightness (ach/h at 50 Pa)**
		Roof	**Wall**	**Floor**	**Window**	
Base Case	1930s/1949s House	2.3	1.7	1.2	2.8	15
	1950s/1960s Flat	2.3	1.5	1.2	2.8	15
Scenario 1: Building Regulation, Approved Document (Part L)		0.16	0.3	0.25	1.4	10
Scenario 2: Passivhaus Standard		0.15	0.15	0.15	0.78	0.6

On the ground floor, the living room is north-facing and the kitchen faces south, both featuring large window areas without shading. On the first floor, the main bedroom is also south-facing with smaller windows. The single bedroom is quite compact with two exposed external walls facing north and east, also with small windows. A double bedroom is located facing the north, and the roof overhangs provide some shading for the upper-floor windows.

Table 1 summarises the assigned U-values for each case study scenario [44–46,55], where double glazing was used for the base case and the Part L scenario, and triple low-e glazing filled with argon was used for the Passivhaus scenario.

The second case study property is a top-floor flat in an eight-story building block located in the London Borough of Newham, southeast England, as shown in Figure 3. This building contains 100 flats, including one-bedroom and two-bedroom units. The building was constructed between 1950 and 1966 with cavity walls and double-glazed windows, though the age of the windows is not known. Standard specifications for 1960s construction details [54] were therefore used to develop the base case models, with U-values of 2.3 W/(m^{2}K) for the roof, 1.5 W/(m^{2}K) for external walls, and 2.8 W/(m^{2}K) for glazing [55], as shown in Table 1, and an SHGC value of 0.763. All adjacent walls and floors, except for the seventh-floor corridor, were considered adiabatic (Figure 3c).

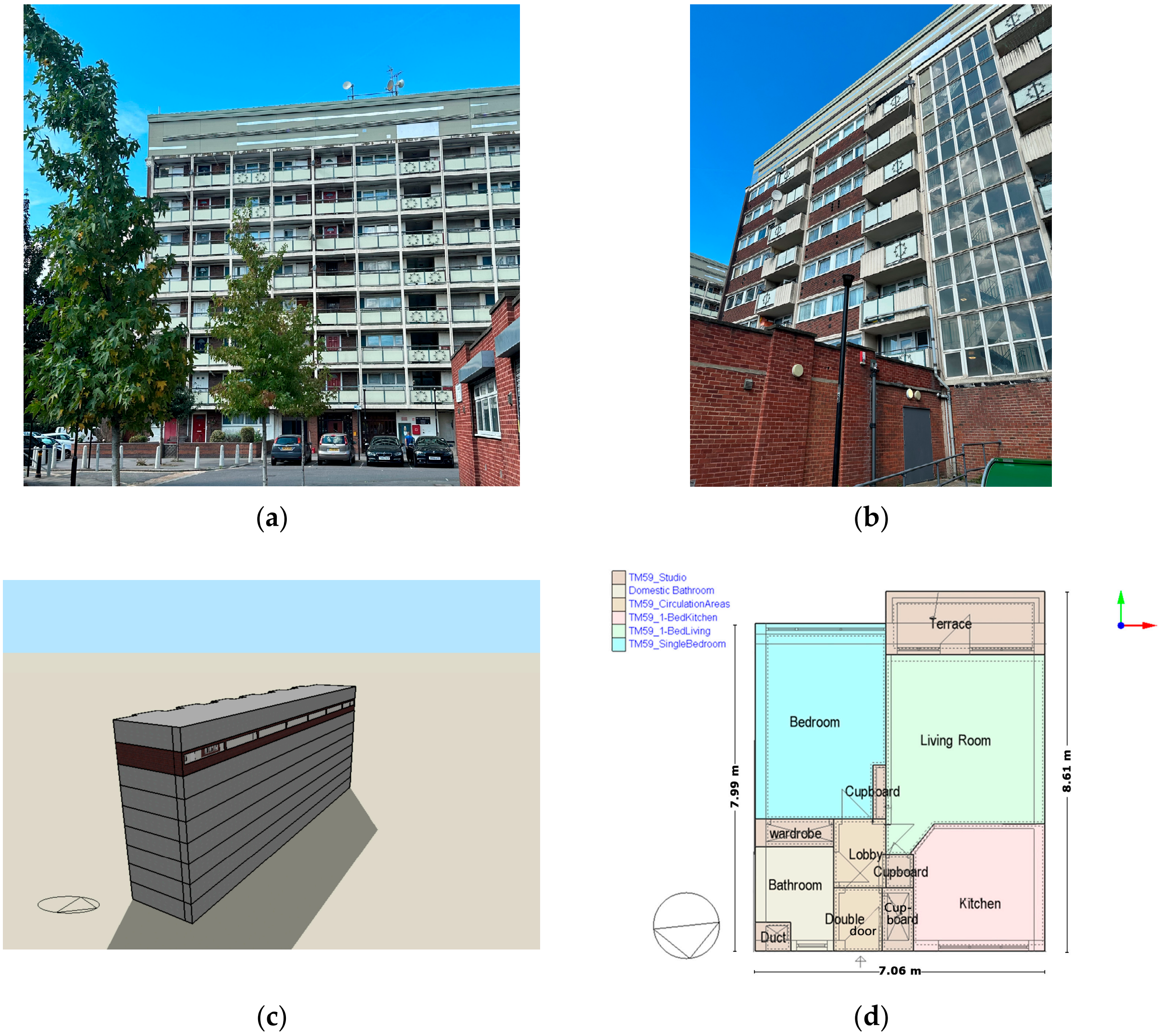


Figure 3. (**a**,**b**) The building block; (**c**) a 3D model of the case study flat; (**d**) floor plan.

The flat has two exposed external surfaces and comprises one bedroom, a bathroom, a kitchen, and a living room, accommodating a single occupant. The living room faces south and includes a large window and a glazed door (Table 2) that opens onto a shaded terrace. The kitchen is oriented to the north, also with a large window and a shaded open corridor. The bedroom has two exposed surfaces facing south and east, with a sizable south-facing window that lacks shading.

Table 2. Detailed information on opening area and percentage for both case study properties.

CSB	Zones	Total Window Area (m^2)	Openable Area (%)
House	Living room	2.35	38
	Kitchen	2.33	38
	Main bedroom	1.16	39
	Single bedroom	1.16	39
	Double bedroom	2.33	38
	WC	0.22	50
	Bathroom	0.42	22
	Corridor_ Ground level	0.70	75
	Corridor_ First level	1.16	39
Flat	Living room	4.26	47
	Bedroom	3.12	60
	Kitchen	1.89	60
	Bathroom	0.63	50

3. Results and Discussion

3.1. TM59 Overheating Risk (Summer)

The building walls and roof were upgraded with a layer of insulation to achieve the specified U-values for Part L and Passivhaus in both properties. Tables 3 and 4 summarise the insulation and construction materials. It is important to highlight that the reason behind the excessive accuracy of the insulation thicknesses is to achieve the required U-values in DesignBuilder. For the house, the solid walls consist of two layers: solid brick (0.242 m) and plaster (0.013 m). In contrast, the flat features cavity walls (0.26 m) composed of four layers: brick (0.1 m), air cavity (0.05 m), concrete block (0.1 m), and plaster (0.013 m).

Table 3. The assigned insulation material for the case study scenarios for the house.

House	U-Values W/(m^2K)	Total Wall Thickness (m)	Insulation Thickness (m)
Base case	1.7	0.255	–
Part L	0.3	0.338	0.0824
Passivhaus	0.15	0.438	0.1824

Table 4. The assigned insulation material for the case study scenarios for the flat.

Flat		U-Values W/(m^2K)	Wall Thickness (m)	Insulation (m)
Base case		1.5	0.26	–
Part L	Cavity	0.3	0.26	0.05
	EWI	0.3	0.34	0.08
Passivhaus		0.15	0.44	0.18

3.1.1. First Case Study: End-of-Terrace House

Table 5 presents the results of the summer simulation. Notably, all bedrooms met Criterion A (%) but did not satisfy Criterion B (hrs) for both current and future weather scenarios. In the "base case scenario", both the living room (north) and the kitchen (south) passed the summer assessment under current weather conditions. However, for the 2050 scenario, only the living room passed the test. For the Passivhaus scenario, the results indicate improvements across all zones, with all areas passing the assessment for the current weather scenario, as insulation played a role in reducing the warm air entering the rooms. Nevertheless, all bedrooms failed the test for future weather conditions, regardless of their orientation. The south-facing bedroom experienced more uncomfortable hours compared to the north-facing ones, attributed to its orientation and smaller window area relative to its size. Additionally, the single bedroom (north-facing) performed worse than the double bedroom (also north-facing) due to it having two exposed walls (south and east) that contributed to higher solar gain.

Table 5. House summer simulation based on CIBSE TM59 for current and future scenarios using criteria A (%) and criteria B (h).

Current Scenario	Orient.	Base Case	Part L		Passivhaus	
			(IWI)	(EWI)	(IWI)	(EWI)
Main bedroom	South	49 h	35.5 h	32 h	20.5 h	12.5 h
Double/BD	North	34 h	14 h	9.5 h	9 h	4 h
Single BD	North	50.5 h	30 h	17.5	20 h	6.5 h
Living room	North	0.18%	0.13%	0%	0%	0%
Kitchen	South	0.65%	0.39%	0.1%	0.21%	0%
Future Scenario 2050	**Orient.**	**Base Case**	**Part L**		**Passivhaus**	
			(IWI)	**(EWI)**	**(IWI)**	**(EWI)**
Main bedroom	South	389 h	299 h	275.5	222.5 h	191 h
Double BD	North	278.5 h	177.5 h	156 h	148.5 h	131 h
Single bedroom	North	372.5 h	233 h	183.5	201.5 h	156.5 h
Living room	North	1.85%	1.8%	1.27%	1.54%	0.99%
Kitchen	South	3.85%	2.28%	1.24%	1.64%	0.78%

Note: The red background colour indicates "failing the test", while the green background colour indicates "passing the test".

Comparisons between external wall insulation (EWI) and internal wall insulation (IWI) for both the Part L and Passivhaus scenarios revealed a notable reduction in the total number of discomfort hours for all bedrooms with EWI compared to IWI, as shown in Table 6. EWI prevents the walls from absorbing solar heat, allowing for a more comfortable indoor temperature. For Part L, all zones met the criteria under the current climate scenario with EWI, while only the south-facing main bedroom failed when using IWI. In the Passivhaus scenario, both the kitchen (south) and the living room (north) passed the assessment for the future climate scenario. However, all bedrooms failed, with discomfort hours exceeding acceptable limits significantly: 5.9 times the limit for the main bedroom, 4.9 times for the single bedroom, and 4 times for the double bedroom when using EWI.

It should be noted that all bedrooms were significantly impacted by the future weather scenario as they exceeded the thresholds established by the CIBSE TM59 benchmarks. In the Passivhaus (EWI) scenario, the high number of discomfort hours in the first-floor main bedroom—5.9 times the acceptable limit—can be attributed to its southward orientation and limited window opening area. Additionally, the single bedroom, which faces north and east and is relatively small, demonstrated a discomfort level 4.9 times above the acceptable range, primarily due to its two exposed surfaces. Also, the double bedroom on the first floor facing north experienced the least overheating among the rooms, accounting for 4.09% of annual discomfort hours. A possible reason for the excessive overheating on the first floor is excessive heat gain through the uninsulated roof in addition to natural buoyancy effects.

Table 6. Flat summer simulation based on CIBSE TM59 for current/future scenarios using criterion A (%) and criterion B (h).

Current Weather	Orient.	Base Case	Part L		Passivhaus	
			Cavity Ins.	(EWI)	(IWI)	(EWI)
Bedroom	South	10.5 h	3 h	2 h	5 h	1.5 h
Living room	South	0%	0%	0%	0%	0%
Kitchen	North	0%	0%	0%	0%	0%
Future Scenario 2050	**Orient.**	**Base Case**	**Part L**		**Passivhaus**	
			Cavity Ins.	**(EWI)**	**(IWI)**	**(EWI)**
Bedroom	South	141 h	100 h	94.5 h	102.5	84.5 h
Living room	South	0.61%	0%	0%	0%	0%
Kitchen	North	0.63%	0%	0%	0%	0%

Note: The red background colour indicates "failing the test", while the green background colour indicates "passing the test".

Similarly, the south-facing kitchen on the ground floor with large window openings passed both summer and winter assessments for all scenarios. It is noteworthy that despite all bedrooms failing the assessment in the Passivhaus (EWI) scenario, there was a significant reduction in total discomfort hours: 50.8% for the main bedroom, 52.9% for the double room, and 57.9% for the single bedroom, compared to the base case scenario. The Passivhaus scenario demonstrated a reduction in discomfort hours across all zones compared to the other simulation scenarios, contrary to the findings of previous studies [44,45].

3.1.2. Second Case Study: Top-Floor Flat

Table 6 summarises the results of the summer simulation for the top-floor flat. The findings indicate that all zones passed the summer assessment for current weather conditions; however, the bedroom failed to meet the criteria and exceeded the thresholds for overheating risk defined by CIBSE TM59 in all scenarios for the future weather scenario. Notably, in the Passivhaus (EWI) scenario, the bedroom experienced 2.64 times the acceptable number of discomfort hours, primarily due to it having two exposed surfaces oriented south and east, which resulted in high solar gain.

For the future weather scenario, there was a significant improvement in discomfort hours when transitioning to Passivhaus standards. Although the Passivhaus scenarios with both EWI and IWI did not pass the assessments, they demonstrated the most significant reductions in total discomfort hours during sleeping periods, decreasing by 40% and 27.3%, respectively, compared to the base case scenario. Additionally, the south-facing living room passed the tests due to the shaded terrace, which effectively reduced solar gain through the windows.

3.2. PMV Thermal Comfort (Winter)

Winter simulations were conducted with closed windows, followed by an investigation into the impact of natural ventilation when indoor temperatures exceeded 24 degrees for the worst-case scenarios.

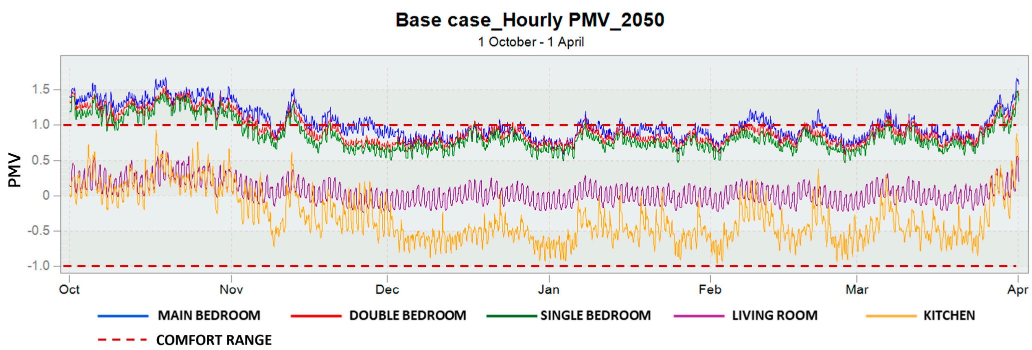
3.2.1. First Case Study: End-of-Terrace House

Table 7 presents a summary of the Predicted Mean Vote (PMV) results, showing discomfort hours for all zones across both current and future weather scenarios. In the base case, only the living room fell within the comfortable range for current weather conditions, while the kitchen slightly exceeded acceptable limits at 0.93%. However, both zones remained in the comfort range for the future climate scenario.

Table 7. Percentage of discomfort hours exceeding the acceptable comfort limit for the house when windows were closed.

Current Weather Scenario	Orient.	Base Case	Part L		Passivhaus	
			(IWI)	(EWI)	(IWI)	(EWI)
Main bedroom	South	23.92%	66.05%	65.66%	100%	100%
Double bedroom	North	13.94%	79.42%	81%	100%	100%
Single bedroom	North	6.34%	64.95%	65.50%	97.25%	98.92%
Living room	North	0%	0%	0%	0%	0%
Kitchen	South	0.93%	0%	0%	0%	0%
Future Weather Scenario: 2050	**Orient.**	**Base Case**	**Part L**		**Passivhaus**	
			(IWI)	**(EWI)**	**(IWI)**	**(EWI)**
Main bedroom	South	38.83%	88.16%	88.87%	100%	100%
Double bedroom	North	26.79%	98.21%	99.06%	100%	100%
Single bedroom	North	21.66%	85.76%	89.06%	99.54%	99.95%
Living room	North	0%	0%	0%	0%	0%
Kitchen	South	0%	0.21%	0.08%	0.11%	0.08%

Regarding the bedrooms, the single bedroom exceeded the comfort range by 6.34%, followed by the double bedroom at 13.94% and the main bedroom, which performed the worst at 23.92% during the current weather scenario. The situation deteriorated for the future weather scenario, with the single bedroom at 21.66%, the double bedroom at 26.79%, and the main bedroom at 38.83%, as illustrated in Figure 4a.



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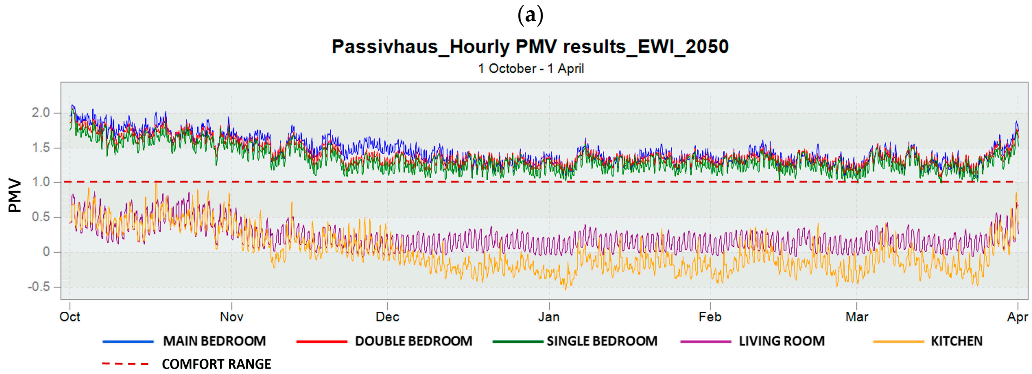


(**b**)

Figure 4. (**a**) End-of-terrace house base case scenario—hourly PMV results for future climate scenarios; (**b**) End-of-terrace house passivhaus scenario with EWI—hourly PMV results for future climate scenarios.

In the Passivhaus scenario, none of the bedrooms remained within the comfort range, indicating a high risk of overheating during the winter, particularly when EWI is applied, as shown in Figure 4b. This may be attributed to the closed windows in the simulation settings. To further investigate this issue, an additional set of simulations was conducted to assess the impact of natural ventilation on improving the building's thermal performance during the winter in the Passivhaus scenario with EWI.

In this set of simulations, a mixed-mode approach was applied, where the heating system was switched off (when temperature exceeded the set point) and natural ventilation was allowed when indoor temperatures reached 24 degrees Celsius (°C) during October, November, and March (identified as the most uncomfortable periods according to the results). This assessment focused on the worst-case scenario for Passivhaus with EWI in both current and future weather conditions.

The results indicated that the mixed-mode strategy achieved optimal thermal comfort across all zones in the current weather scenario, aligning with previous research on passive design solutions [18–20]. It significantly reduced the risk of overheating in the bedrooms, which averaged 10.88% in the future weather scenario, as shown in Table 8.

Table 8. Percentage of discomfort hours during occupied periods exceeding the acceptable comfort limit with windows closed compared to a mixed mode for the house.

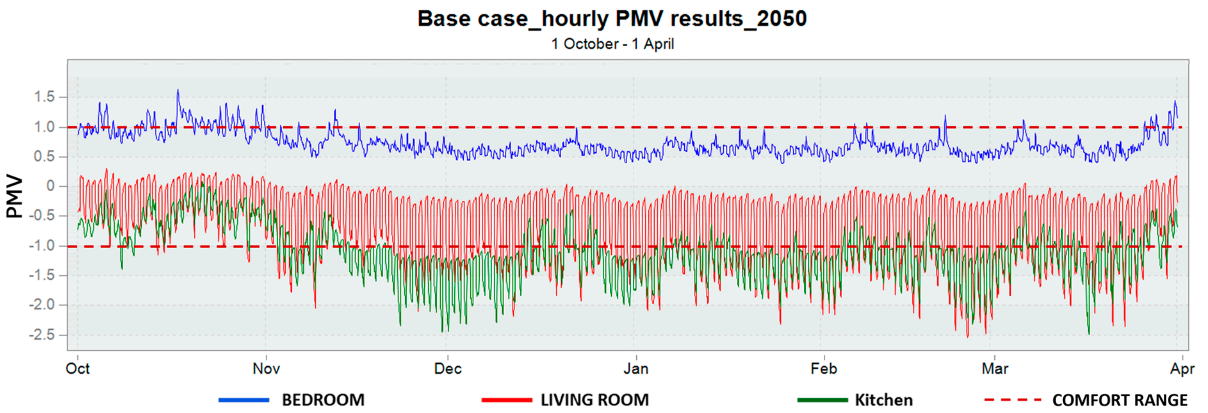
Current Weather Scenario	Orient.	Base Case		Passivhaus (EWI)	
		Window Closed	**Mixed Mode**	**Window Closed**	**Mixed Mode**
Main bedroom	South	23.92%	1.76%	100%	1.88%
Double bedroom	North	13.94%	0.57%	100%	0.85%
Single bedroom	North	6.34%	1.03%	98.92%	3.48%
Living room	North	0%	0%	0%	0%
Kitchen	South	0.93%	2.41%	0%	0%
Future Weather Scenario: 2050	**Orient.**	**Base Case**		**Passivhaus (EWI)**	
		Window Closed	**Mixed Mode**	**Window Closed**	**Mixed Mode**
Main bedroom	South	38.83%	11.97%	100%	10.83%
Double bedroom	North	26.79%	8.65%	100%	8.52%
Single bedroom	North	21.66%	11.36%	99.95%	13.97%
Living room	North	0%	0%	0%	0%
Kitchen	South	0%	0%	0%	0%

3.2.2. Second Case Study: Top-Floor Flat

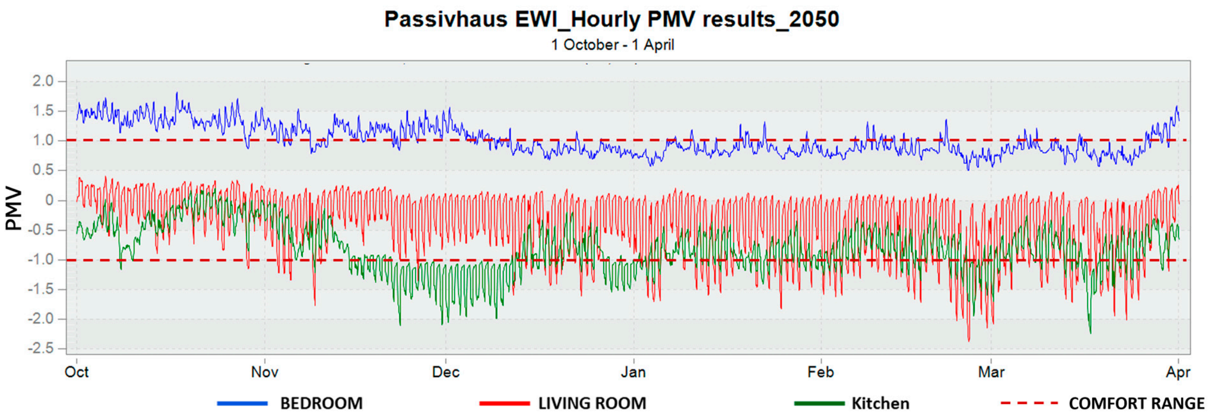
Table 9 illustrates a summary of PMV results demonstrating the hours of discomfort across all zones for current and future climate scenarios, factoring in closed windows. The findings indicate that the bedroom was at significant risk of overheating in the winter when the model was retrofitted to both Part L and Passivhaus standards, as shown in Figure 5. Notably, Part L outperformed Passivhaus in minimiing discomfort hours. In the future climate scenario, the Passivhaus (EWI) option showed a slight improvement in reducing total discomfort hours for the bedroom compared to IWI. Conversely, the kitchen experienced excessively cold indoor conditions during the winter, attributed to its northward orientation along a shaded open corridor; however, the Passivhaus scenarios achieved a significant reduction in discomfort hours compared to the base case scenario.

Table 9. Percentage of discomfort hours exceeding the acceptable comfort limit for the flat when windows were closed.

Current Weather Scenario	Orient.	Base Case	Part L		Passivhaus	
			Cavity Ins.	(EWI)	(IWI)	(EWI)
Bedroom	South	1.95%	24.36%	23.95%	35.21%	32.81%
Living room	South	5.03%	1.39%	1.39%	1.44%	1.82%
Kitchen	North	78.32%	48.44%	48.69%	38.12%	40.57%
Future Weather Scenario: 2050	**Orient.**	**Base Case**	**Part L**		**Passivhaus**	
			Cavity Ins.	**(EWI)**	**(IWI)**	**(EWI)**
Bedroom	South	10.99%	35.55%	35.23%	45.83%	43.86%
Living room	South	3.00%	0.72%	0.72%	1.01%	1.35%
Kitchen	North	53.25%	18.89%	18.89%	17.62%	19.78%



(**a**)



(**b**)

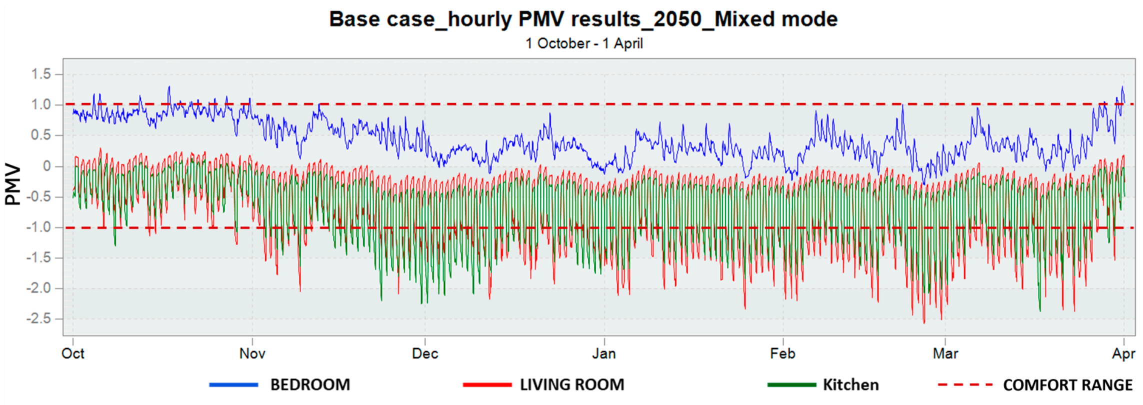
Figure 5. (**a**) Top-floor flat base case scenario—hourly PMV results for the future climate scenario; (**b**) Top-floor flat passivhaus scenario using EWI—hourly PMV results for future climate scenarios.

The same set of simulations for both the base case and Passivhaus with EWI scenarios was conducted on the flat to evaluate the impact of natural ventilation on enhancing occupants' thermal comfort during periods identified as having the highest excess of discomfort. In this case, as the kitchen was excessively cold, the heating set point temperature was increased to 22 degrees for the current weather scenario and set to 19 degrees for the future weather scenario, reflecting the transition to a warmer climate.

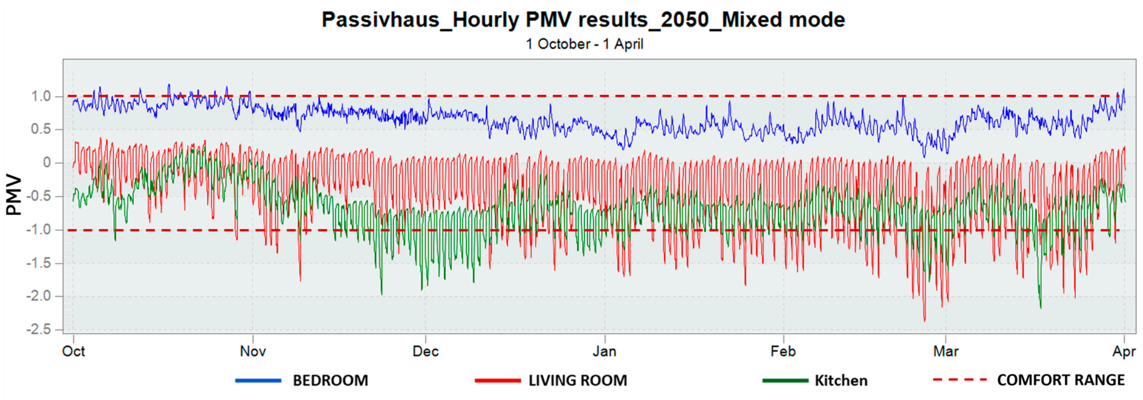
Table 10 demonstrates the percentage of discomfort hours that exceeded the acceptable comfort limits for all zones, considering a mixed-mode approach for both current and future climate scenarios. The results indicate a significant improvement in achieving optimal thermal comfort in the bedroom for the current weather scenario when compared to closed windows, with a low risk of overheating at 2.54% for the base case and 2.70% for Passivhaus in the future weather scenario, as shown in Figure 6. Additionally, both the living room and the kitchen remained within the comfort range, as the model was retrofitted to Passivhaus standards.

Table 10. Percentage of discomfort hours exceeding the acceptable comfort limit with windows closed compared to a mixed mode for the flat.

Current Weather Scenario	Orient.	Base Case		Passivhaus (EWI)	
		Window Closed	Mixed Mode	Window Closed	Mixed Mode
Bedroom	South	1.95%	0%	32.81%	0%
Living room	South	5.03%	5.07%	1.82%	1.59%
Kitchen	North	78.32%	5.37%	40.57%	0.59%
Future Weather Scenario: 2050	**Orient.**	**Base Case**		**Passivhaus (EWI)**	
		Window Closed	**Mixed Mode**	**Window Closed**	**Mixed mode**
Bedroom	South	10.99%	2.54%	43.86%	2.70%
Living room	South	3.00%	3.00%	1.35%	1.31%
Kitchen	North	53.25%	3.30%	19.78%	0.59%



(**a**)



(**b**)

Figure 6. (**a**) Base case scenario—hourly PMV results for the future climate scenario with a mixed mode; (**b**) Passivhaus scenario with EWI—hourly PMV results for future climate scenarios with a mixed mode.

3.3. Energy Performance

This section investigates the energy consumption for heating during the winter season in current and future climate scenarios (2050).

3.3.1. First Case Study: End-of-Terrace House

Figure 7 illustrates the energy consumption results for all case study scenarios with closed windows, encompassing both current and future climate scenarios. In the base case scenario, the energy required for heating purposes decreased by 31.45% in the future climate scenario compared to the current weather scenario, reflecting the transition to a warmer climate. The Part L scenario reduced energy consumption by 29.54% compared to the base case, while both Passivhaus scenarios achieved a reduction of 41.1%. This significant decrease is attributed to the use of superinsulation and low-emissivity (low-e) glazing. It is important to note that the placement of insulation material, whether internal or external, did not significantly affect energy savings for heating during the winter for both the Part L and Passivhaus scenarios.

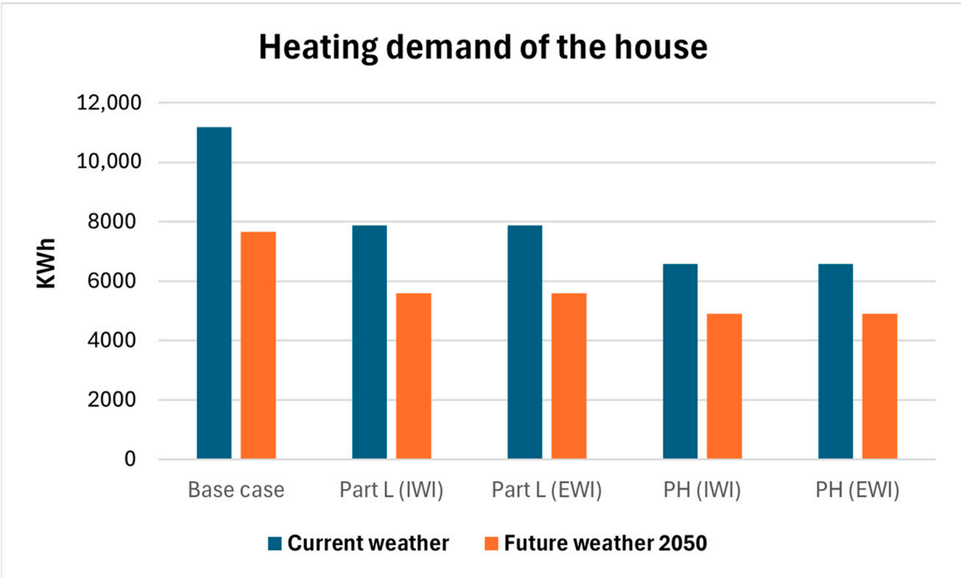


Figure 7. Heating demand of the house for current and future climate scenarios.

3.3.2. Second Case Study: Top Floor Flat

In the base case, the energy required for heating purposes decreased by 15.67% for the future climate compared to the current weather scenario. It is important to note that the high energy consumption in the base case may be attributed to thermal bridging, as the uninsulated roof led to significant heat losses. For the future climate, energy consumption for the Part L scenario was reduced by approximately 37% compared to the base case. In contrast, energy savings for both Passivhaus scenarios exceeded 41.6% compared to the base case, as illustrated in Figure 8.

Comparisons between EWI and IWI did not reveal a significant improvement in energy savings. For the future climate scenario, there was only a negligible 0.01% relative reduction in energy consumption between the Passivhaus EWI and Passivhaus IWI scenarios, which could be attributed to margins of error.

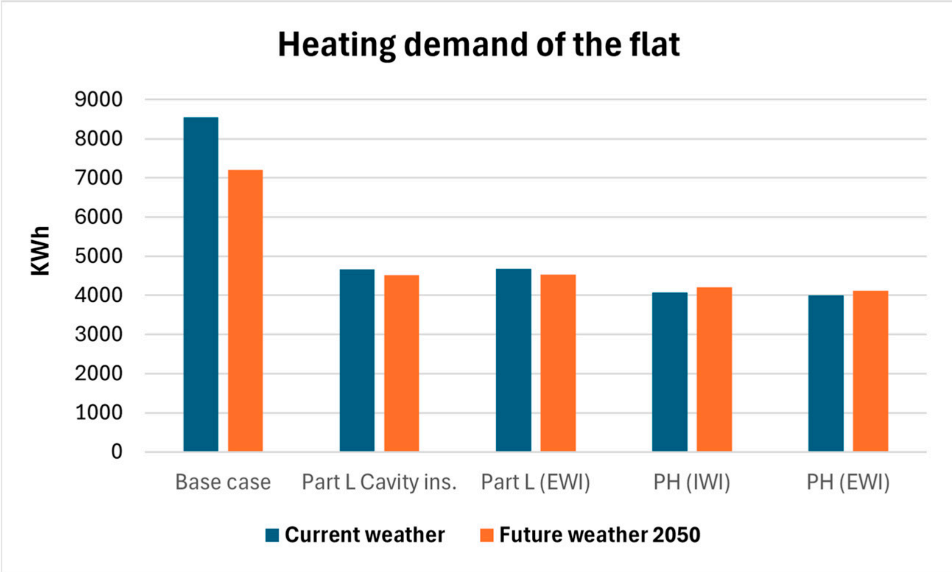


Figure 8. Heating demand of the flat for current and future climate scenarios.

4. Conclusions

This paper investigated thermal comfort and energy efficiency in two social houses, focusing on the application of insulation materials, both internal and external. Four scenarios were analysed and evaluated to identify the most effective proposal for maximising energy savings and improving thermal comfort for occupants in two selected case study buildings. In summary, we can infer the following:

1. The application of insulation materials significantly improved thermal comfort;
2. External wall insulation (EWI) scenarios provided better comfort conditions in the summer, despite only slight reductions in discomfort hours for bedrooms, and no significant change in energy consumption in the winter compared to internal wall insulation (IWI);
3. During the summer, the results indicated that bedrooms were significantly impacted by the projected climate scenario;
4. Under the future weather scenario, south-facing bedrooms in both properties were the most problematic, exceeding comfort hours by 5.9 times in the end-of-terrace house and 2.6 times in the top-floor flat under the Passivhaus scenario. This variability is attributed to other factors such as different building construction methods and window sizes;
5. Although the Passivhaus scenario did not meet future weather criteria, it reduced discomfort hours across all zones compared to other simulation scenarios;
6. During the winter, the mixed-mode ventilation strategy enhanced thermal comfort in bedrooms.

Further investigation is required to assess night-time thermal comfort in bedrooms, and further studies are required to assess the impacts of other passive measures, occupant behaviour, construction methods, dynamic shading measures, and materials on the risk of overheating in buildings.

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