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Overheating Risk from Domestic Retrofit

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Executive Summary

This work contributes to Objective 3 of the Demonstration of Energy Efficiency Potential (DEEP) research project, "To use a range of these models to evaluate the benefits of adopting a whole house approach to retrofit and the unintended consequences of neglecting such an approach". This study uses dynamic thermal simulation to evaluate the risks of overheating from domestic retrofit, and how this can be mitigated using a whole house approach.

Two of the DEEP field trial houses were used for this study. House 56 TR is a two-storey semi-detached house built in 1920, with 91m^2 floor area and double-glazed windows on two opposite façades (south-west and north-east) that enable cross-ventilation. House 17BG is a three-storey back-to-back end-terrace house built in 1890, with 65m^2 floor area with windows on one façade (south-west) and so relied on single-sided ventilation. Single-sided ventilation, as often found in flats, exacerbates overheating. The openable windows in both houses were equipped with restrictors that limited how far the windows could be opened. Both houses underwent a staged sequential retrofit until a whole house retrofit was completed.

The risk of overheating was assessed before retrofit (base case) and at each retrofit stage using dynamic thermal simulation in accordance with the method in CIBSE TM59. The living room and one bedroom of each house were assessed during waking hours (criterion a) and the bedroom of each house during sleeping hours (criterion b). The assessment considered current and future (2060s) climates in different UK locations: London, Manchester, and Glasgow. The assessment was based on ten-years of weather data in each case, so that the number of years that overheating occurred could be compared. This analysis aimed to identify if retrofit increased the risk of overheating.

The risk of overheating was then re-assessed, before retrofit (base case) and after the whole house retrofit (WHR), after applying simple mitigation measures: increased natural ventilation from extended periods of window opening, and exterior shading using shutters. This analysis aimed to identify if these passive measures could mitigate overheating risk, and the impact of whole house retrofit on any residual risk.

Under the current climate, for house 56TR which could be cross-ventilated, overheating occurred most years in London and some years in Manchester. The whole house retrofit made no difference to overheating for this house (Table I, top left quadrant). There was no overheating for this house when the mitigation strategies were applied, either before or after retrofit, in any location, according to both criteria (Table I, top right quadrant).

Under the current climate, for house 17BG, which relied on single-sided ventilation, overheating only occurred some years in London before retrofit (Table I, bottom left quadrant). The whole house retrofit increased the prevalence of overheating for this house such that overheating occurred in all ten years in London, and overheating occurred in two years in Manchester, according to criterion a. However, there was no overheating for this house after applying the mitigation strategies, either before or after retrofit, in any location, according to both criteria (Table I, bottom right quadrant).

Under the current climate, whole house retrofit sometimes increased the risk of overheating, and especially in London. However, this risk was completely eliminated by the use of increased natural ventilation from extended periods of window opening, combined with exterior shading using shutters. For house 56TR, which could be cross-ventilated, increased ventilation was the most effective strategy and additional shading was not needed to eliminate overheating. For house 17BG, which relied on single-sided ventilation, exterior shading was the most effective strategy, but increased ventilation was also needed to completely eliminate overheating.

Table I: The number of years in a decade that overheating occurred for each case-study house, in three different locations, and under the current climate (base = before retrofit and WHR = after whole house retrofit; cells are highlighted green for 0-1 year of overheating, orange for 2-5 years, and red for 6-10 years; numbers are bold where the whole house retrofit increased the prevalence of overheating compared with the base case)

House	Criterion*	Current climate						Current climate with mitigation					
		London		Manchester		Glasgow		London		Manchester		Glasgow	
		Base	WHR	Base	WHR	Base	WHR	Base	WHR	Base	WHR	Base	WHR
56TR	a	5	5	0	0	0	0	0	0	0	0	0	0
	b	8	8	2	2	0	0	0	0	0	0	0	0
17BG	a	4	**10**	0	**2**	0	0	0	0	0	0	0	0
	b	1	**3**	0	0	0	0	0	0	0	0	0	0

* Criterion a includes years when overheating occurred in the living room or in the bedroom during waking hours, while the count for criterion b includes years when overheating occurred in the bedroom during sleeping hours.

Under a future climate, for house 56TR which could be cross-ventilated, overheating occurred every year in London and Manchester, and most years in Glasgow; the whole house retrofit made no difference to overheating for this house (Table II, top left quadrant). There was no overheating for this house when the mitigation strategies were applied, either before or after retrofit, in Manchester or Glasgow, according to both criteria. Overheating still occurred most years in London according to criterion b, but the whole house retrofit slightly reduced the prevalence from seven years to six (Table II, top right quadrant).

Table II: The number of years in a decade that overheating occurred for each case-study house, in three different locations, and under a future (2060s) climate (base = before retrofit and WHR = after whole house retrofit; cells are highlighted green for 0-1 year of overheating, orange for 2-5 years, and red for 6-10 years; numbers are bold where the whole house retrofit increased the prevalence of overheating compared with the base case)

House	Criterion*	Future climate						Future climate with mitigation					
		London		Manchester		Glasgow		London		Manchester		Glasgow	
		Base	WHR	Base	WHR	Base	WHR	Base	WHR	Base	WHR	Base	WHR
56TR	a	10	10	7	7	2	1	2	1	0	0	0	0
	b	10	10	10	10	6	6	7	6	0	0	0	0
17BG	a	10	10	6	**10**	1	**6**	8	**10**	0	1	0	0
	b	10	10	2	**3**	0	**1**	5	3	0	0	0	0

* The count for criterion a includes years when overheating occurred in the living room or in the bedroom during waking hours, while the count for criterion b includes years when overheating occurred in the bedroom during sleeping hours.

Under a future climate, for house 17BG, which relied on single-sided ventilation, overheating occurred every year in London, most years in Manchester, and some years in Glasgow (Table II, bottom left quadrant). The whole house retrofit increased the risk of overheating for this house in Manchester and Glasgow. There was very little or no overheating for this house when the mitigation strategies were applied, either before or after retrofit, in Manchester or Glasgow, according to both criteria. Overheating still occurred most years in London according to criterion a, and this was exacerbated by the whole house retrofit according to criterion a.

Under a future climate, whole house retrofit sometimes increased the risk of overheating in all locations. This risk could be almost completely eliminated in Manchester and Glasgow by the use of increased natural ventilation from extended periods of window opening, combined with exterior shading using shutters. However, overheating still occurred most years in London. This is not surprising since under future conditions the average daily maximum temperature in London is expected to exceed 30 °C, see Table III.

Table III: Mean and average daily maximum temperature[1] in all considered locations.

	Current climate		Future climate	
City	Mean temperature (°C)	Average daily maximum temperature (°C)	Mean temperature (°C)	Average daily maximum temperature (°C)
London	16.4	26.0	20.0	31.3
Manchester	14,5	23.2	17.4	27.2
Glasgow	13.7	20.9	16.2	24.5

[1] These figures arise from the analysis of the weather files used in this work; see Section 4.1.

These findings support the need for a holistic whole house approach to retrofit that includes the provision of adequate shading and ventilation. That way, whole house retrofit with mitigation will not increase overheating risk, except under a future climate for some house types and where risk is already high. Houses (or flats) with single-sided ventilation are more at risk from overheating under future climate in London than those with cross-ventilation. Therefore, it appears likely that mechanical cooling may be required in some homes and in some locations. Whole house retrofit with the provision of adequate shading would reduce the energy demand for cooling in these cases.

The findings also highlighted the risk that piecemeal retrofit, or whole house retrofit, can increase the risk of overheating if shading and ventilation are not addressed. Two additional risk factors were identified in this study: floor insulation noticeably increased the overheating risk for the house with single-sided ventilation and no mitigation, and the results of a parametric analysis indicated that internal wall insulation may increase overheating risk more than external wall insulation.

Further experimental work to validate these findings is recommended. However, the TM59 method provided a useful tool for comparative overheating assessment and especially when used with ten years of weather data. Only two-house types were assessed, but generalisations can be made: 56TR is a relatively common house form in the UK, and 17BG provides a worst-case scenario as it has reduced ventilation due to having windows on only one façade. Further work to develop overheating assessment criteria that are more robust to modelling uncertainty, and to map overheating risk across the UKs housing stock, is recommended.

Overall, the results are clear: we should not be relying on poor fabric thermal efficiency to mitigate overheating. It is encouraging that whole house retrofit that includes the provision of adequate ventilation, and external shading is the best approach to reducing overheating risk. The existing body of evidence in the literature should be consulted to understand the socio-technical barriers to improving natural ventilation and providing external shading.

1. Introduction

This report describes work carried out for the Department for Energy Security and Net Zero (DESNZ) under their Demonstration of Energy Efficiency Potential (DEEP) research project. This work contributes to Objective 3, as stated in the invitation to tender (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/837866/Invitation-to-Tender-for-Demonstration-of-Energy-Efficiency-Potential-DEEP.pdf "To use a range of these models to evaluate the benefits of adopting a whole house approach to retrofit and the unintended consequences of neglecting such an approach". Specifically, this report focuses on the impact of retrofit on summertime overheating as predicted by dynamic thermal simulation.

Overheating can be defined as the state at which high indoor temperature can have a detrimental impact on occupants' thermal comfort, health or productivity [1]. According to Lomas and Porritt [2] the main drivers of overheating are: climate change, urbanisation, tolerance of occupants to heat, increased thermal efficiency of homes, and construction practices.

With regards to increased efficiency of homes, it has been shown that retrofit work can render homes more vulnerable to overheating [3,4]. Similar findings were reported by [5], where two similar side-by-side houses were monitored while only one was retrofitted with interior insulation. The insulated house had higher operative temperatures in the summer[1]. However, when a simple mitigation strategy was implemented, consisting of night ventilation and interior shading, operative temperature reduced to a level similar to that of the uninsulated house. In this case, insulation retrofit only slightly increased the propensity of the house to overheat.

In this work, overheating risk assessment was carried out for two of the DEEP field trial houses (56TR and 17BG). This was done before retrofit, at each stage of a sequential retrofit, and after the whole house retrofit was completed. The assessment was carried out by dynamic thermal simulation in accordance with CIBSE TM59. The analysis considered both current and future (2060s) weather in three different UK locations: London, Manchester, and Glasgow. The aim was to identify when overheating occurs, the factors that influence overheating, and if simple passive mitigation strategies (such as increased natural ventilation and shading) can be effective.

This report presents the case study houses that were assessed (Section 2), describes the overheating assessment method used (Section 3), and details the modelling inputs (Section 4). The assessment results for both houses are presented before retrofit, and at the end of each retrofit stage (Section 5). A parametric analysis was used to rank the factors that impact on overheating (Section 6), and the impact of simple passive mitigation measures assessed (Section 7), before discussing the main findings of this work and drawing conclusions (Section 8).

[1] Operative temperature is calculated from the air temperature and the mean radiant temperature to better represent thermal comfort but can be adequately represented by air temperature in most cases.

2. Case study houses

The two case-study houses, 56TR and 17BG, were part of the DEEP field work and underwent sequential retrofit to individual thermal elements (i.e., floors, walls etc.). The calibrated models of these houses with all the geometry and construction details were provided by Leeds Beckett University (see Section 4 for full details). For more information regarding the retrofit programme, modelling and calibration please refer to the DEEP Methods 2.02 Report [6] and the DEEP Methods 2.03 Report [7].

House 56 TR is a two-storey semi-detached house built in 1920, with 91m^2 floor area. House 17BG is a three-storey back-to-back end-terrace house built in 1890, with 65m^2 floor area. The two houses were chosen because ventilation is known to impact on overheating: 56TR has windows on two opposite facades and so can be cross ventilated, while 17BG only has windows on one façade and must rely on single-sided ventilation. Single-sided ventilation, as often found in flats, exacerbates overheating. The openable windows in both houses were equipped with restrictors that limited how far the windows could be opened.

House 56TR has one party wall (see Figure 1) and faces south-west. It has double glazed windows on two opposite walls, on the south-west and north-east wall. The openable windows are equipped with restrictors that limit opening to 150 mm from the frame. Figure 2 shows the floor plans of the house and Table 1 displays the U-values of the retrofitted elements, plus whole house infiltration rate, before and after retrofit.

Figure 1: South-east (top) and north-west (bottom) view of 56TR house (openable windows are highlighted in light red)

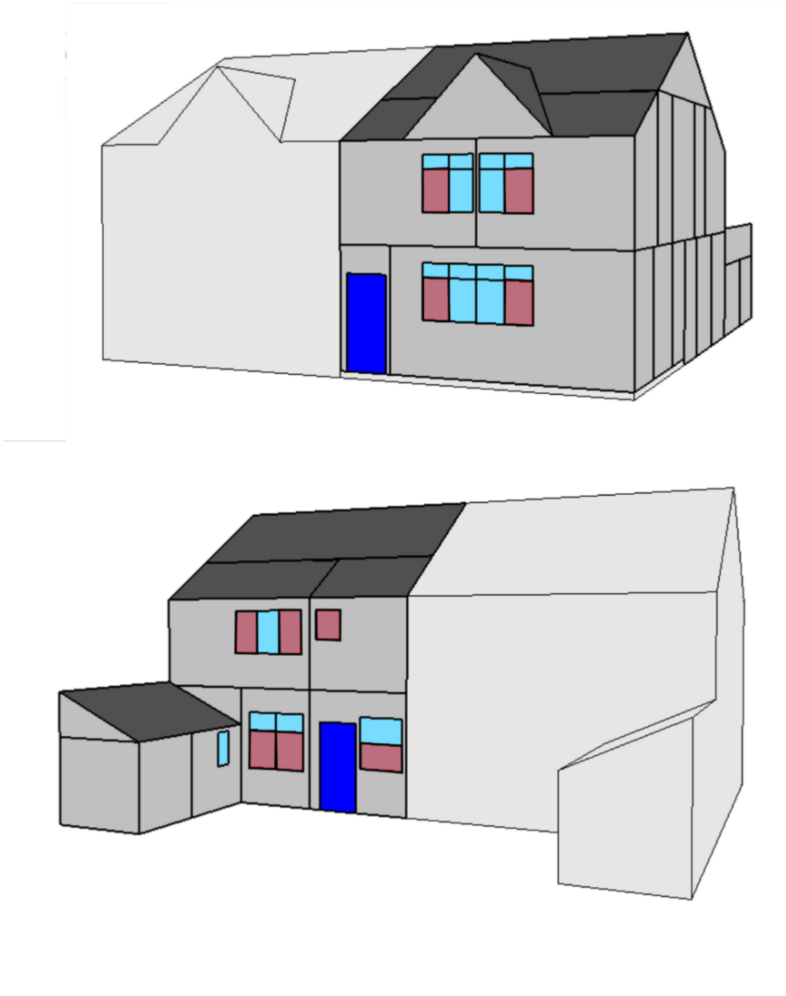

Figure 2: Floor plans of 56TR house (windows are shown by blue lines)

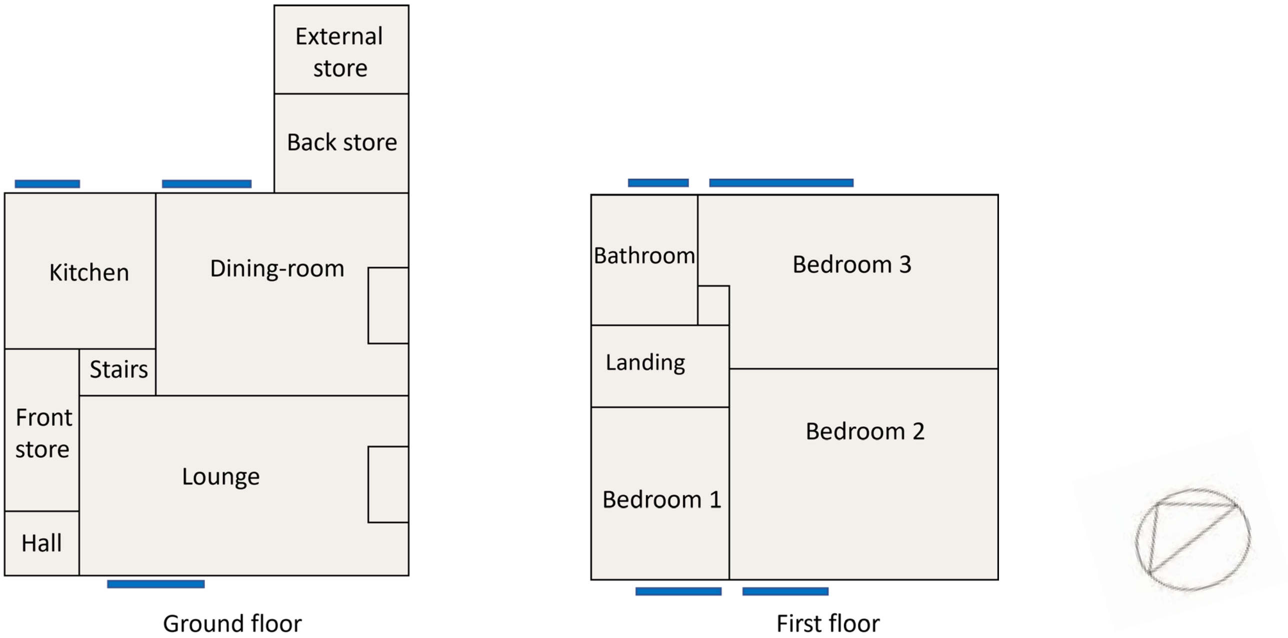

Table 1: U-values of 56TR house envelope's elements, plus whole-house infiltration rate [6]

		U-value (W/(m²·K))		***Infiltration rate[1] (ach)***	
Element	**Construction name**	Before retrofit	After retrofit	Before retrofit	After retrofit
Floor	56TR solid ground floor	0.91	0.91		
	56TR suspended timber floor	0.72	0.23		
Wall	56TR solid brick south downstairs	1.13	0.59		
	56TR solid brick south upstairs	1.55	1.23		
	56TR solid brick gable	2.05	0.80		
	56TR solid brick north	2.05	1.01		
Roof	56TR clay tiles occupied	0.56	0.42		
	RdSAP clay tiles occupied	2.57	2.57		
	56TR loft space ceiling	0.23	0.17		
Whole house				0.40	0.44

[1] *The infiltration rates were calculated from the measured air permeability value (q50) divided by 20*

House 17BG has a south-south-west orientation. It shares a common wall with adjacent houses on one side and at the back. It only has double glazed windows on the south-south-west façade and so only has single-sided ventilation and cannot be cross-ventilated (see Figure 3). The windows that are openable are equipped with safety restrictors (windows open to a maximum of 100mm from the frame). Figure 4 displays the floor plans of the home whilst Table 2 shows the U-values of the envelope's house retrofitted elements before and after retrofit.

Figure 3: Exterior view of 17BG house (openable windows are highlighted in light red)

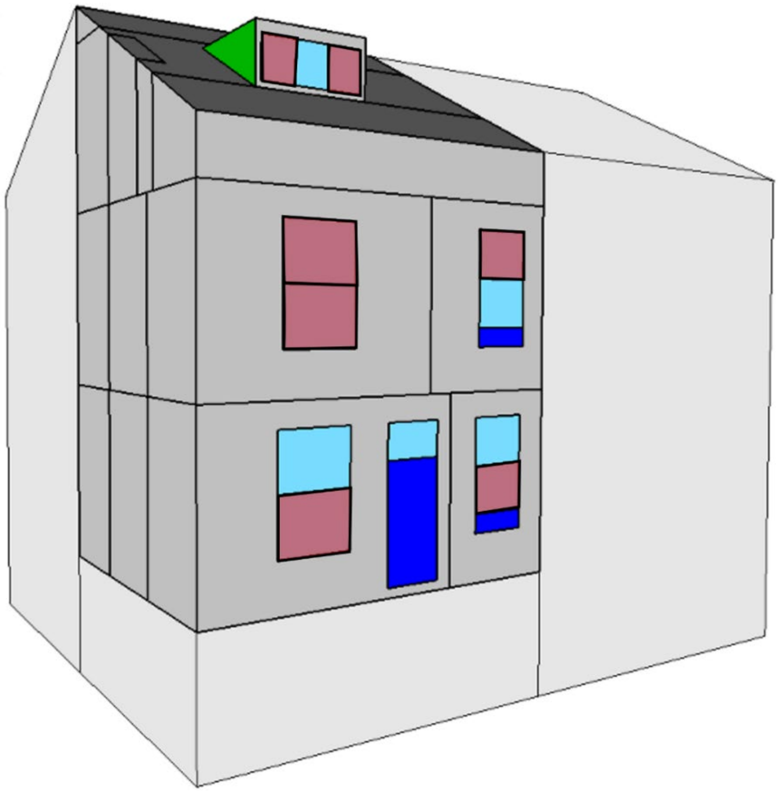

Figure 4: Floor plans of 17BG house (windows are shown by blue lines)

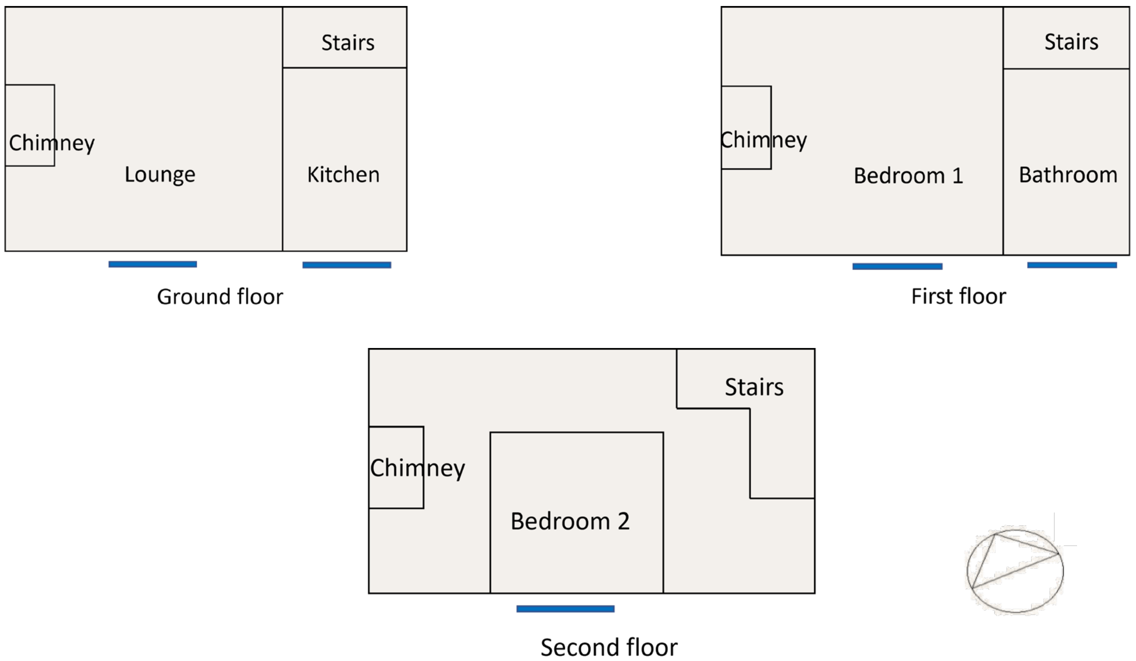

Table 2: U-values of 17BG house envelope's elements, plus whole house infiltration rate [6]

		U-value (W/(m²·K))		***Infiltration rate[1] (ach)***	
Element	**Construction name**	Before retrofit	After retrofit	Before retrofit	After retrofit
Floor	17BG suspended timber floor	1.04	0.17		
Wall	17BG solid brick wall iwi measured (internally insulated)	1.01	0.63		
	17BG solid brick wall gf & ff (walls in ground and first floor)	1.92	0.55		
	17BG solid brick wall room-in-roof	2.03	0.48		
	17BG dormer walls	1.54	0.67		
Roof	17BG clay tiles occupied	0.60	0.29		
	17BG clay tiles unoccupied	2.95	0.29		
	17BG dormer roof	2.37	0.24		
	17BG loft space ceiling apex	0.53	0.25		
Whole house				0.78	0.47

[1] *The infiltration rates were calculated form the measured air permeability value (q50) divided by 20*

3. Overheating assessment method

The risk of summertime overheating in the case study houses was assessed using dynamic thermal simulation after the method specified in CIBSE TM59 [8]. The method is used to demonstrate compliance with the Building Regulations for new residential buildings, as described in the Approved Document O [9], and so is deemed appropriate for this study.

TM59 defines two assessment criteria for the naturally ventilated[2] case study houses:

- Criterion a: the number of hours of exceedance, when $\Delta T \geq 1°C$, should be ≤ 3% of the occupied hours[3] for the period from May to September inclusive. This criterion applies to living rooms, kitchens, and bedrooms.

- Criterion b: the number of hours of exceedance, when $T_{op} > 26°C$, should be ≤ 1% of annual sleeping hours[4]. This criterion applies only to bedrooms and is intended to assess sleep quality.

The values of ΔT and T_{op} are defined as follows:

- $\Delta T = T_{op} - T_{max}$
- T_{op} is the operative temperature of the assessed room.

The maximum[5] acceptance temperature, T_{max}, is defined by:

- $T_{\max} = 0.33T_{rm} + 21.8$

Where, T_{rm} is the weighted running mean temperature:

- $T_{rm} = (1 - \alpha)(T_{od1} + aT_{od-2} \ + a^2 T_{od-3} \dots)$
- T_{od1}, T_{od-2} are the daily mean outdoor temperatures of the previous days
- a is a constant (taken to be equal to 0.8).

The exponential form of the equation for the weighted running mean temperature means that the days that are closer to the present day have a stronger impact on T_{rm}whilst the influence of preceding days on $T_{rm}$are diminished.

The assessment was carried out using 10 years of weather data in all cases, by using Recent Weather Decade (RWD) and Future Weather Decade (FWD) files (see DEEP Project Report 6.01 [12]). In the results, the hours of exceedance (%) calculated for each of the ten years are presented as a box plot which displays the median, the lower and upper quartiles, the interquartile range and the whiskers that show the rest of the data; extreme values are shown as outliers.

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[2] In the context of TM59, naturally ventilated houses are those with no mechanical cooling, in which occupants can regulate the indoor environment by opening/closing the windows.
[3] Lounges and kitchens are assumed to be occupied from 9 am to 10 pm, bedrooms are occupied 24 h a day.
[4] Sleeping hours are assumed to be from 10 pm to 7 am.
[5] Note that $T_{\max}$ as defined above is applicable to the general population, in the case that a home is occupied by vulnerable people $T_{\max}$ should be decreased by 1 °C, see CIBSE TM52 guide [28] for more details.

4. Modelling inputs

The dynamic thermal simulation of the case study houses was carried out using EnergyPlus simulation software (version 9.5) [10].This is a widely used software tool and validated in the context of ANSI/ASHRAE Standard 140-2011 [11]. The modelling inputs that are required for the simulation, described in detail in this section, can be categorised as follows:

- Weather and ground temperatures
- Geometry and construction
- Airflow and ventilation
- Space heating and internal gains

The DesignBuilder [12] models of the case study houses had been calibrated[6] after the method described by [13] to ensure the average heat loss predicted by the simulation matched the measured heat loss of each case [6]. Small changes were made to these models so that they were suitable for overheating analysis: changing the way zones with stairs were joined, adding thermal mass to account for furnishings and using a zonal network method to predict natural ventilation. These, changes, detailed below and summarised in Table 3, did not change the average heat loss.

Table 3: Changes made to the calibrated models supplied by Leeds Beckett University

Change	Notes
Merging of zones connected by horizontal openings	Zones in different floors connected by staircases merged into one zone (see Section 4.2)
Addition of internal mass	Internal mass that accounts for furniture was added (see Section 4.2)
Modelling of airflow	The Airflow Network (AFN) was employed instead of using scheduled natural ventilation rates (see Section 4.3)

4.1. Weather and ground temperatures

Overheating was assessed under both current and future weather conditions in three different locations: London, Manchester, and Glasgow. The Recent Weather Decade (RWD) and Future Weather Decade (FWD) files that were developed for the DEEP project (see DEEP Project Report 6.01[14] were used in the place of a single year[7]. The RWD file was derived from ten years of weather observation (2010-2019) for each location. The FWD file was derived by applying morphing[8] techniques to represent future (2060s) weather.

Overheating will vary from year to year as some summers are warmer than others and hot spells or heat waves are erratic. The use of ten years of data in the RWD and FWD files is,

[6] In this calibration process some of the model inputs were updated based on actual measurements.
[7] Typically, a Design Summer Year (DSY) that contains data for only one year is used.
[8] Morphing is the technique that adjusts mathematically historical weather observations utilising climate projections.

therefore, a better approach to understanding overheating in different rooms and over years of fluctuating weather than simply using a single year. Overheating hours of exceedance (criterion a and criterion b) were displayed in a box plot that contains the ten results, along with a table that states the number of years that the overheating assessment failed (see Sections 5 and 7). This removes some of the limitations of a deterministic overheating assessment where pass or fail is based on one year of weather data and any uncertainty in the result is ignored.

The monthly mean temperatures of the ground under the house were calculated from a correlation with the external air temperature, for all 120 months of the RWD/FWD files, after the method described in BS 5250:2011 [15]. This method accounts for the time lag between changes in ground temperature and air temperature over the year. The Energy Management System facility (EMS) in EnergyPlus was used to schedule these ground temperatures. This extra step was required because EnergyPlus normally only uses 12 ground temperatures for a one-year simulation.

4.2. Geometry and construction

The case study houses were modelled with each room as a separate thermal zone. The zonal network method required for the overheating analysis necessitated those zones connected by stairs to be merged into a single thermal zone. Party walls were modelled as adiabatic walls.

The models of the case study houses had been calibrated for average heat loss, but the rate that the homes warm up and cool down was not part of the calibration, and the models did not consider the thermal mass of fixtures, fittings, and furnishings. Indoor air temperature predictions, as required for overheating analysis, can be particularly sensitive to this rate of heating and cooling [16] and so additional thermal mass was added based on the recommendations of ASHRAE 90.2.2007 [17] as illustrated in [18]; in this document, 3.6 kg of 5 cm thick wood[9] per square foot is assumed. This figure comes from an American document but in the absence of any evidence for UK homes it was used in this work as well. This thermal mass was represented in EnergyPlus via the InternalMass object. The surface area of furniture used in the models is shown in Table A.1 of the appendix.

4.3. Airflow and ventilation

Airflow and ventilation were modelled using the Airflow Network (AFN) method in EnergyPlus. This is a zonal network method that calculates the airflow through each façade, including window openings, and between each room and floor. The flow coefficient and flow exponent values for each case study house were adjusted so that the average infiltration rate matched (within +/-3%) the measured infiltration[10]. Infiltration rates were predicted at zone level and the average calculated using the volumes of the thermal zones as weighting factors. This

[9] Assuming a wood density of 753 kg/m^3 [18].

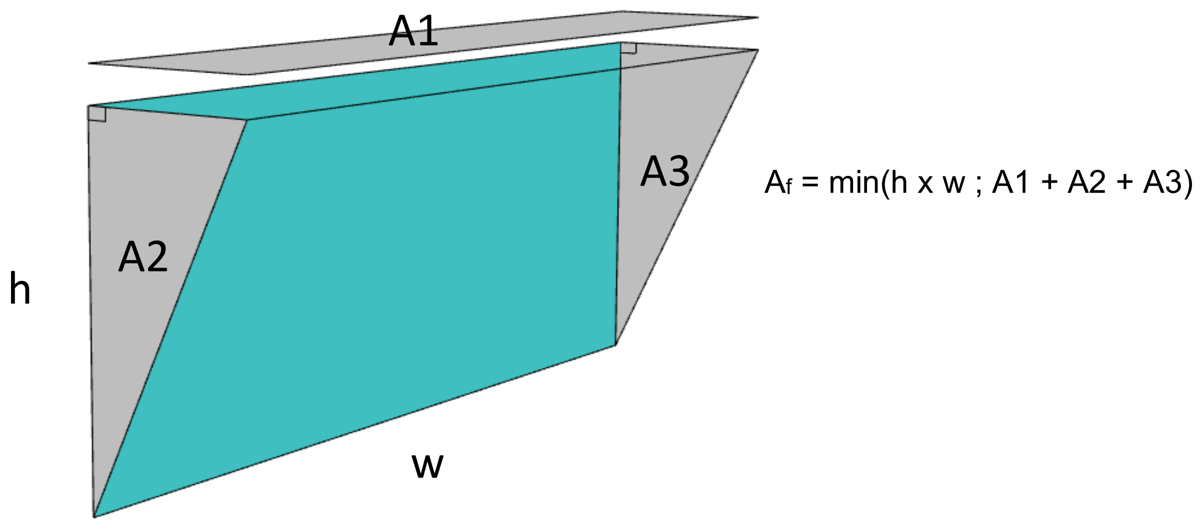
[10] The measured infiltration was calculated from the blower door airtightness test result, Q50, divided by 20. This is the same as the method used by the Standard Assessment Procedure [29].

calibration was carried out for each retrofit stage and the resulting flow coefficient and flow exponent values are given in Tables A.2-A.5 of the appendix.

Internal doors were assumed to be open at all times, except those in bedrooms which were assumed to be closed during sleeping hours. The opening of windows was modelled after the method described in TM59: the windows in a room are opened when it is summer (May to September inclusive), the room air temperature has exceeded 22°C, and the room is occupied[11]. The EMS facility of EnergyPlus was used to control the operation of windows with season, air temperature, and time of day.

The effective area of openable windows is equal to the product of its discharge coefficient and free area. The free area is the area of the aperture through which air can flow [19] and can be calculated in different ways, introducing uncertainty [20]. For this work, the free area was calculated as shown in Figure 5.

Figure 5: Free area (A_f) of openable windows



4.4. Space heating and internal gains

Overheating was assessed in the summer months (May to September inclusive) when there was no space heating. However, the case study houses were modelled as being heated in the remaining months (October to April inclusive) for completeness. The EnergyPlus ideal loads air system was used with set-point and set-back temperatures and schedules from the National Calculation Methodology (NCM) [21]; these can be found in Table A.6 of the appendix. Internal gains were ascribed to the models in accordance with TM59 and NCM for the summer and winter period respectively. Details are given in Tables A.7-A.9 of the appendix.

[11] Lounges and kitchens are assumed to be occupied from 9 am to 10 pm, bedrooms are occupied 24 hours a day, as defined in TM59.

5. Assessment of overheating before and after retrofit

The risk of overheating was assessed for each of the case study houses before any retrofit work took place (baseline model) and at the end of each retrofit stage. In all cases, overheating was assessed as described in Section 3. Criterion a was applied in two characteristic rooms: the living room and bedroom 1 in 56TR, and the living room and bedroom 2 in 17BG. Criterion b was applied to these bedrooms. The assessments were carried out using Recent Weather Decade (RWD) and Future Weather Decade (FWD) files as described in Section 4. This analysis seeks to identify if retrofit increases the risk of overheating. In this work some years means that overheating occurred for no more than five years, whilst most years means that overheating occurred for more than five years.

5.1. 56TR house

The case study house 56TR was assessed before retrofit (BASL), at three intermediate stages, and after the whole house retrofit (WHR) as shown in Table 4.

Table 4: Stages of retrofit work in 56TR house

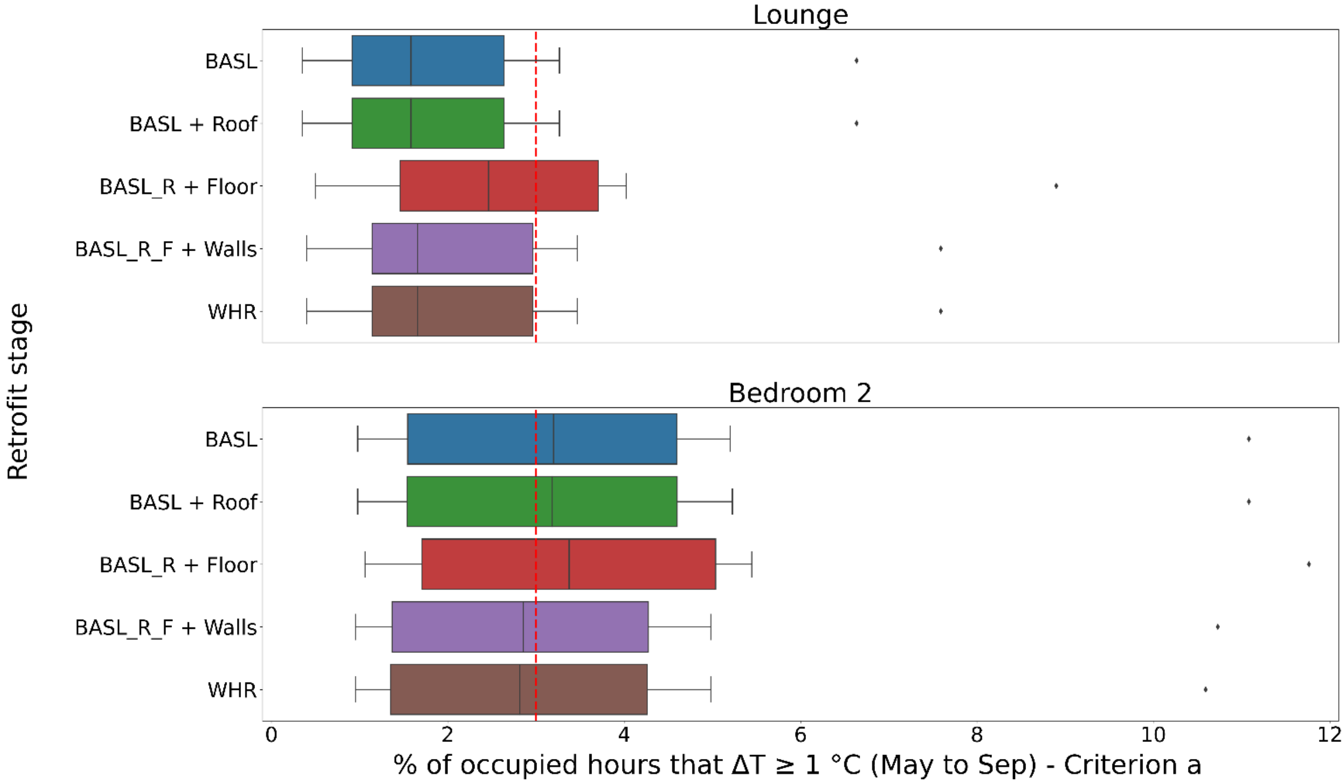
Model #	Retrofit stage	Code name
0	Pre-retrofit baseline	BASL
1	Model 0 + roof insulation	BASL + Roof
2	Model 1 + floor insulation	BASL_R + Floor
3	Model 2 + wall insulation	BASL_R_F + Walls
4	Whole house retrofit *	WHR

* Insulation added below damp course and to sloping ceilings

5.1.1 Overheating risk in a Recent Weather Decade

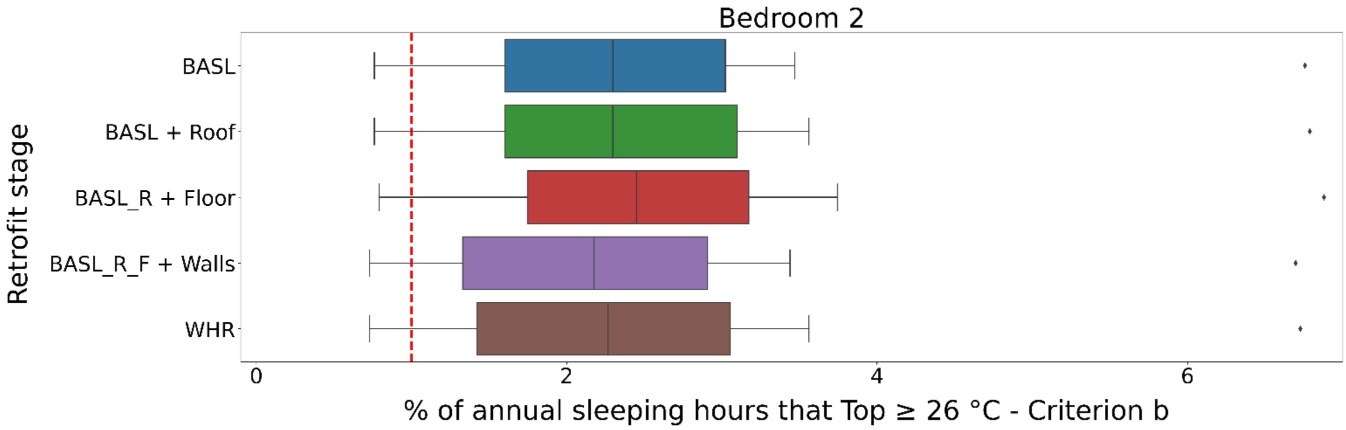
For the London RWD, overheating occurred in some years in the living room and bedroom, according to criterion a, for the pre-retrofit baseline and at each retrofit stage (Figure 6). Overheating occurred in most years in the bedroom, according to criterion b, for the pre-retrofit baseline as well as at each retrofit stage (Figure 7). The retrofit had little impact on the risk of overheating for this house in London, though the model with roof and floor insulation (BASL_R + Floor) overheated, in both rooms under both criteria, more than at any other retrofit stage.

Figure 6: Overheating assessment for 56TR with London RWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
	Number of years that overheating occurs according to criterion a				
Living room	2/10	2/10	4/10	3/10	3/10
Bedroom 2	5/10	5/10	5/10	5/10	5/10

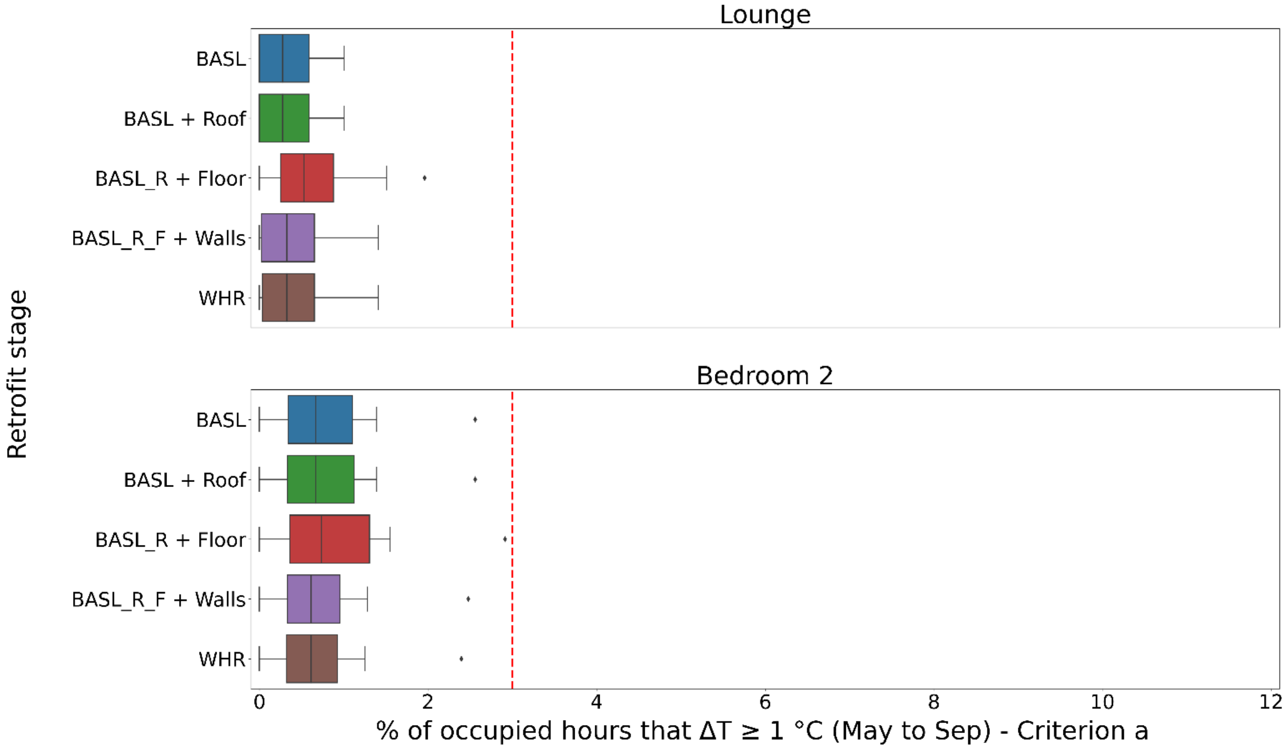
Figure 7: Overheating assessment for 56TR with London RWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
	Number of years that overheating occurs according to criterion b				
Bedroom 2	8/10	8/10	9/10	8/10	8/10

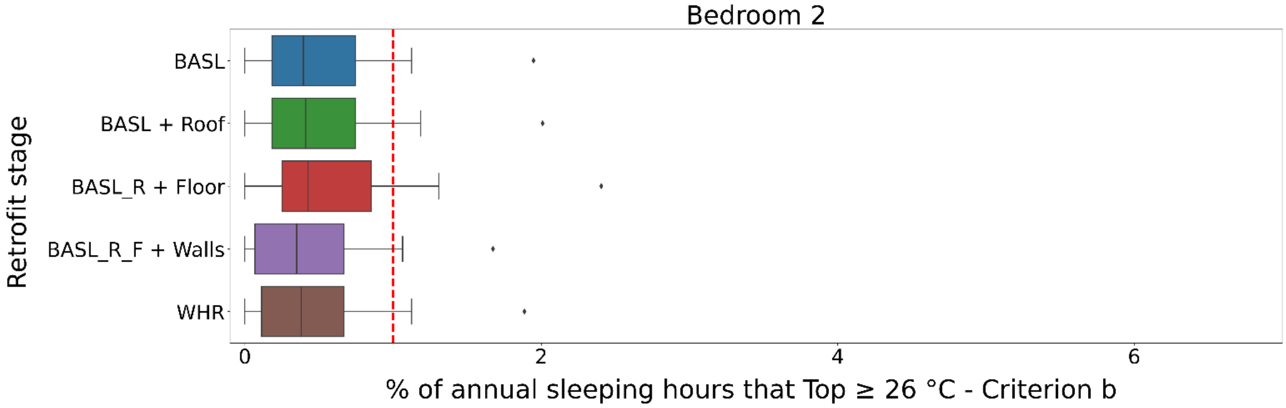
For the Manchester RWD, no overheating occurred in the living room and bedroom, according to criterion a (Figure 8). Overheating occurred in two years for the pre-retrofit baseline, and at each retrofit stage in the bedroom, according to criterion b (Figure 9). The retrofit had very little impact on overheating risk for this house in Manchester.

Figure 8: Overheating assessment for 56TR with Manchester RWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Living room	0/10	0/10	0/10	0/10	0/10
Bedroom 2	0/10	0/10	0/10	0/10	0/10

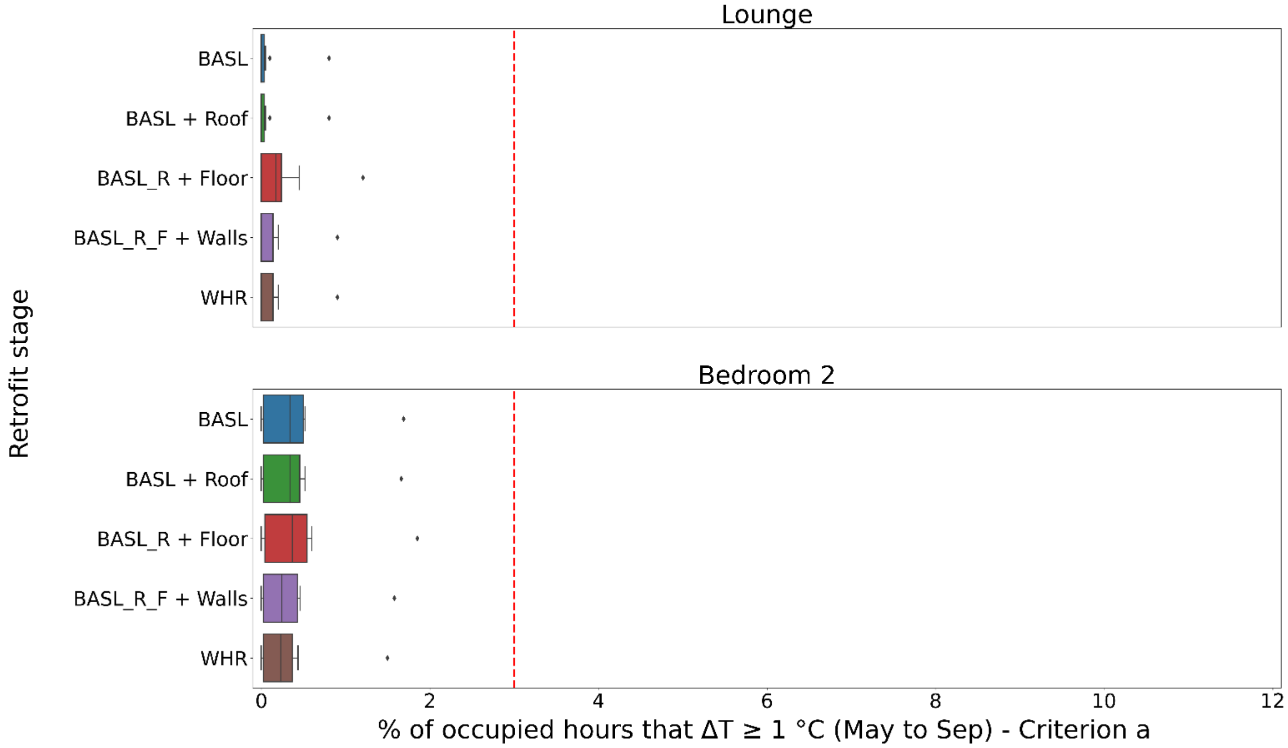
Figure 9: Overheating assessment for 56TR with Manchester RWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion b				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Bedroom 2	2/10	2/10	2/10	2/10	2/10

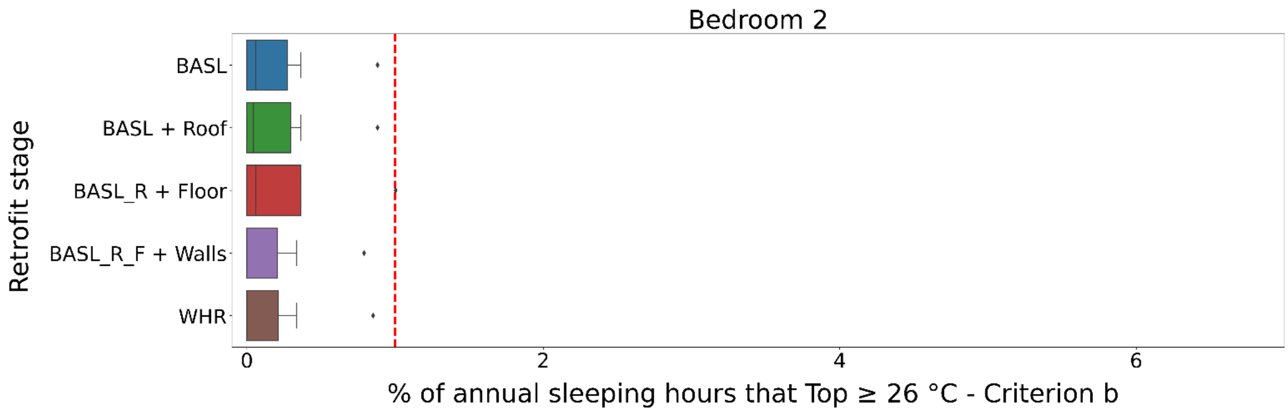
For the Glasgow RWD there was no overheating according to criterion a (Figure 10). Overheating only occurred in one year for the BAS_R + Floor retrofit model according to criterion b (Figure 11). Overheating is not a problem for this house in Glasgow.

Figure 10: Overheating assessment for 56TR with Glasgow RWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Living room	0/10	0/10	0/10	0/10	0/10
Bedroom 2	0/10	0/10	0/10	0/10	0/10

Figure 11: Overheating assessment for 56TR with Glasgow RWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion b				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Bedroom 2	0/10	0/10	1/10	0/10	0/10

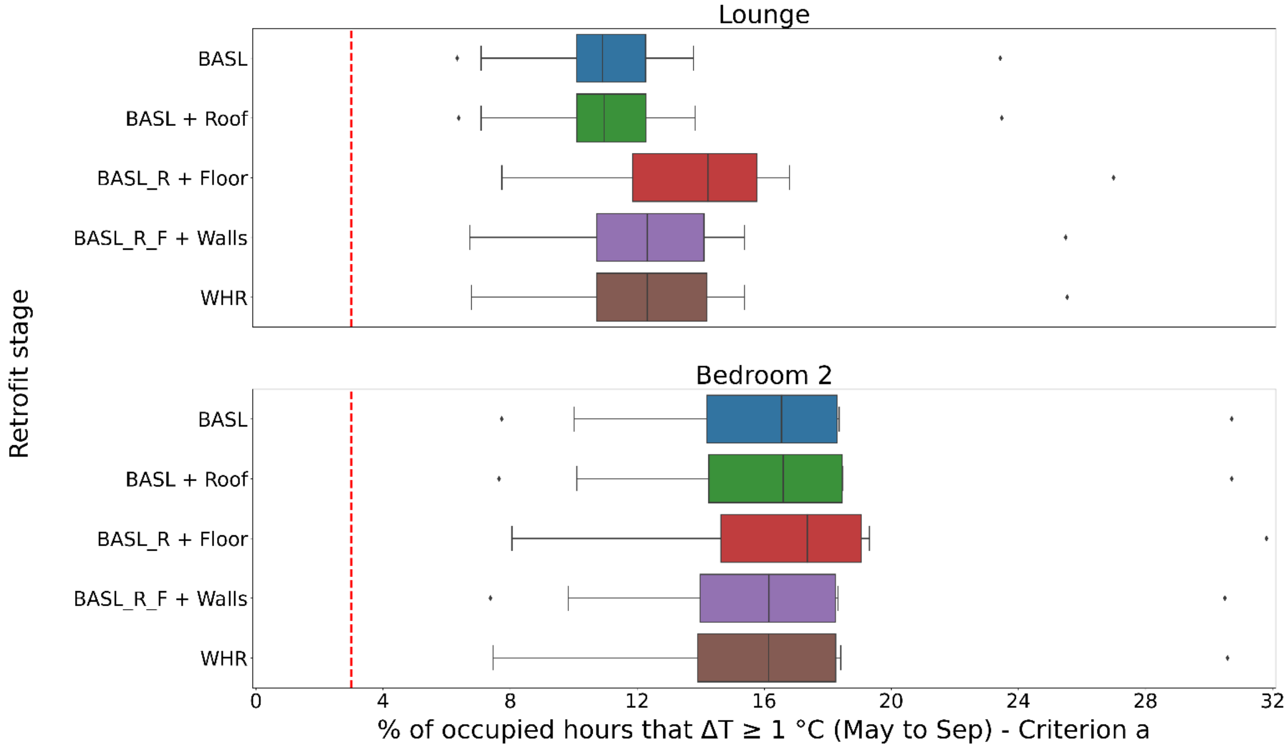
5.1.2 Overheating risk in a Future Weather Decade

For the London FWD, overheating occurred every year in the living room and bedroom, according to criterion a, for the pre-retrofit baseline and at each retrofit stage (Figure 12). Overheating also occurred in every year in the bedroom according to criterion b, for the pre-retrofit baseline and at each retrofit stage (Figure 13). The retrofit had little impact on overheating for this house in London, though the model with roof and floor insulation (BASL_R + Floor) overheated, in both rooms under both criteria, with slightly higher median hours of exceedance.

For the Manchester FWD, overheating occurred in some years in the living room and bedroom (with the exception of retrofit stage BASL_R+Floor in the living room, where overheating occurred in most years), according to criterion a, for the pre-retrofit baseline and at each retrofit stage (Figure 14). Overheating occurred in all years in the bedroom according to criterion b for the pre-retrofit baseline and at each retrofit stage (Figure 15). The retrofit had little impact on overheating for this house in Manchester, though the model with roof and floor insulation (BASL_R + Floor) overheated, in both rooms under both criteria, with slightly higher median hours of exceedance.

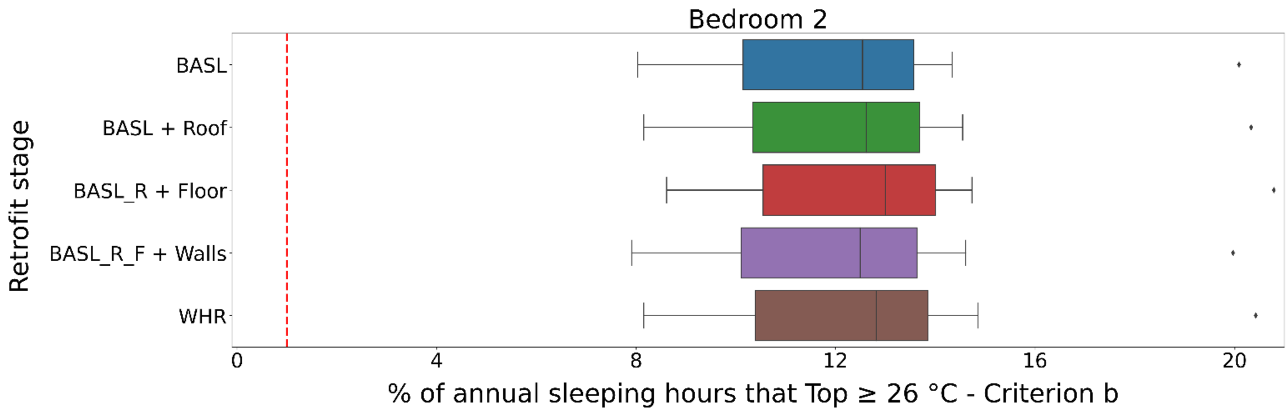
For the Glasgow FWD, overheating occurred in just one year in the living room, and some years in the bedroom, according to criterion a, for the pre-retrofit baseline and at each retrofit stage (Figure 16). Overheating occurred in most years in the bedroom according to criterion b for the pre-retrofit baseline and at each retrofit stage (Figure17). The retrofit had little impact on overheating for this house in Glasgow, though the model with roof and floor insulation (BASL_R + Floor) overheated, in both rooms under both criteria, with marginally higher median hours of exceedance.

Figure 12: Overheating assessment for 56TR with London FWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



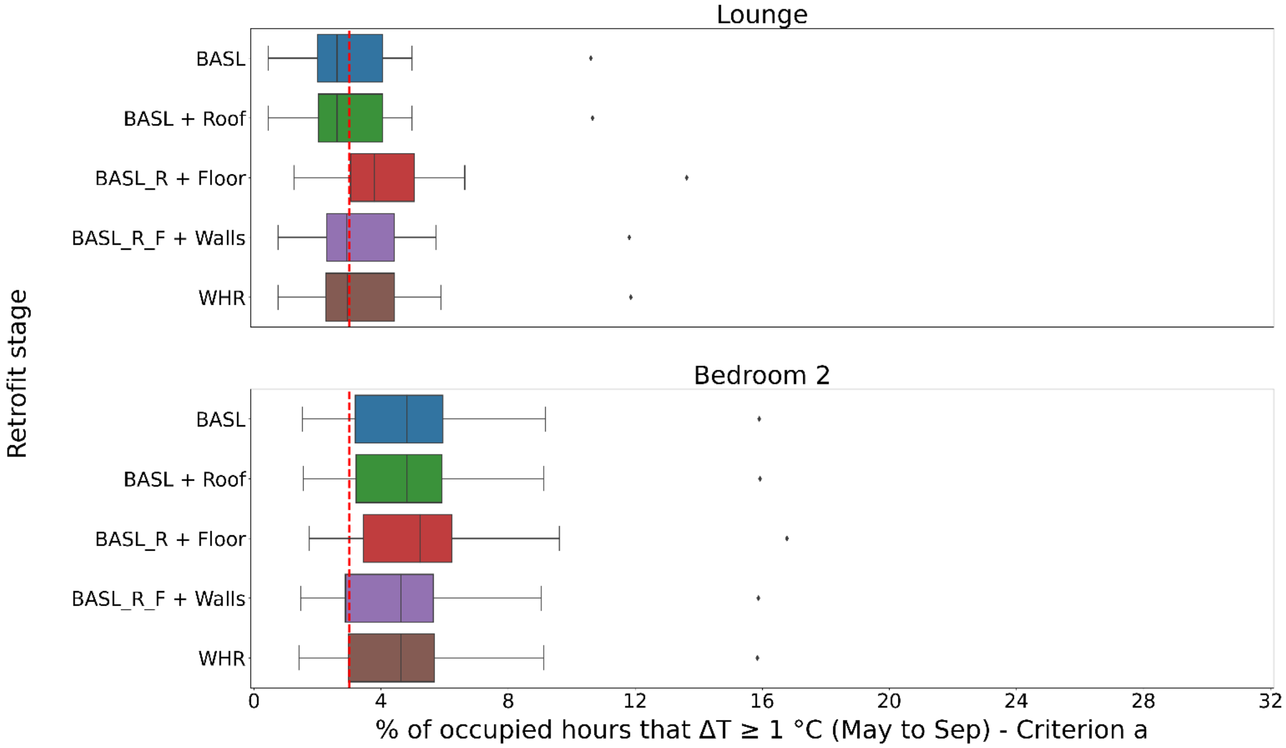
	Number of years that overheating occurs according to criterion a				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Living room	10/10	10/10	10/10	10/10	10/10
Bedroom 2	10/10	10/10	10/10	10/10	10/10

Figure 13: Overheating assessment for 56TR with London FWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



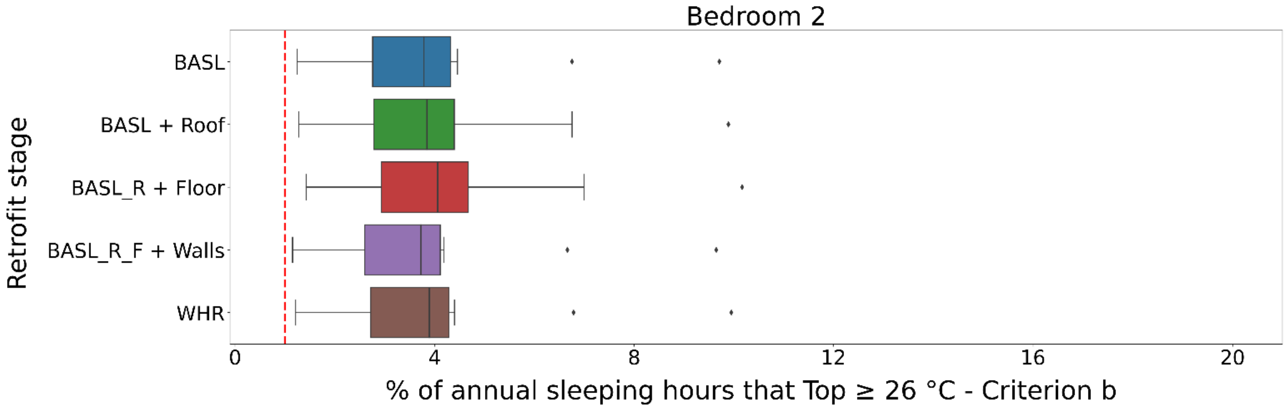
	Number of years that overheating occurs according to criterion b				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Bedroom 2	10/10	10/10	10/10	10/10	10/10

Figure 14: Overheating assessment for 56TR with Manchester FWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



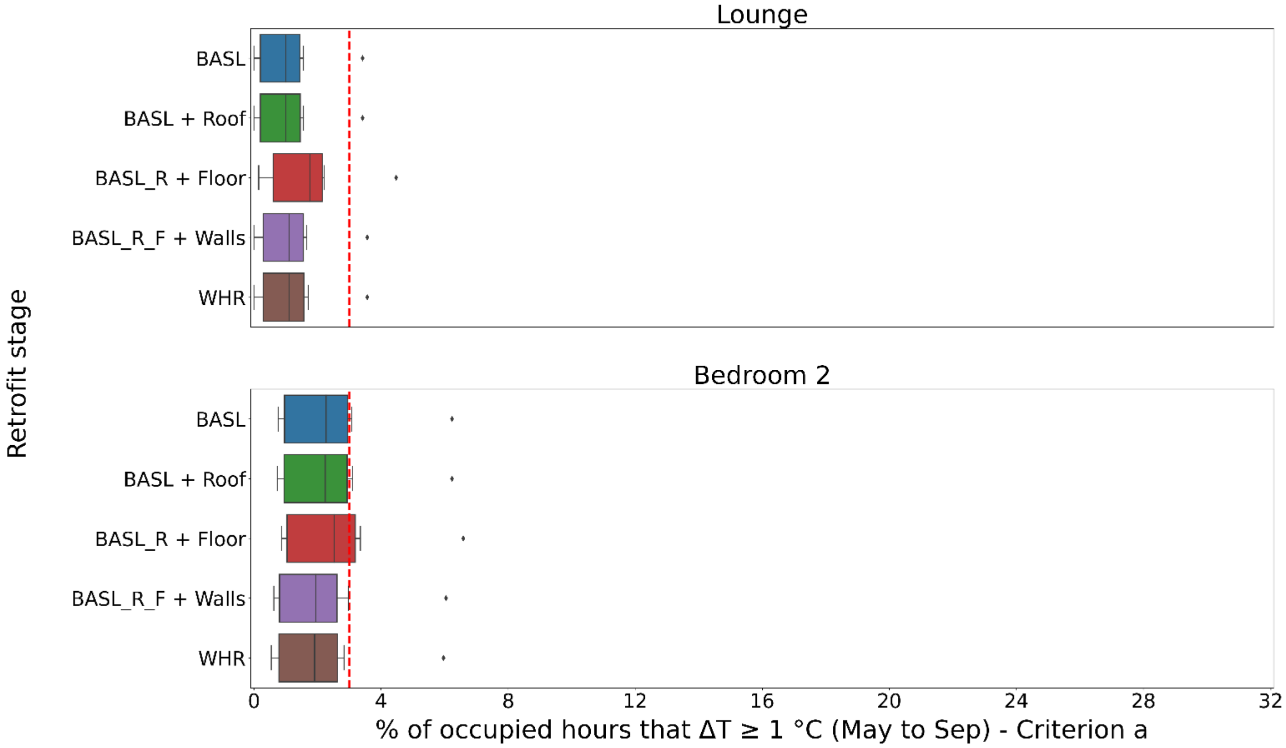
	Number of years that overheating occurs according to criterion a				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Living room	4/10	4/10	7/10	4/10	4/10
Bedroom 2	7/10	7/10	8/10	7/10	7/10

Figure 15: Overheating assessment for 56TR with Manchester FWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



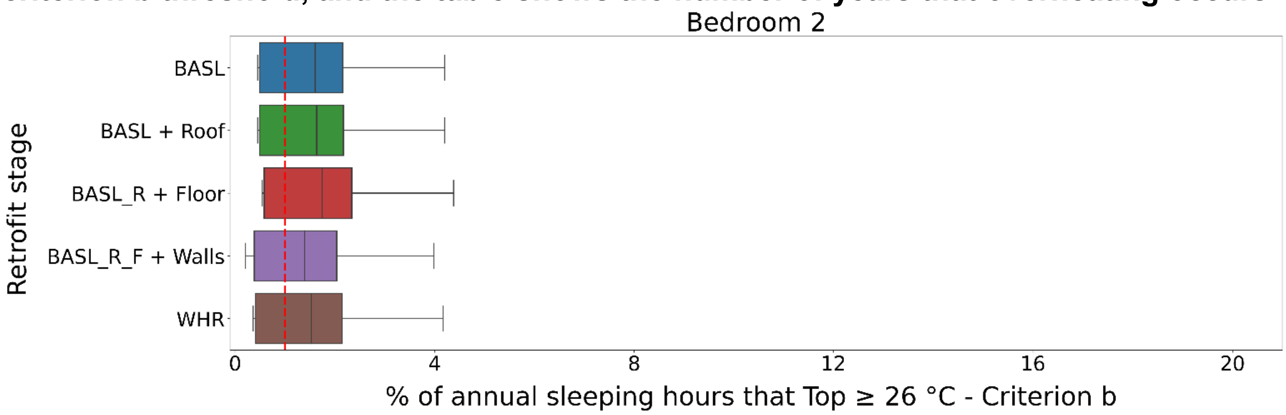
	Number of years that overheating occurs according to criterion b				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Bedroom 2	10/10	10/10	10/10	10/10	10/10

Figure 16: Overheating assessment for 56TR with Glasgow FWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Living room	1/10	1/10	1/10	1/10	1/10
Bedroom 2	2/10	2/10	4/10	1/10	1/10

Figure 17: Overheating assessment for 56TR with Glasgow FWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion b				
Room	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Bedroom 2	6/10	6/10	6/10	6/10	6/10

5.2.

5.3. 17BG house

The case study house 17BG was assessed before retrofit (BASL), at four intermediate stages, and after the whole house retrofit (WHR) as shown in Table 5.

Table 5: Stages of retrofit work in 17BG house

Model #	Retrofit stage	Code name
0	Pre-retrofit baseline	BASL
1	Model 0 + Airtightness	BASL + Airtightness
2	Model 1 + dormer insulation	BASL_A + Dormer
3	Model 2 + floor insulation	BASL_A_D + Floor
4	Model 3 + wall insulation	BASL_A_D_F + Walls
5	Whole house retrofit *	WHR

* Kitchen, bathroom, and room-in-roof insulated

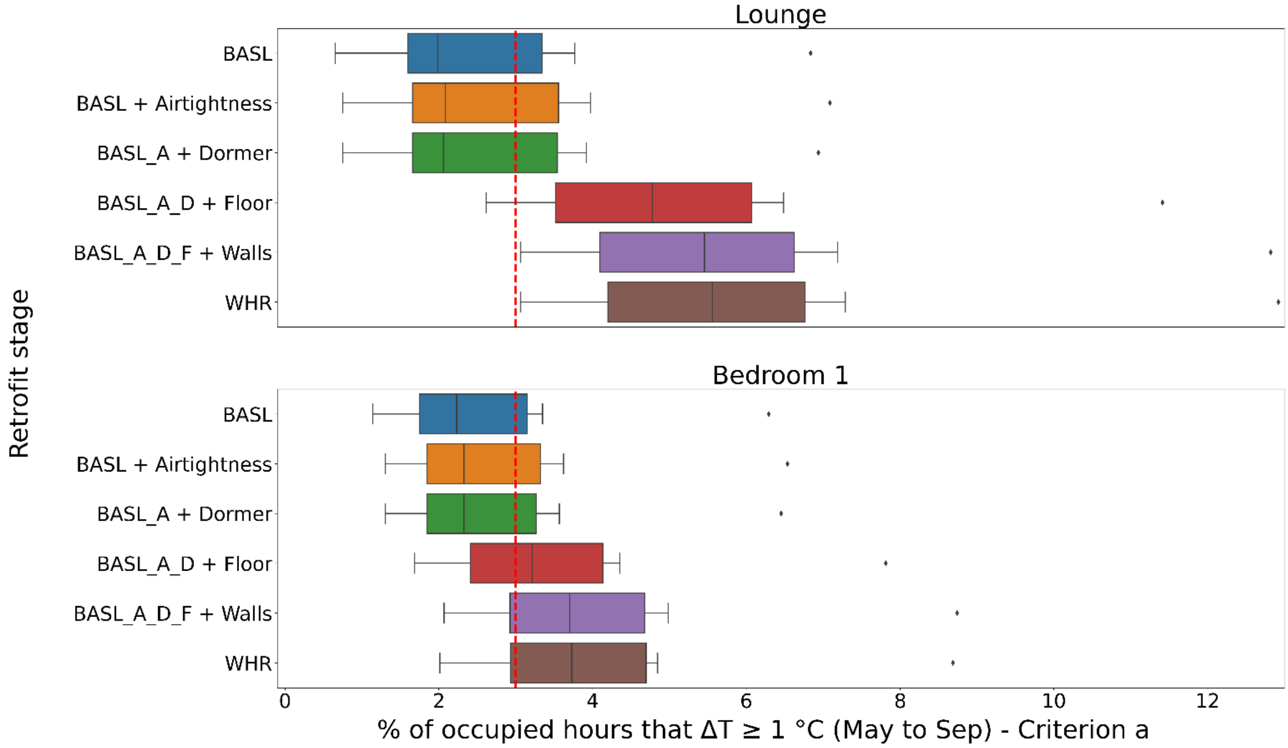
5.2.1 Overheating risk in a Recent Weather Decade

For the London RWD, overheating occurred in the living room and bedroom at all stages, according to criterion a, but the number of years that overheating occurred increased with the retrofit stage from three years for the pre-retrofit baseline (BASL) to all ten years for the whole house retrofit (WHR) (Figure 18). Overheating occurred in just one year in the bedroom, according to criterion b at the pre-retrofit baseline, but increased to three years after the installation of floor insulation (BASL_A_D + Floor) and at subsequent retrofit stages (Figure 19). The retrofit substantially increased overheating risk for this house in London.

For the Manchester RWD, some overheating occurred in the living room and bedroom, according to criterion a, after the installation of floor insulation (BASL_A_D + Floor) and at subsequent retrofit stages (Figure 20). No overheating occurred in the bedroom according to criterion b for the pre-retrofit baseline or at each retrofit stage (Figure 21), though retrofit increased the percentage hours of exceedance. The retrofit slightly increased the overheating risk for this house in Manchester.

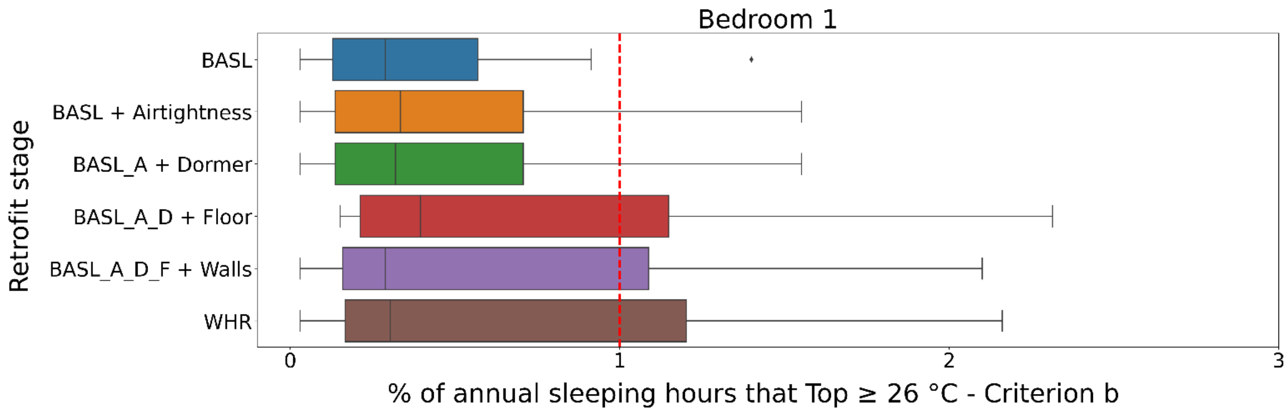
For the Glasgow RWD there was no overheating according to criterion a (Figure 22) or criterion b (Figure 23) for any room at the pre-retrofit baseline or any retrofit stage. The retrofit had no impact on overheating, though higher median hours of exceedance were observed after the installation of the floor insulation.

Figure 18: Overheating assessment for 17BG with London RWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



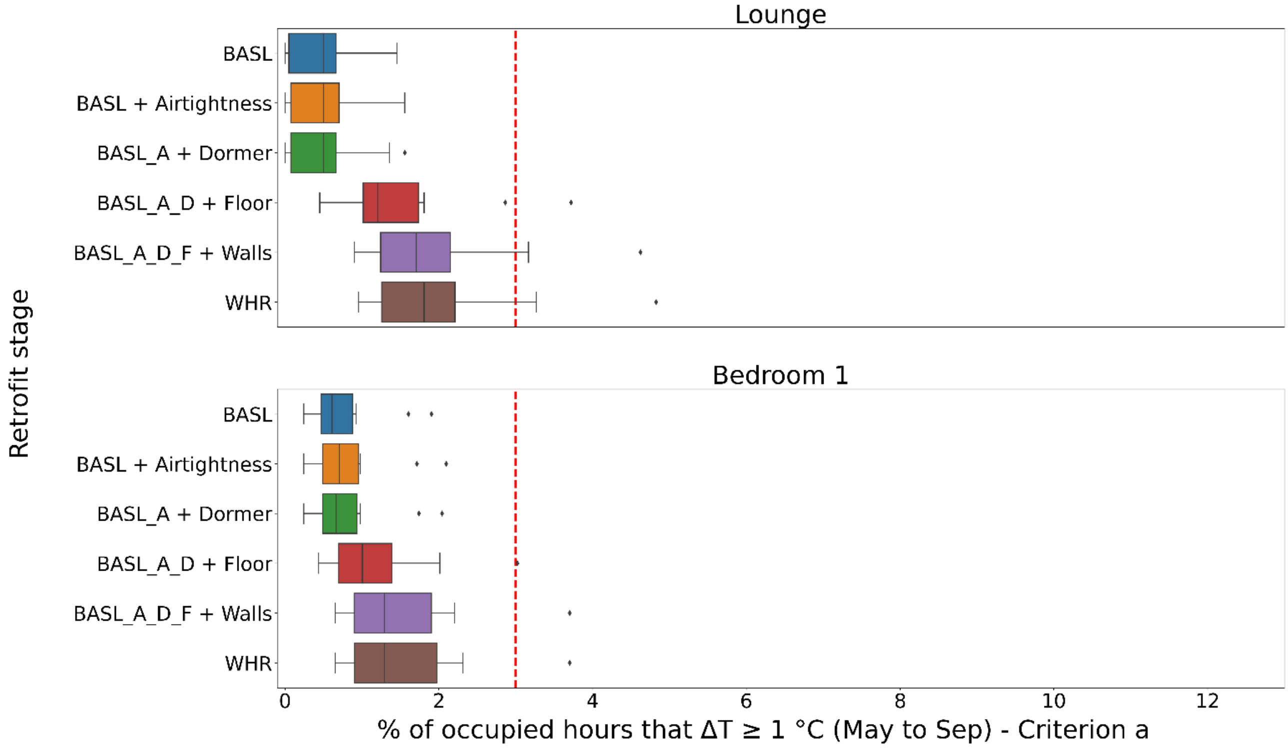
		Number of years that overheating occurs according to criterion a				
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Living room	3/10	4/10	4/10	8/10	10/10	10/10
Bedroom 1	4/10	4/10	4/10	7/10	7/10	7/10

Figure 19: Overheating assessment for 17BG with London RWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



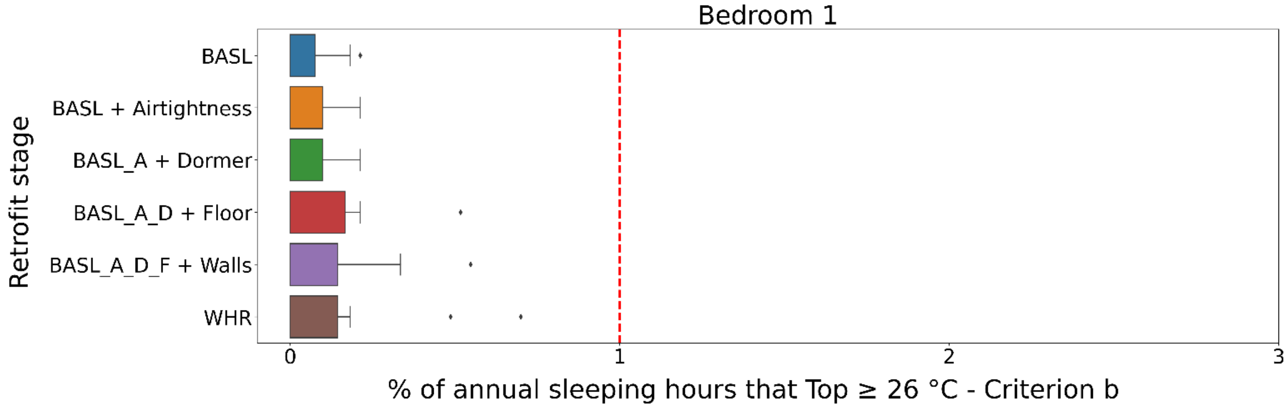
		Number of years that overheating occurs according to criterion b				
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Bedroom 1	1/10	1/10	1/10	3/10	3/10	3/10

Figure 20: Overheating assessment for 17BG with Manchester RWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



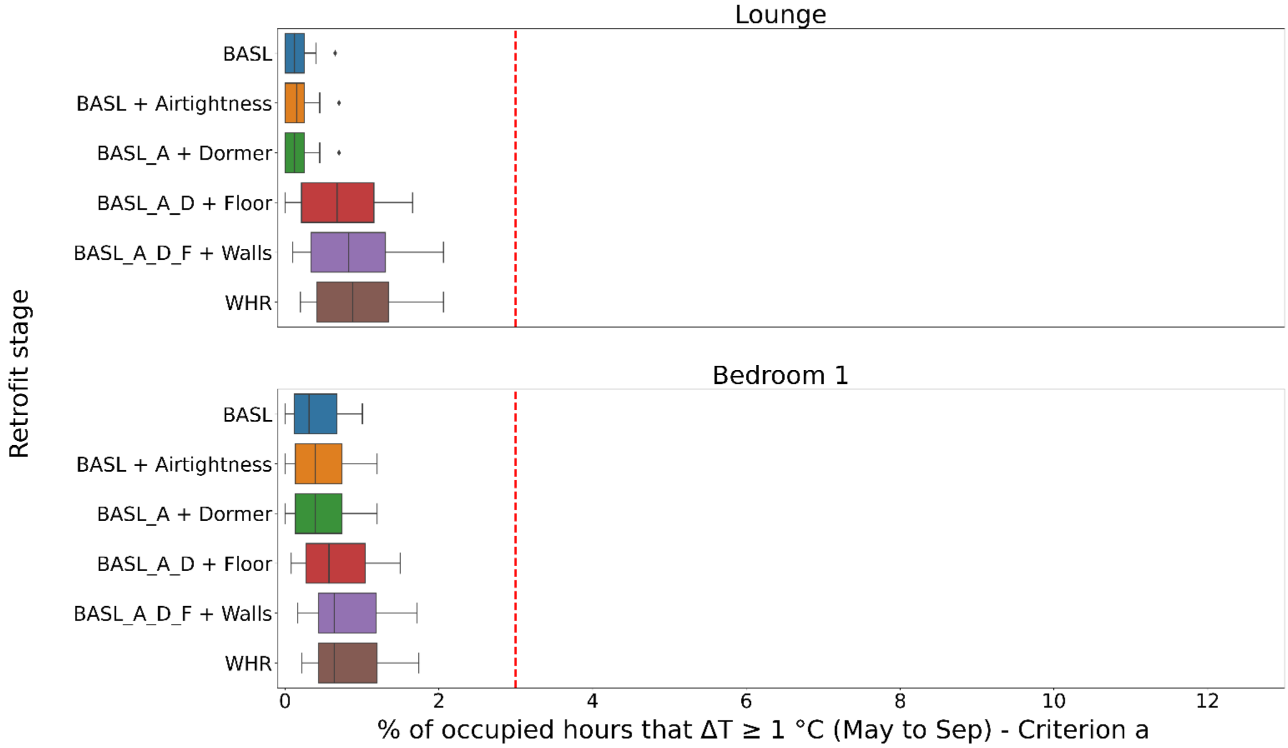
	Number of years that overheating occurs according to criterion a					
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Living room	0/10	0/10	0/10	1/10	2/10	2/10
Bedroom 1	0/10	0/10	0/10	1/10	1/10	1/10

Figure 21: Overheating assessment for 17BG with Manchester RWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



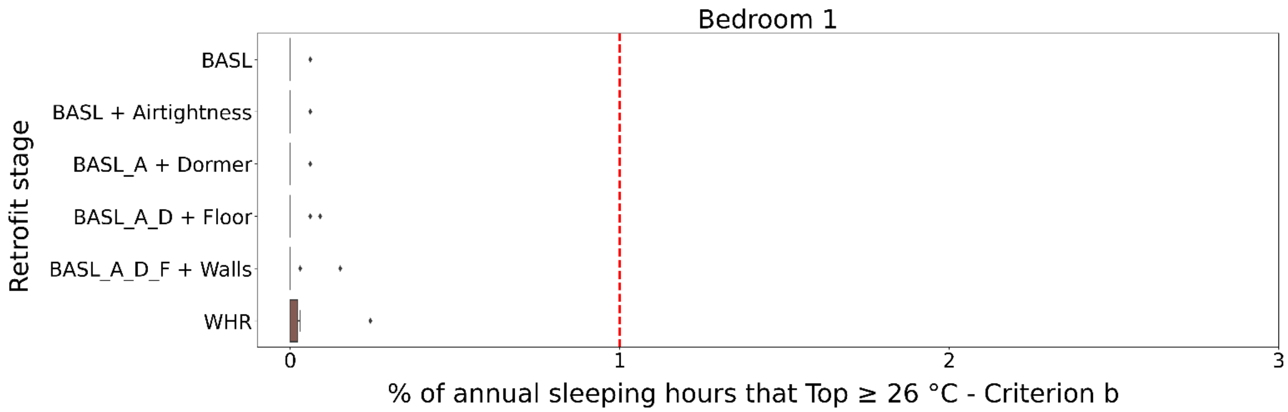
	Number of years that overheating occurs according to criterion b					
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Bedroom 1	0/10	0/10	0/10	0/10	0/10	0/10

Figure 22: Overheating assessment for 17BG with Glasgow RWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a					
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Living room	0/10	0/10	0/10	0/10	0/10	0/10
Bedroom 1	0/10	0/10	0/10	0/10	0/10	0/10

Figure 23: Overheating assessment for 17BG with Glasgow RWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion b					
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Bedroom 1	0/10	0/10	0/10	0/10	0/10	0/10

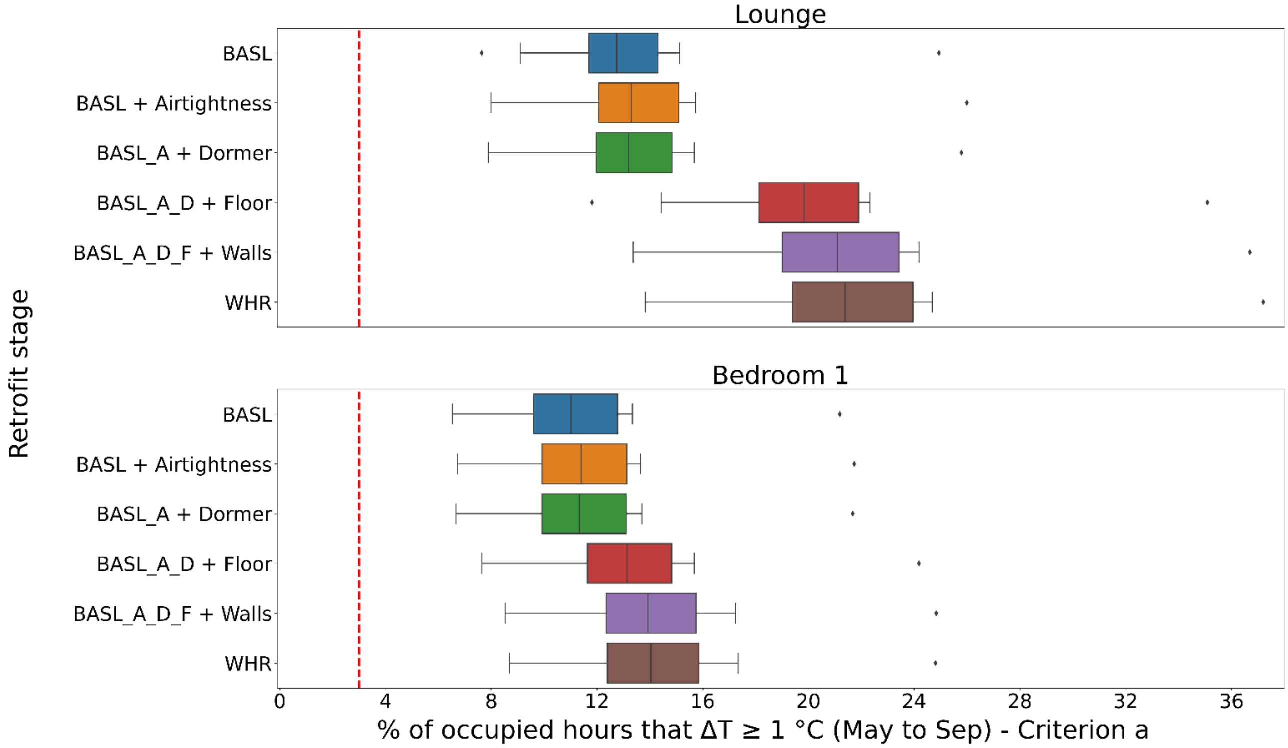
5.2.2 Overheating risk in a Future Weather Decade

For the London FWD, overheating occurred every year in the living room and bedroom, according to criterion a, for the pre-retrofit baseline and at each retrofit stage (Figure 24). Overheating also occurred every year in the bedroom according to criterion b, for the pre-retrofit baseline and all retrofit stages (Figure 25). This house in London overheated every year regardless of retrofit stage, but the retrofit increased the level of overheating, and especially after the installation of floor insulation (BASL_A_D + Floor).

For the Manchester FWD, overheating occurred in the living room and bedroom at all stages, according to criterion a, but the number of years that overheating occurred increased with the retrofit stage from six years for the pre-retrofit baseline (BASL) to all ten years for the whole house retrofit (WHR) (Figure 26). Overheating also increased in the bedroom according to criterion b, from two years for the pre-retrofit baseline and the first two retrofit stages to four years after the installation of floor insulation (BASL_A_D + Floor) (Figure 27). The retrofit increased overheating risk for this house in Manchester.

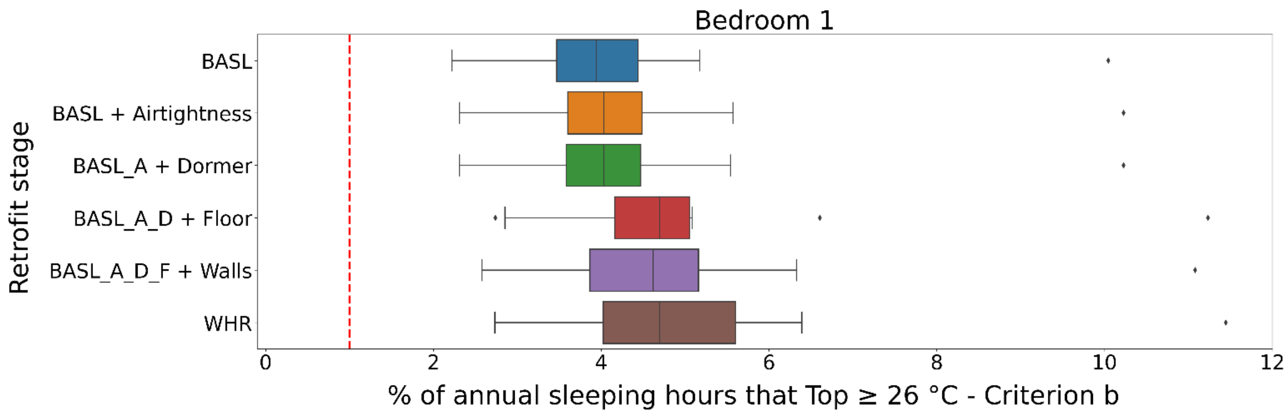
For the Glasgow FWD, overheating occurred in the living room and bedroom at all stages, according to criterion a, but the number of years that overheating occurred increased with the retrofit stage from only one year for the pre-retrofit baseline (BASL) to six years for the whole house retrofit (WHR) (Figure 28). Overheating also increased in the bedroom according to criterion b, from zero years for the pre-retrofit baseline and the first two retrofit stages to one year after the installation of floor insulation (BASL_A_D + Floor). The retrofit increased overheating risk for this house in Glasgow.

Figure 24: Overheating assessment for 17BG with London FWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



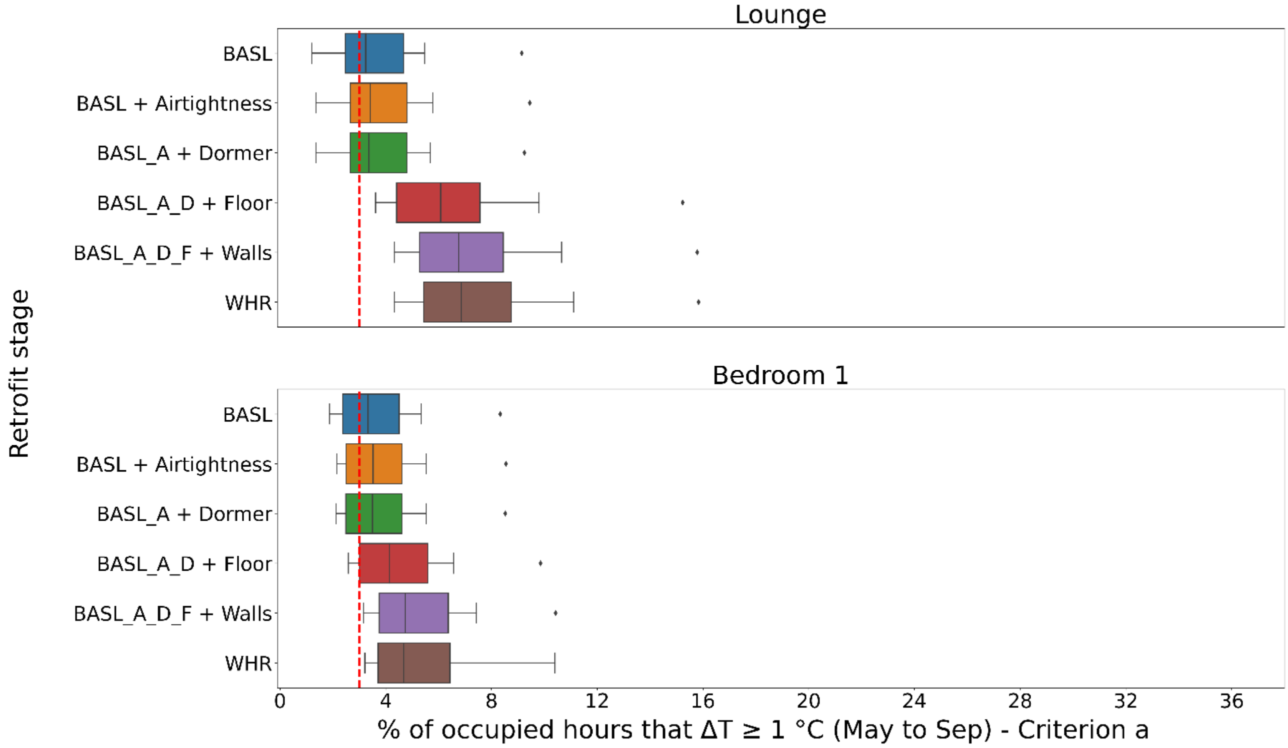
		Number of years that overheating occurs according to criterion a				
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Living room	10/10	10/10	10/10	10/10	10/10	10/10
Bedroom 1	10/10	10/10	10/10	10/10	10/10	10/10

Figure 25: Overheating assessment for 17BG with London FWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



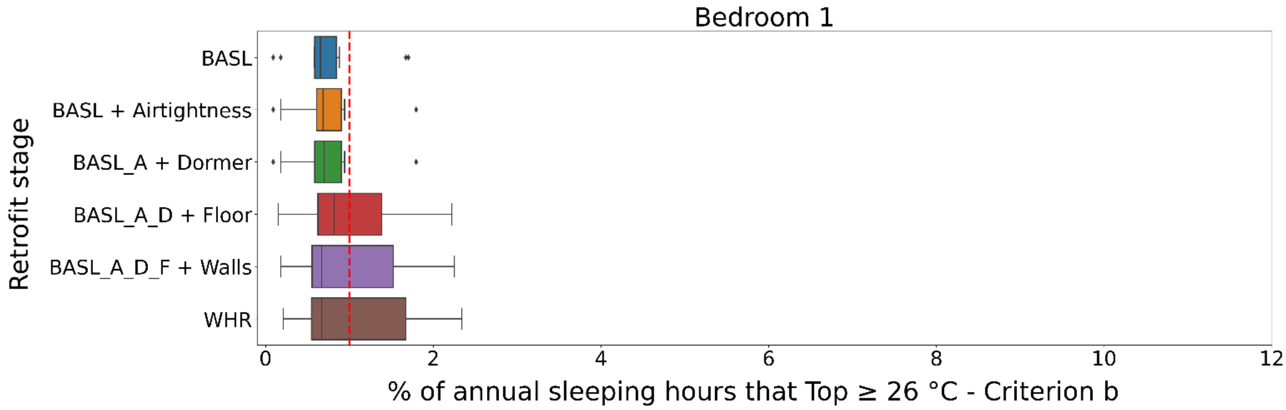
		Number of years that overheating occurs according to criterion b				
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Bedroom 1	10/10	10/10	10/10	10/10	10/10	10/10

Figure 26: Overheating assessment for 17BG with Manchester FWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



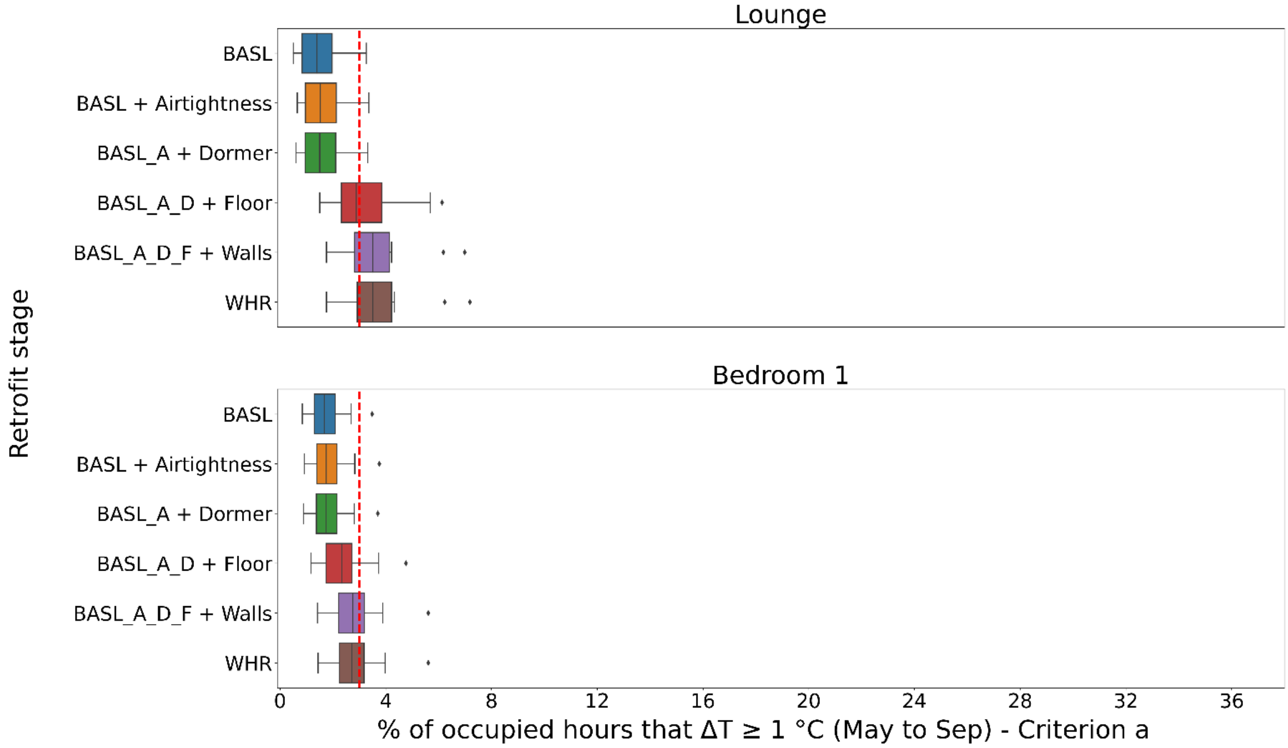
		Number of years that overheating occurs according to criterion a				
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Living room	6/10	6/10	6/10	10/10	10/10	10/10
Bedroom 1	6/10	6/10	6/10	7/10	10/10	10/10

Figure 27: Overheating assessment for 17BG with Manchester FWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



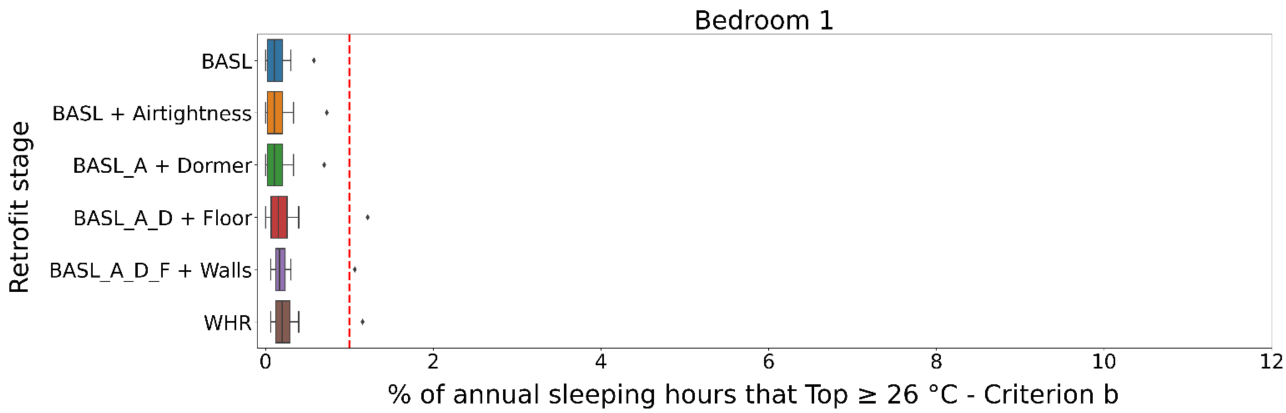
		Number of years that overheating occurs according to criterion b				
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Bedroom 1	2/10	2/10	2/10	4/10	3/10	3/10

Figure 28: Overheating assessment for 17BG with Glasgow FWD - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



		Number of years that overheating occurs according to criterion a				
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Living room	1/10	2/10	2/10	4/10	6/10	6/10
Bedroom 1	1/10	1/10	1/10	2/10	3/10	3/10

Figure 29: Overheating assessment for 17BG with Glasgow FWD - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



		Number of years that overheating occurs according to criterion b				
Room	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Bedroom 1	0/10	0/10	0/10	1/10	1/10	1/10

6. Parametric analysis

A parametric analysis was carried out to rank the influence of different parameters: the heat gains from occupants, the heat gains from lights and appliances, ventilation, infiltration, solar gains, thermal efficiency of the building envelope (Table 6). The method[12] used eliminates each parameter one at a time. For example for Case 2 in Table 6, the heat gains from the occupants were removed from the simulation. The parametric analysis was carried out for both case study houses in their pre-retrofit stage, and according to TM59 criterion a and criterion b. London was chosen as the location for this analysis as overheating risk was much higher. Weather for the year 2018 was selected as this produced the most severe overheating. This analysis seeks to improve our understanding of how different parameters might reduce or increase the risk of overheating and so guide the choice of effective mitigation strategies.

Table 6: The eight cases of the model used for the parametric analysis

Case	Parameter removed from the model	Notes
1	Baseline model	No parameters removed
2	Without occupants	Heat gains from occupants removed
3	Without equipment and lights	Heat gains from equipment and lights removed
4	Without ventilation	Ventilation removed (infiltration still occurs)
5	Without infiltration	Infiltration removed (ventilation still occurs)
6	Without solar gains	All solar gains (through windows) removed
7	Without envelope heat transfer (EWI)	Heat transfer through exterior surfaces removed using adiabatic ***external*** insulation
8	Without envelope heat transfer (IWI)	Heat transfer through exterior surfaces removed using adiabatic ***internal*** insulation

The results of the simulations of the 56TR house (Figure 30 for criterion a and Figure 31 for criterion b) and the 17BG house (Figure 32 for criterion a and Figure 33 for criterion b) are broadly similar. In all cases, removing ventilation leads to the largest increase in overheating. This is followed by removing heat transfer through the external surfaces. Removing infiltration leads to only a small increase in overheating. In all cases but one, removing the solar gains leads to the largest decrease in overheating. In all cases, removing the heat gains from occupants and the heat gains from lights and appliances have a similar impact on reducing overheating.

These results support previous analysis [22,23]. Adding insulation will tend to increase overheating, but ventilation and solar gains have a bigger affect and can therefore be used as mitigation; something which is reflected in building regulations [9]. The heat gains from occupants and lights and appliances should not be ignored: houses that have many people or high electrical loads will be at higher risk of overheating. It can be seen that IWI increases overheating more than EWI, according to criterion a, but not always according to criterion b. This can be attributed to the fact that IWI will reduce the effect of thermal mass. Hence, in the case of criterion b, that assess overheating during night times, less heat will be absorbed in the walls during day times and released into the room during night times in comparison to the case that insulation will be placed externally.

[12] The method is called elimination parametrics and described in full by [30].

Figure 30: Parametric analysis for 56TR with London 2018 weather - the red line shows the criterion a threshold and the dotted black line shows the performance of the baseline model

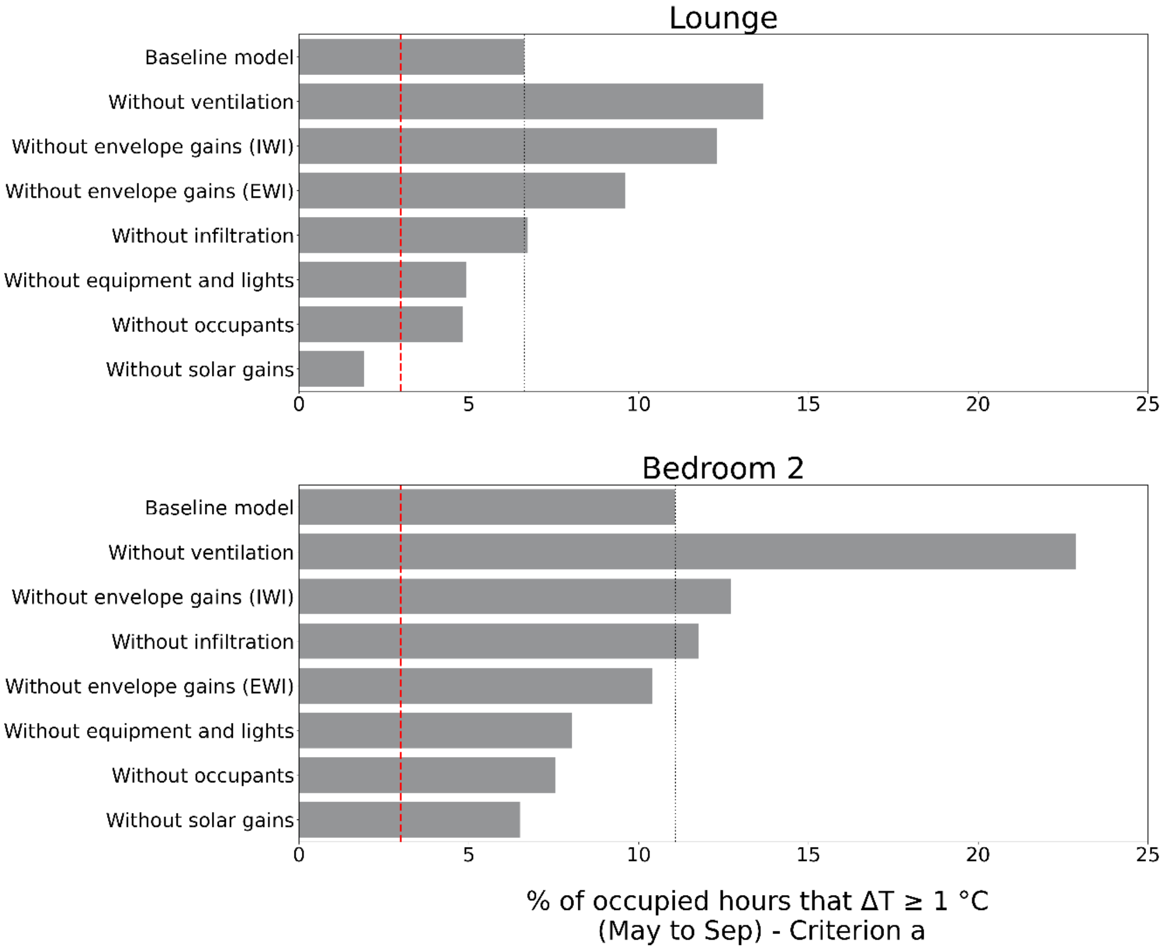


Figure 31: Parametric analysis for 56TR with London 2018 weather - the red line shows the criterion b threshold and the dotted black line shows the performance of the baseline model

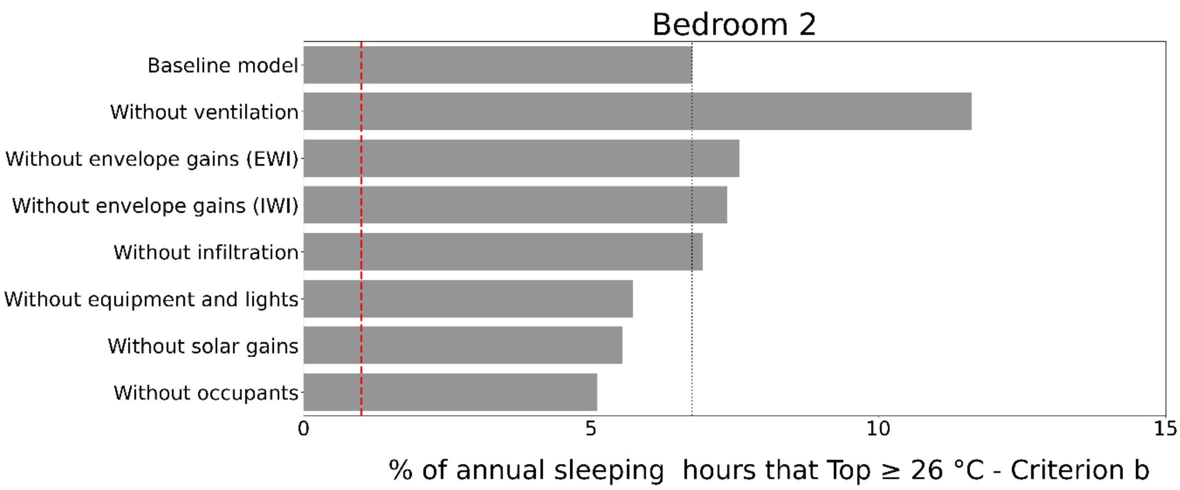


Figure 32: Parametric analysis for 17BG with London 2018 weather - the red line shows the criterion a threshold and the dotted black line shows the performance of the baseline model

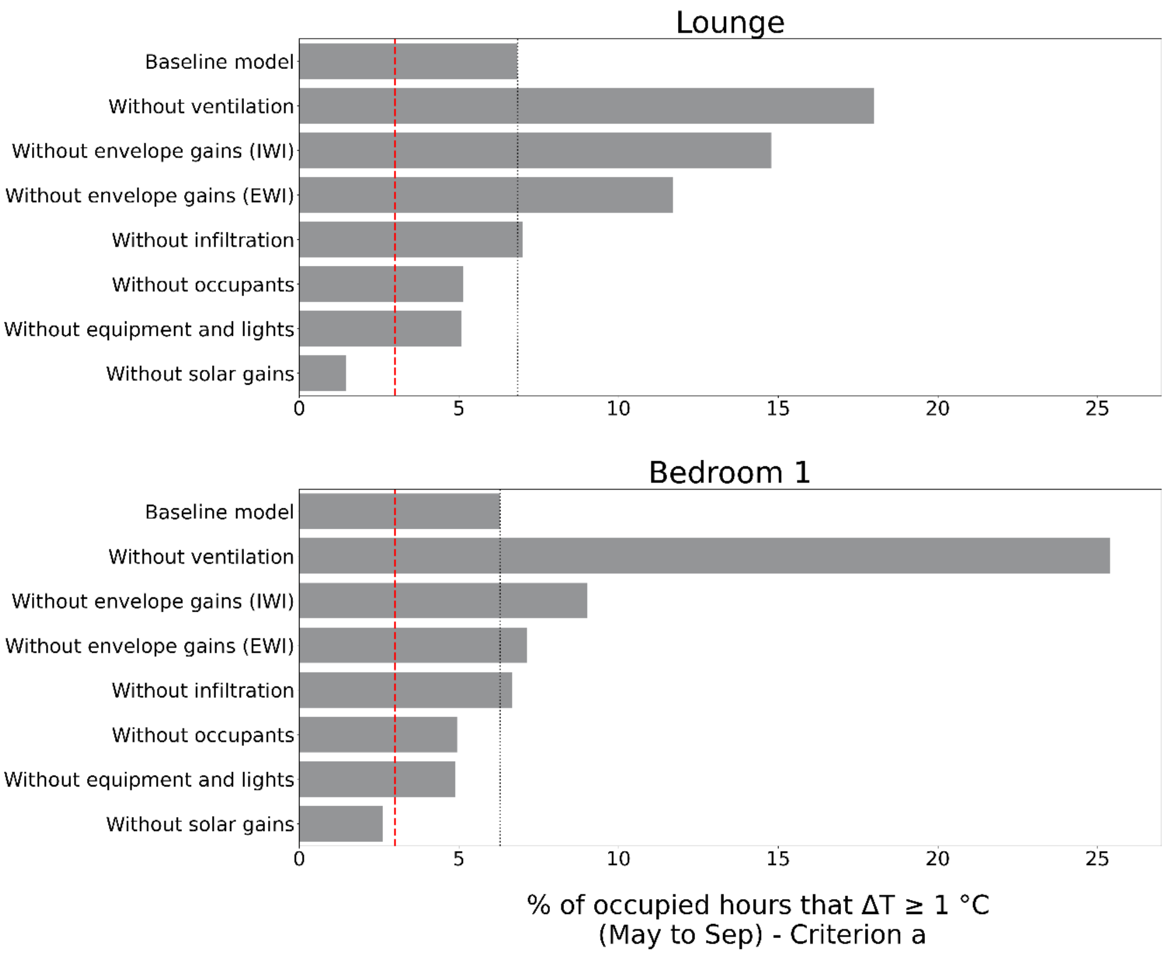
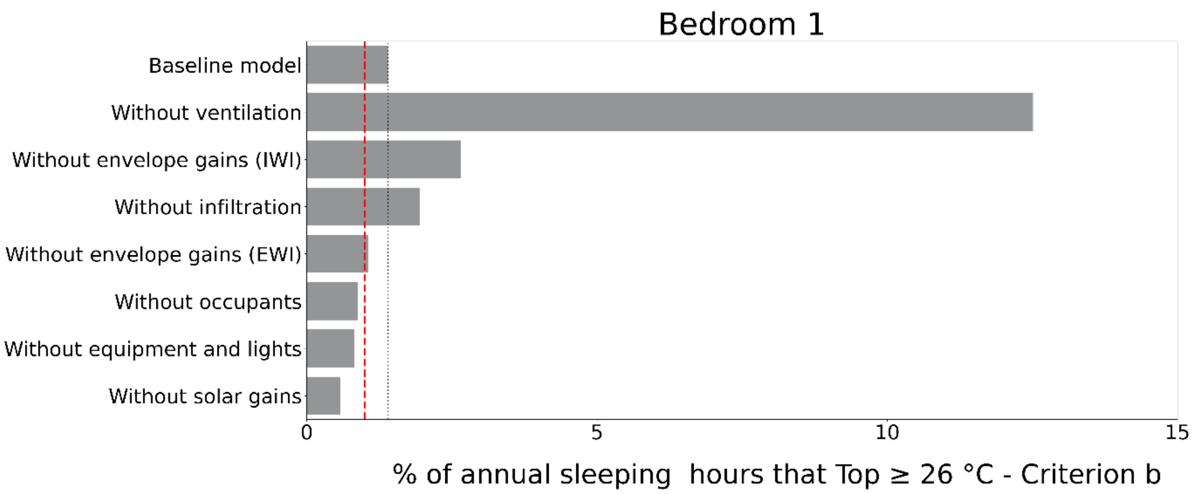


Figure 33: Parametric analysis for 17BG with London 2018 weather - the red line shows the criterion a threshold and the dotted black line shows the performance of the baseline model



7. Mitigating overheating with passive measures

Overheating can occur under current weather conditions and will become more common in future. Previous chapters have shown that overheating can be exacerbated by retrofit (Section 5) and ventilation and shading have a large impact on overheating (Section 6) and can be controlled passively i.e. without resorting to mechanical cooling. Therefore, the following passive measures for mitigating overheating were evaluated:

- Increasing the natural ventilation rates frequently (INV)
- Eliminating the solar gains using external shutters[13] (Sh)
- Increasing ventilation rates and eliminating solar gains using shutters (INV + Sh)

Increased ventilation was achieved by making all windows openable and assuming that they could be opened 24 hours per day. The only limitation was that restrictors were applied during unoccupied hours for security reasons. During occupied hours the opening factor was set equal to one.

The risk of overheating was re-assessed, applying these mitigation measures to each of the case study houses (as described in Section 2) before any retrofit work took place (the baseline model) and after the whole house retrofit. In all cases, overheating was assessed using criterion a in the living room and bedroom and using criterion b in the bedroom (as described in Section 3). The assessments were carried out by dynamic thermal simulation using Recent Weather Decade (RWD) and Future Weather Decade (FWD) files (as described in Section 4).

This analysis seeks to identify if these passive measures can mitigate overheating risk, and the impact of whole house retrofit on any residual risk. Each house was assessed before retrofit (BASL) and after the whole house retrofit (WHR). The results with no mitigation are compared with the three mitigation strategies: INV, Sh, and INV+Sh.

7.1. 56TR house

7.1.1 Overheating risk in a Recent Weather Decade

For the London RWD, overheating was successfully mitigated in all rooms when ventilation was increased, and external shutters used (strategy INV+Sh) according to criterion a (Figure 34) and criterion b (Figure 35). Increased ventilation alone (strategy INV) was adequate in all cases. Shading alone (strategy Sh) was successful in the living room for all years, according to criterion a, both pre-retrofit and after whole house retrofit. Shading alone was not adequate in the bedroom according to criterion b. The whole house retrofit did not increase the risk of overheating compared to the pre-retrofit house. The whole house retrofit slightly reduced the median hours of exceedance for this house in London when any of the mitigation measures were applied.

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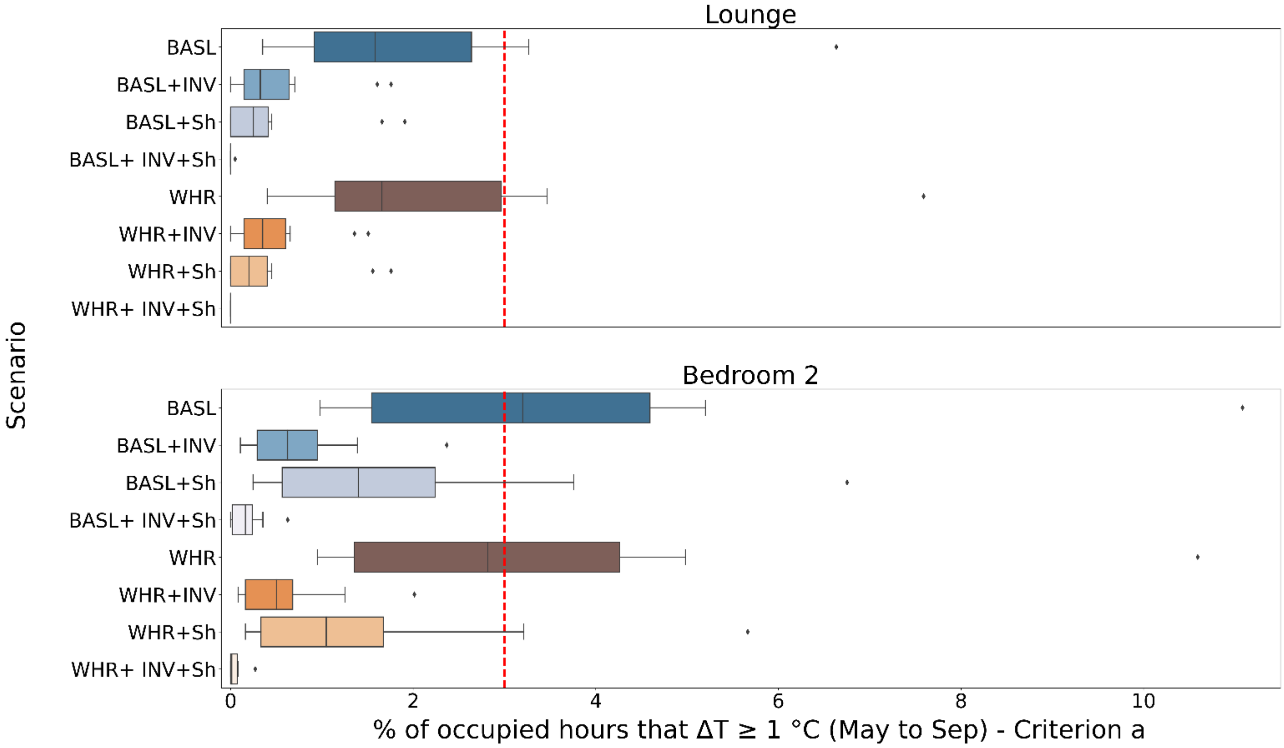
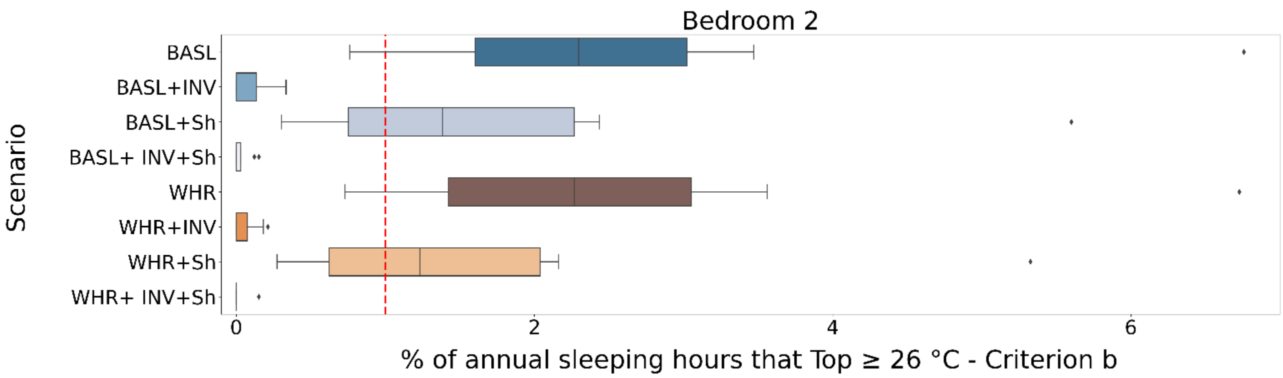
[13] The shutters did not reduce ventilation rates in any of this analysis.

Figure 34: Overheating assessment for 56TR with London RWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Living room	2/10	0/10	0/10	0/10	3/10	0/10	0/10	0/10
Bedroom 2	5/10	0/10	2/10	0/10	5/10	0/10	2/10	0/10

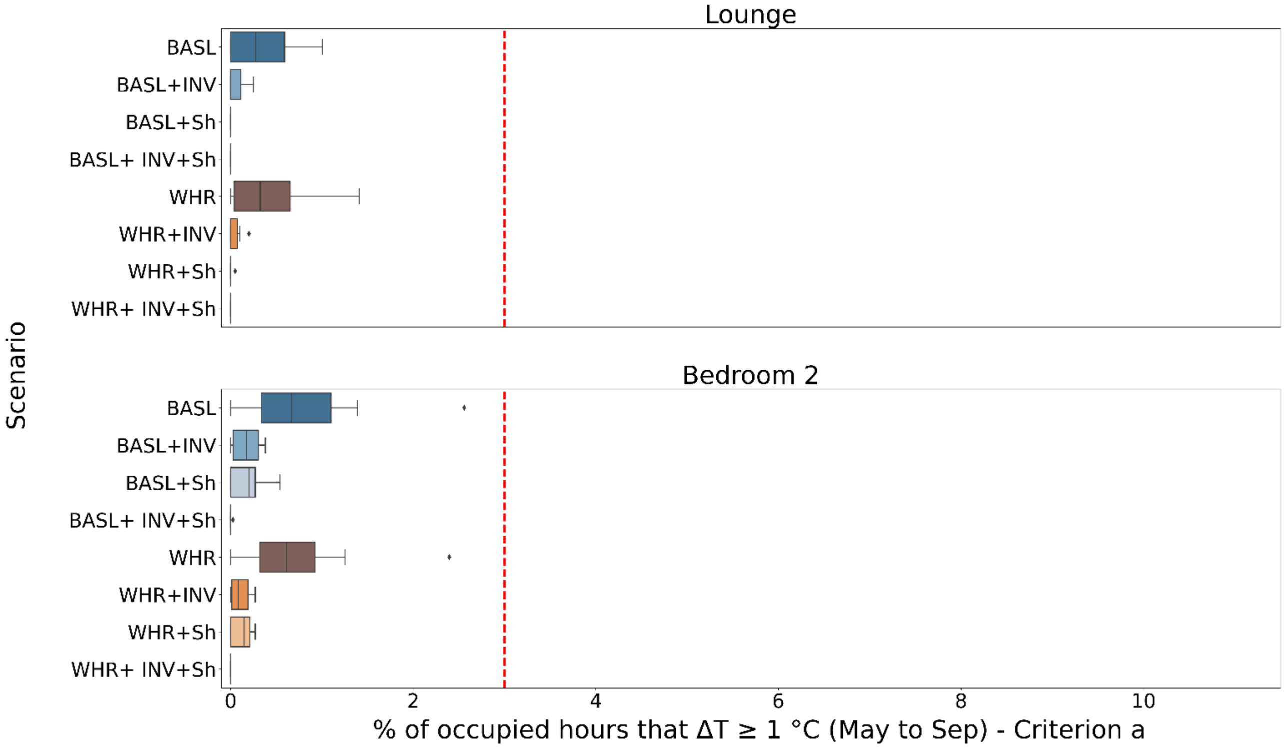
Figure 35: Overheating assessment for 56TR with London RWD and comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion b							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Bedroom 2	8/10	0/10	7/10	0/10	8/10	0/10	6/10	0/10

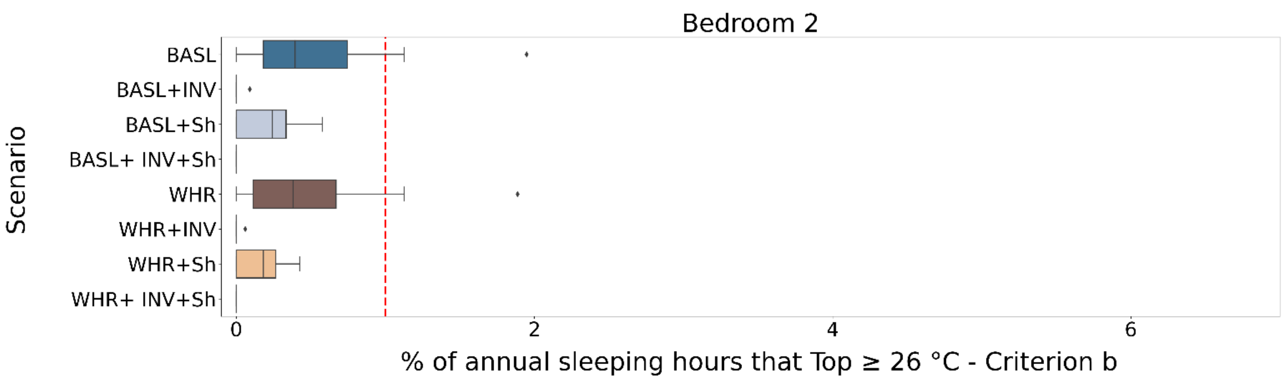
For the Manchester RWD, any overheating was eliminated by the mitigation measures in both the pre-retrofit house and the whole house refurbishment house (Figures 36 and 37). For the Glasgow RWD there was no overheating according to either the criterion a or criterion b thresholds, and the mitigation measures reduced the few hours of exceedance that were below these thresholds (Figures 38 and 39). The retrofit slightly reduced the median hours of exceedance for this house in Manchester and Glasgow when any of the mitigation measures are applied.

Figure 36: Overheating assessment for 56TR with Manchester RWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



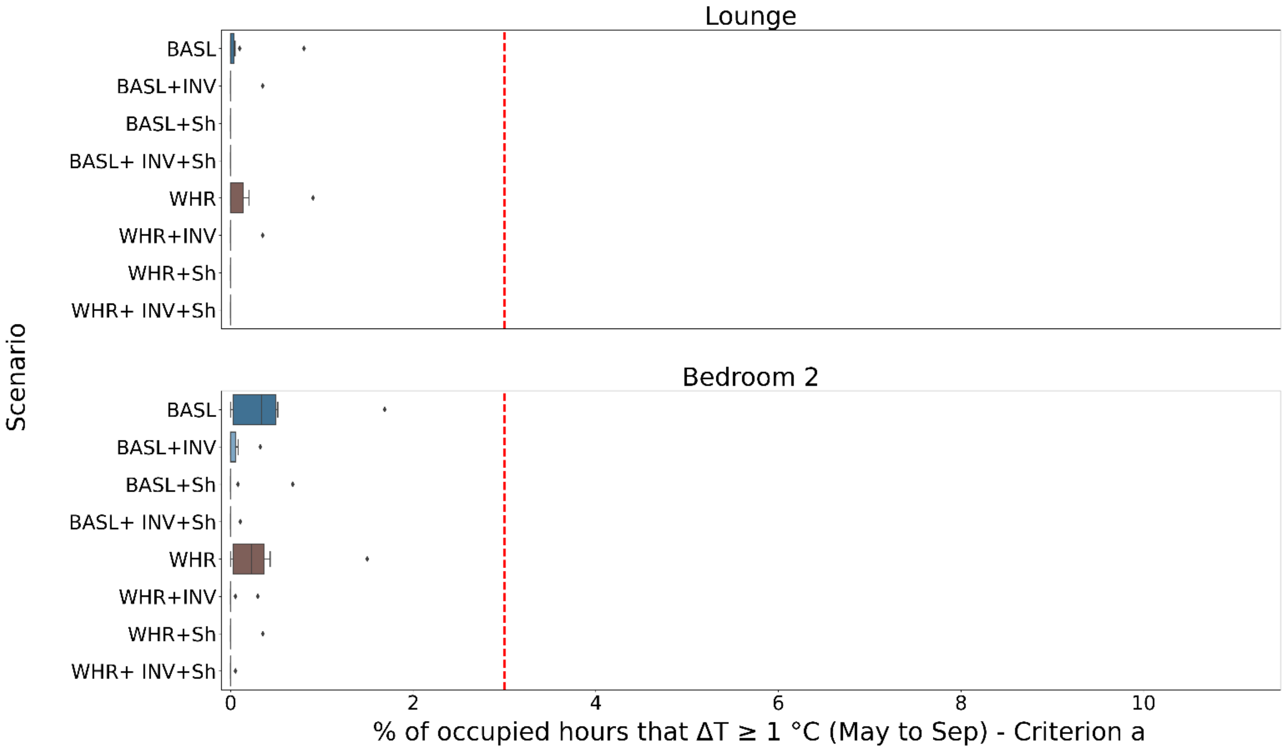
	Number of years that overheating occurs according to criterion a							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Living room	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10
Bedroom 2	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10

Figure 37: Overheating assessment for 56TR with Manchester RWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



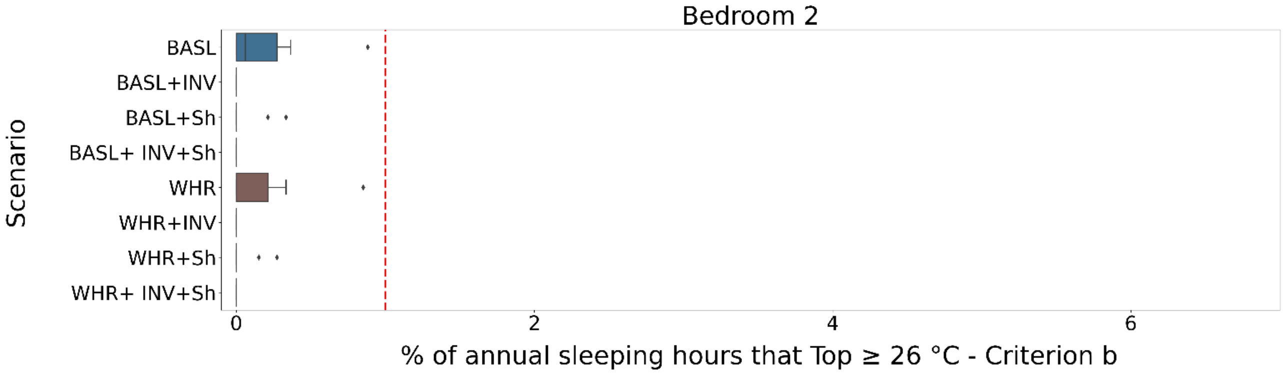
	Number of years that overheating occurs according to criterion b							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Bedroom 2	2/10	0/10	0/10	0/10	2/10	0/10	0/10	0/10

Figure 38: Overheating assessment for 56TR with Glasgow RWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
	Number of years that overheating occurs according to criterion a							
Living room	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10
Bedroom 2	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10

Figure 39: Overheating assessment for 56TR with Glasgow RWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs

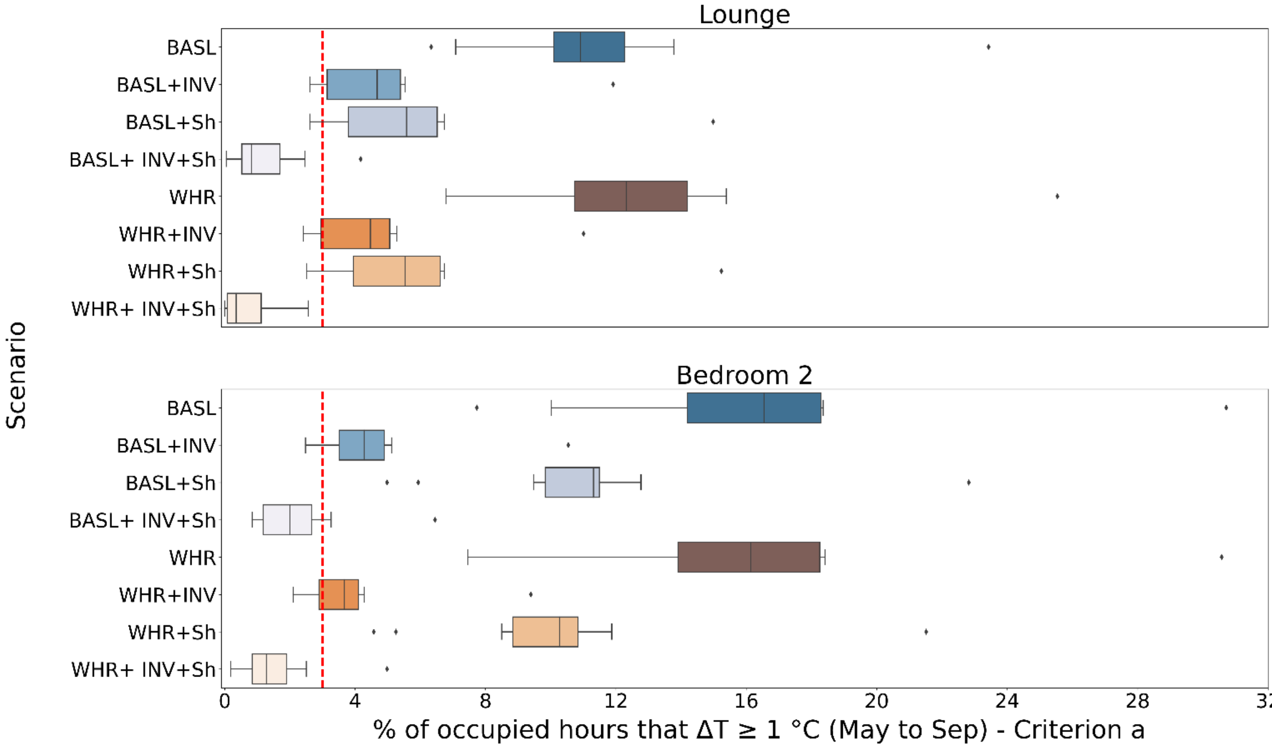


Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
	Number of years that overheating occurs according to criterion b							
Bedroom 2	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10

7.1.2 Overheating risk in a Future Weather Decade

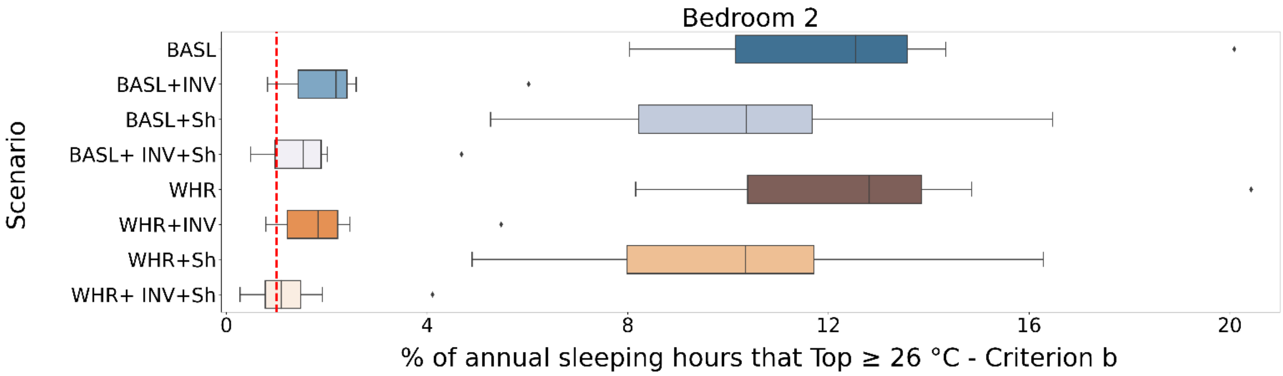
For the London FWD, overheating was mitigated for all but one year according to criterion a, after the whole house retrofit (WHR) when ventilation was increased, and external shutters used (strategy INV+Sh) (Figure 40). Overheating still occurred most years in the bedroom according to criterion b but was reduced by mitigation (Figure 41). For this house in London, the whole house retrofit reduced the risk of overheating compared to the pre-retrofit house when ventilation was increased, and external shutters used.

Figure 40: Overheating assessment for 56TR with London FWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Living room	10/10	7/10	8/10	1/10	10/10	7/10	8/10	0/10
Bedroom 2	10/10	8/10	10/10	2/10	10/10	7/10	10/10	1/10

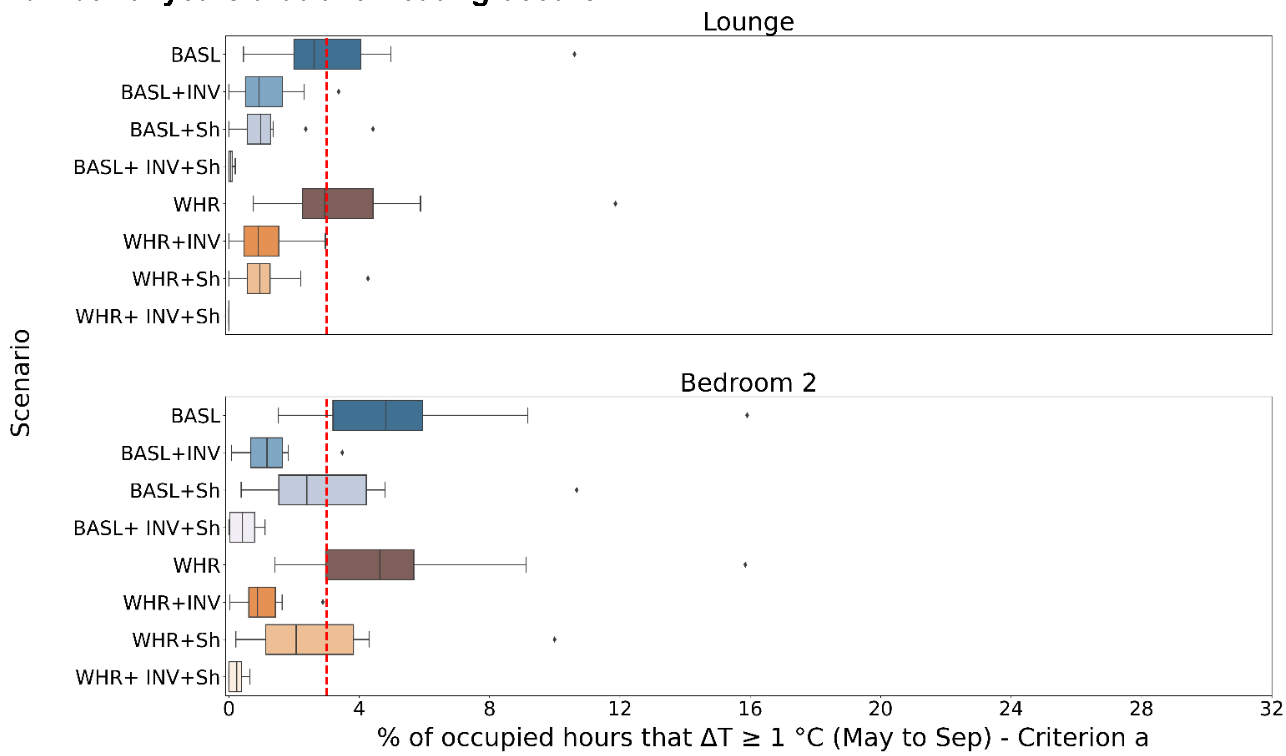
Figure 41: Overheating assessment for 56TR with London FWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion b							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Bedroom 2	10/10	8/10	10/10	7/10	10/10	8/10	10/10	6/10

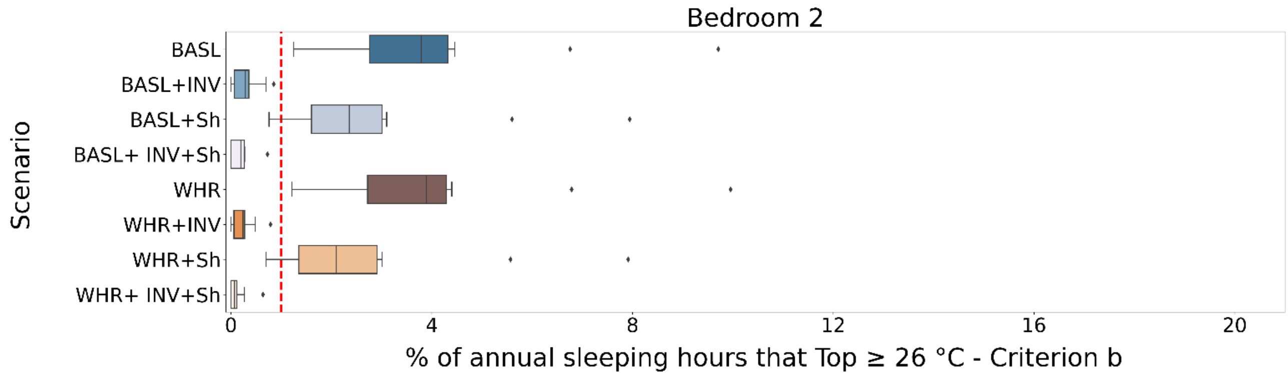
For the Manchester FWD increased ventilation and external shutter use (INV+Sh) successfully mitigated overheating in all rooms for both the pre-retrofit house and the whole house refurbishment house (criterion a (Figure 42) and criterion b (Figure 43)). Additional ventilation alone (strategy INV) was adequate after the retrofit and there was only one year of overheating pre-retrofit. For this house in Manchester, the whole house retrofit did not increase the risk of overheating compared to the pre-retrofit house when any of the mitigation measures were applied as overheating was eliminated and the median hours of exceedance were very similar.

Figure 42: Overheating assessment for 56TR with Manchester FWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
	Number of years that overheating occurs according to criterion a							
Living room	4/10	1/10	1/10	0/10	4/10	0/10	1/10	0/10
Bedroom 2	7/10	1/10	3/10	0/10	7/10	0/10	3/10	0/10

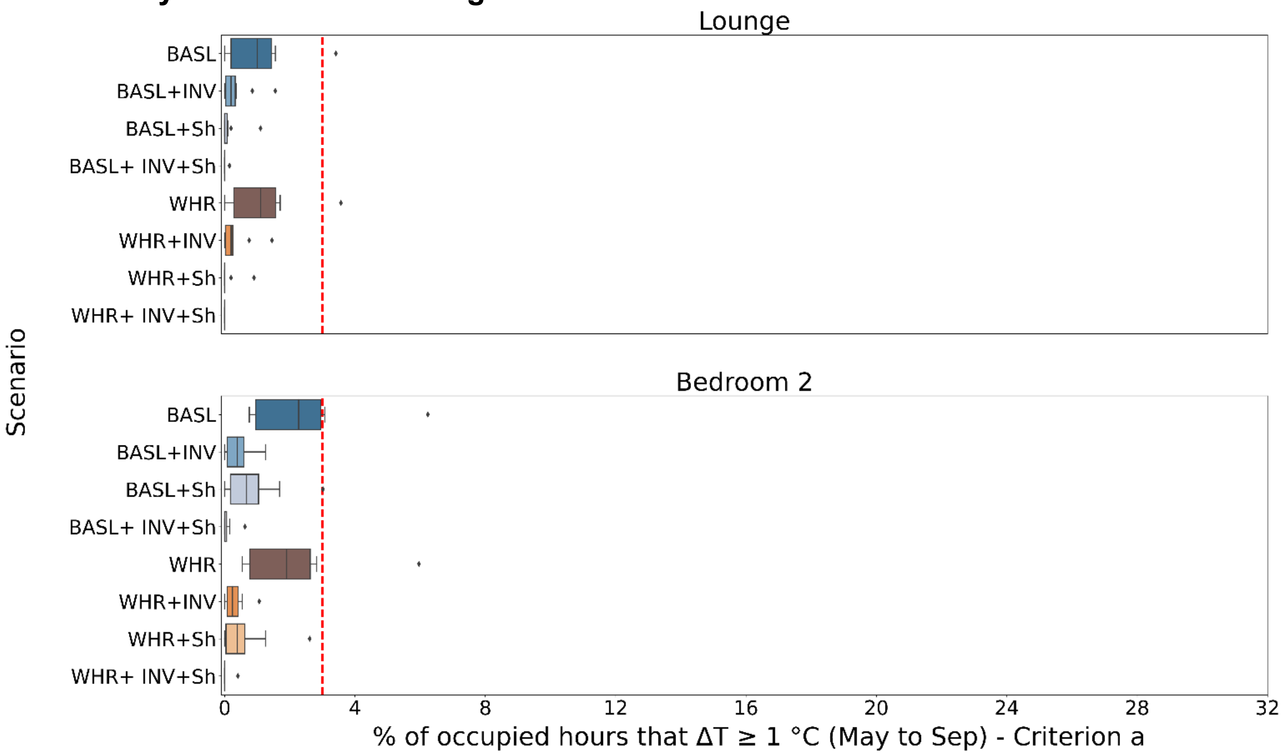
Figure 43: Overheating assessment for 56TR with Manchester FWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
	Number of years that overheating occurs according to criterion b							
Bedroom 2	10/10	0/10	8/10	0/10	10/10	0/10	8/10	0/10

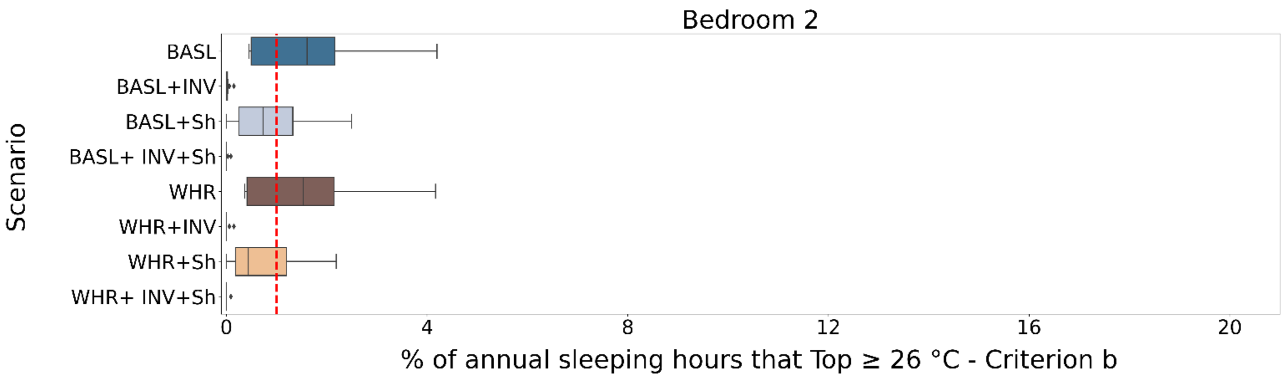
For the Glasgow FWD, overheating was successfully mitigated in all rooms when ventilation was increased (strategy INV) according to criterion a (Figure 44) and criterion b (Figure 45). Shading alone (strategy Sh) was adequate in most cases according to criterion a, though there was one year of overheating in the bedroom of the pre-retrofit house. For this house in Glasgow, the whole house retrofit did not increase the risk of overheating compared to the pre-retrofit house when any of the mitigation measures were applied and the median hours of exceedance were very similar.

Figure 44: Overheating assessment for 56TR with Glasgow FWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Living room	1/10	0/10	0/10	0/10	1/10	0/10	0/10	0/10
Bedroom 2	2/10	0/10	1/10	0/10	1/10	0/10	0/10	0/10

Figure 45: Overheating assessment for 56TR with Glasgow FWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



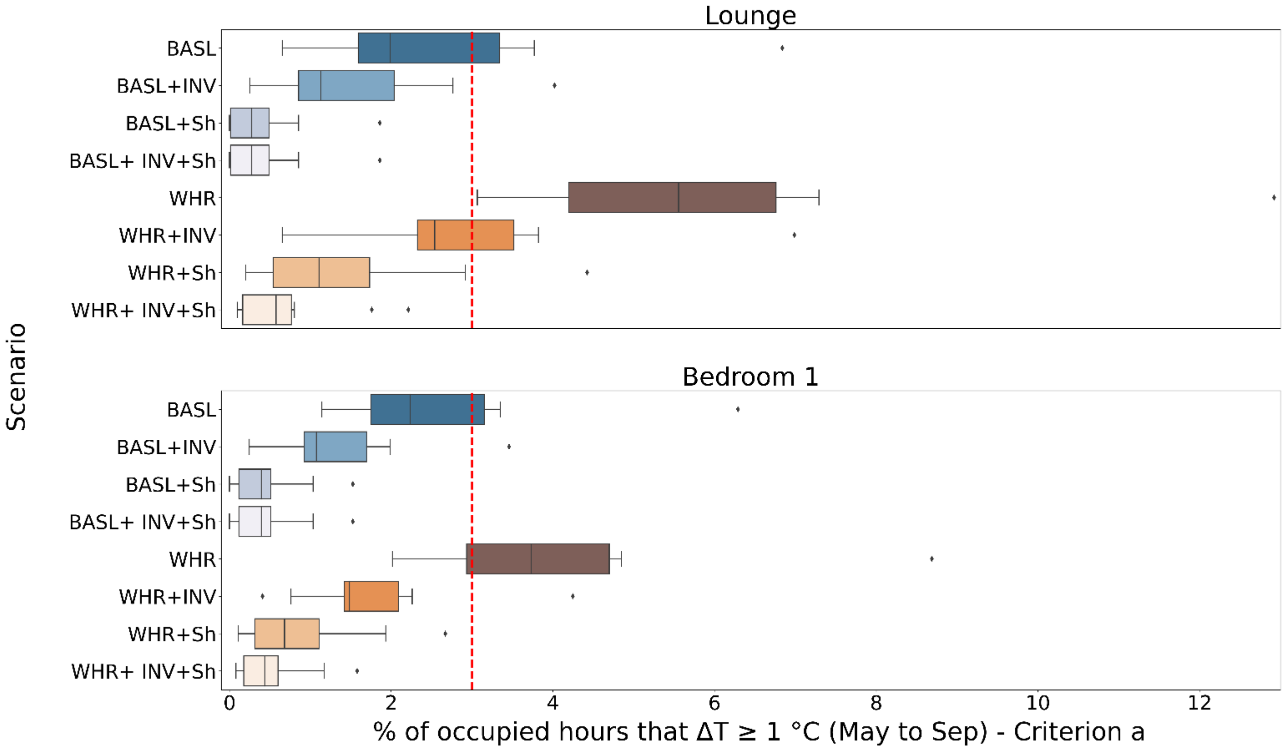
	Number of years that overheating occurs according to criterion b							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Bedroom 2	6/10	0/10	5/10	0/10	6/10	0/10	4/10	0/10

7.2. 17BG house

7.2.1 Overheating risk in a Recent Weather Decade

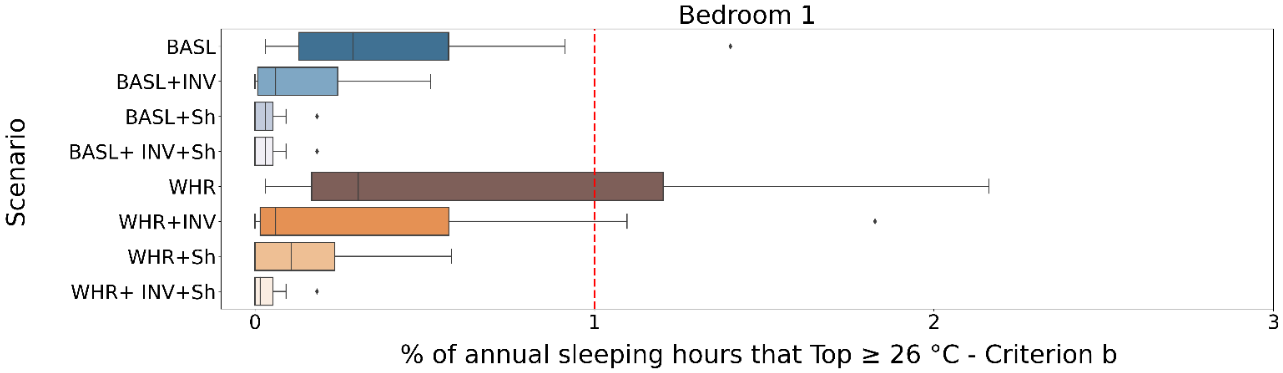
For the London RWD, overheating was successfully mitigated in all rooms when ventilation was increased, and external shutters used (strategy INV+Sh) according to criterion a (Figure 46) and criterion b (Figure 47). Shading alone (strategy Sh) was better than increased ventilation alone (INV) and successfully mitigated overheating pre-retrofit, and for all but one year after the retrofit. For this house in London, the whole house retrofit did not increase the risk of overheating compared to the pre-retrofit house when both mitigation measures were applied. This is because overheating was eliminated, and the median hours of exceedance were very similar.

Figure 46: Overheating assessment for 17BG with London RWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Living room	3/10	1/10	0/10	0/10	10/10	4/10	1/10	0/10
Bedroom 1	4/10	1/10	0/10	0/10	7/10	1/10	0/10	0/10

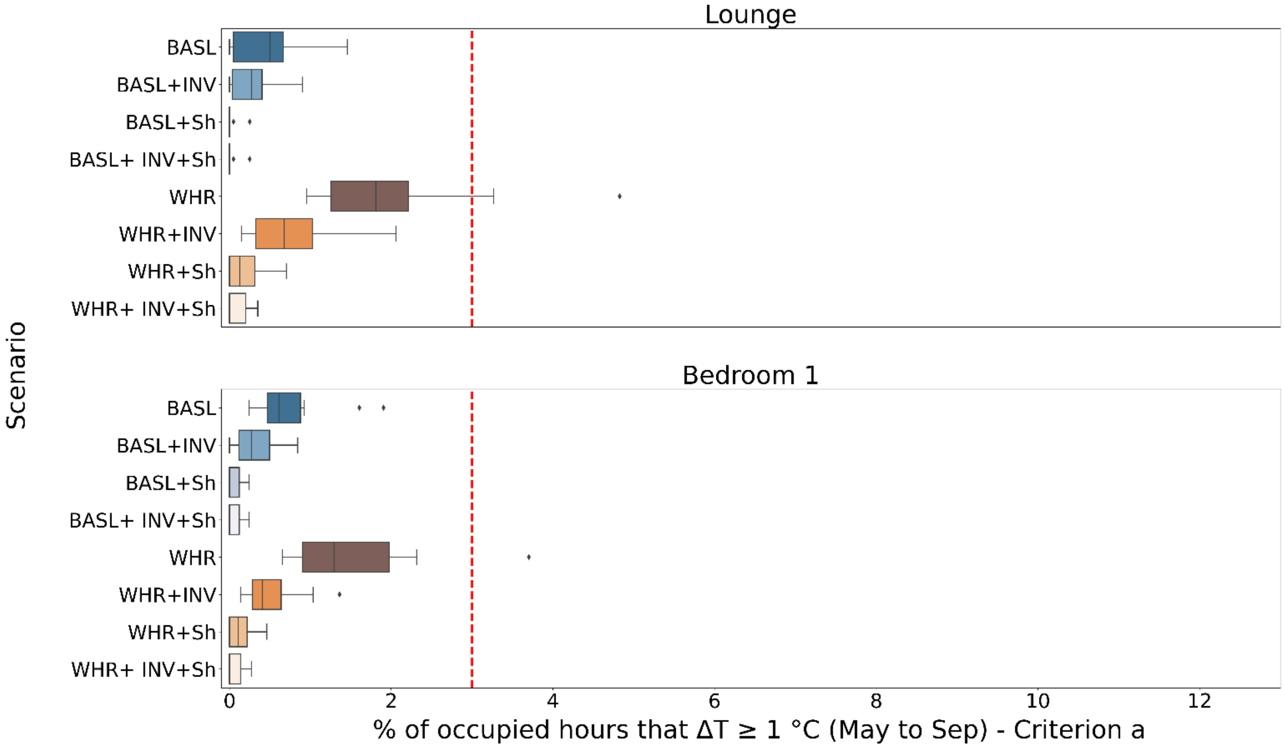
Figure 47: Overheating assessment for 17BG with London RWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion b							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Bedroom 1	1/10	0/10	0/10	0/10	3/10	2/10	0/10	0/10

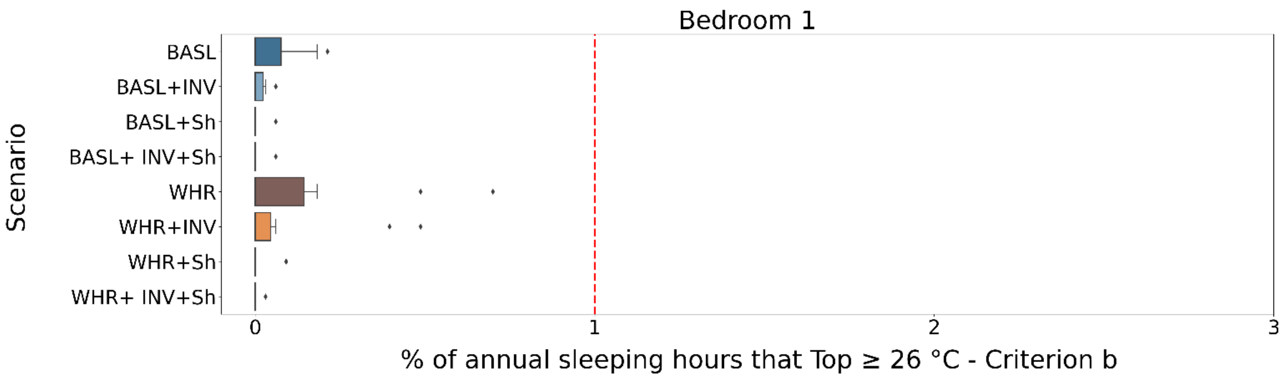
For the Manchester RWD, there was no overheating according to criterion b and the two years of overheating after the whole house retrofit, according to criterion a, were eliminated by any of the mitigation measures (Figures 48 and 49). The whole house retrofit did not increase the risk of overheating compared to the pre-retrofit house when mitigation measures were applied. This is because overheating was eliminated, and the median hours of exceedance were very similar. Shading reduced the hours of exceedance more than ventilation for this house in Manchester.

Figure 48: Overheating assessment for 17BG with Manchester RWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



Room	Number of years that overheating occurs according to criterion a							
	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Living room	0/10	0/10	0/10	0/10	2/10	0/10	0/10	0/10
Bedroom 1	0/10	0/10	0/10	0/10	1/10	0/10	0/10	0/10

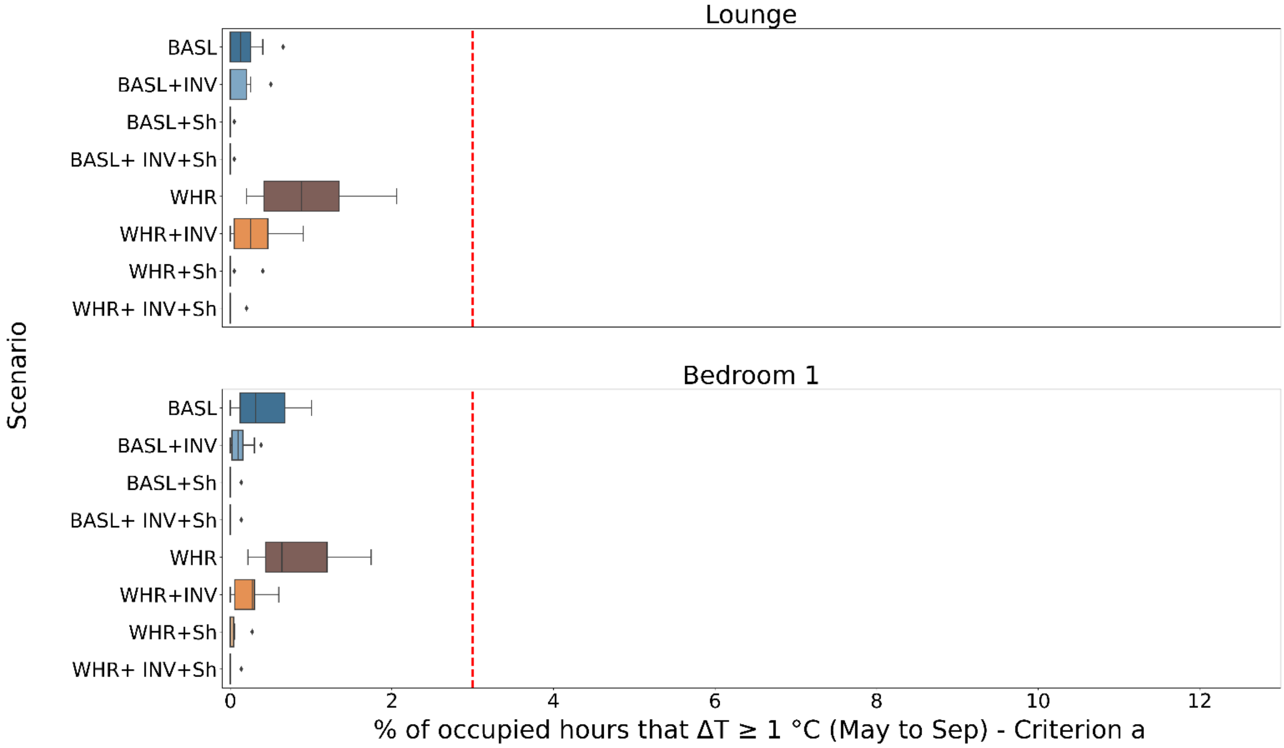
Figure 49: Overheating assessment for 17BG with Manchester RWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



Room	Number of years that overheating occurs according to criterion b							
	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Bedroom 1	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10

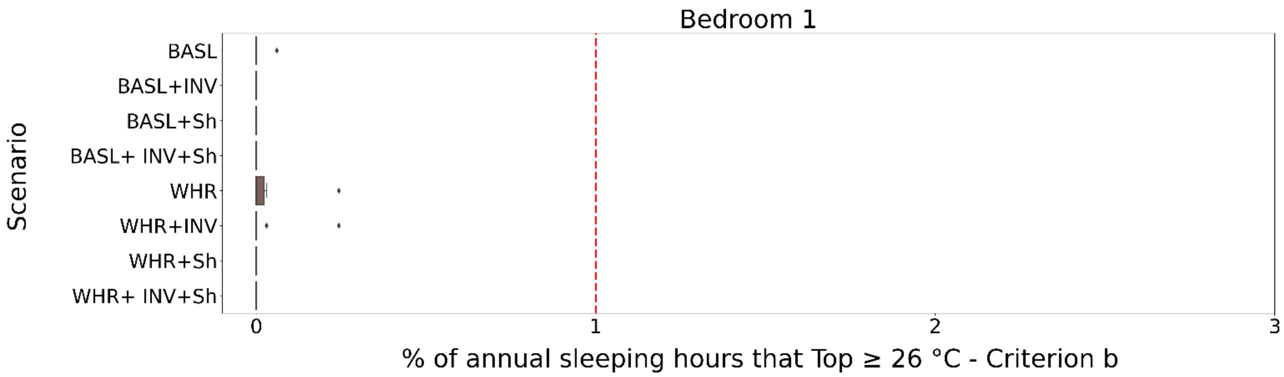
For the Glasgow RWD there was no overheating, but the mitigation measures reduced the hours of exceedance after the retrofit to a similar level as the pre-retrofit house (Figures 50 and 51).

Figure 50: Overheating assessment for 17BG with Glasgow RWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Living room	0	0	0	0	0	0	0	0
Bedroom 1	0	0	0	0	0	0	0	0

Figure 51: Overheating assessment for 17BG with Glasgow RWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs

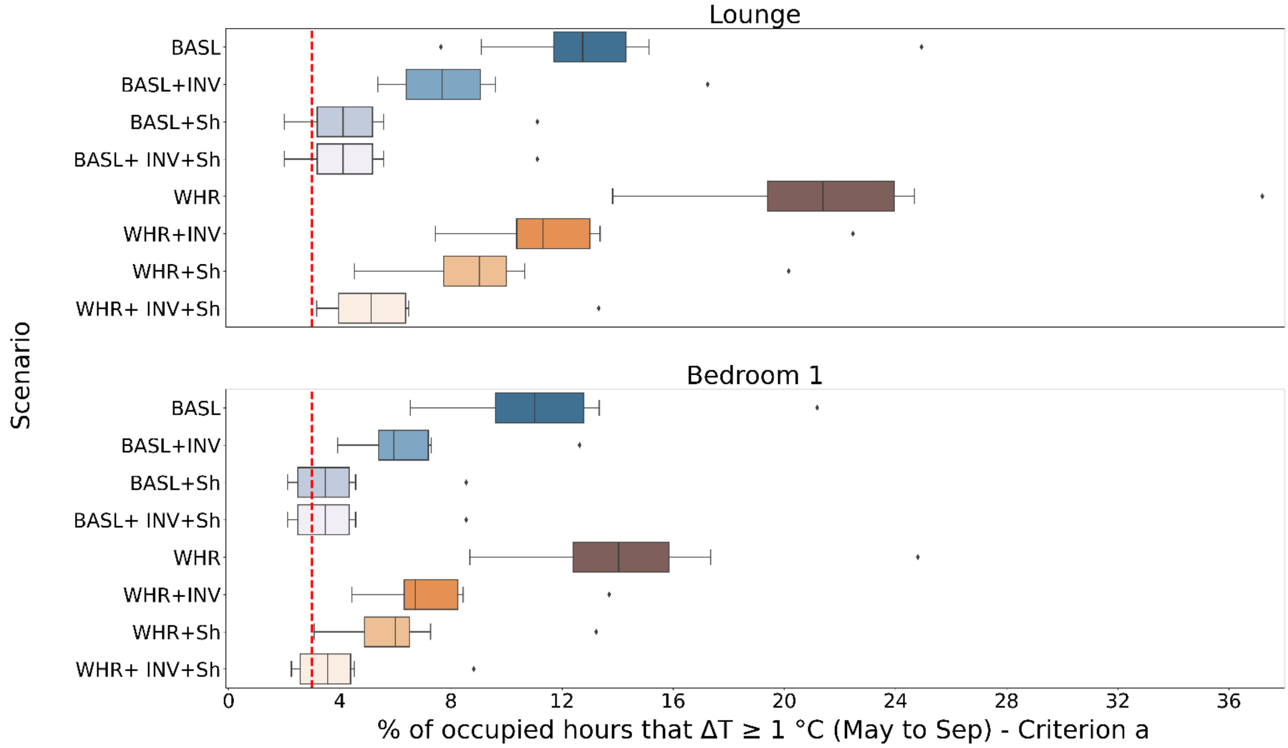


	Number of years that overheating occurs according to criterion b							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Bedroom 1	0/10	0/10	0/10	0/10	0/10	0/10	0/10	0/10

7.2.2 Overheating risk in a Future Weather Decade

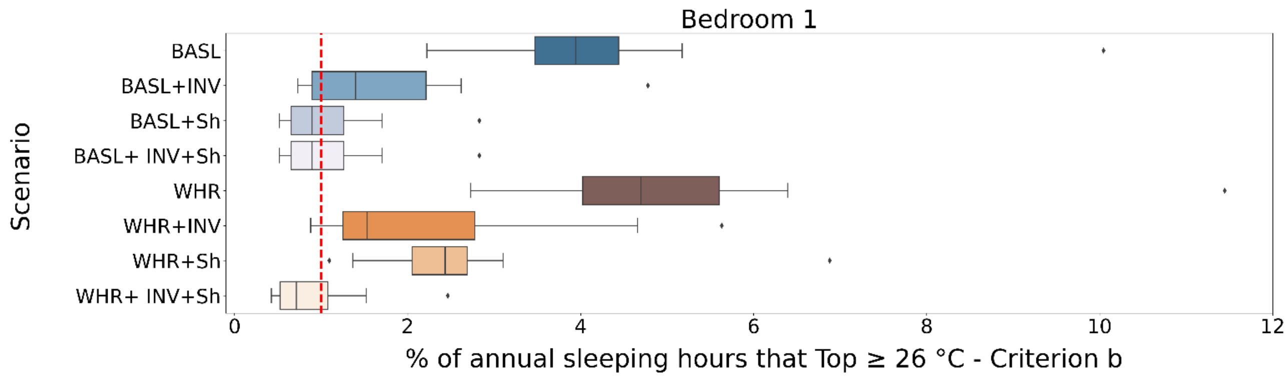
For the London FWD, overheating was reduced but not eliminated when ventilation was increased and external shutters used (strategy INV+Sh) according to criterion a (Figure 52) and criterion b (Figure 53). The whole house retrofit did increase overheating in the living room according to criterion a, but reduced it in the bedroom according to criterion b.

Figure 52: Overheating assessment for 17BG with London FWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
	Number of years that overheating occurs according to criterion a							
Living room	10/10	10/10	8/10	8/10	10/10	10/10	10/10	10/10
Bedroom 1	10/10	10/10	9/10	6/10	10/10	10/10	10/10	6/10

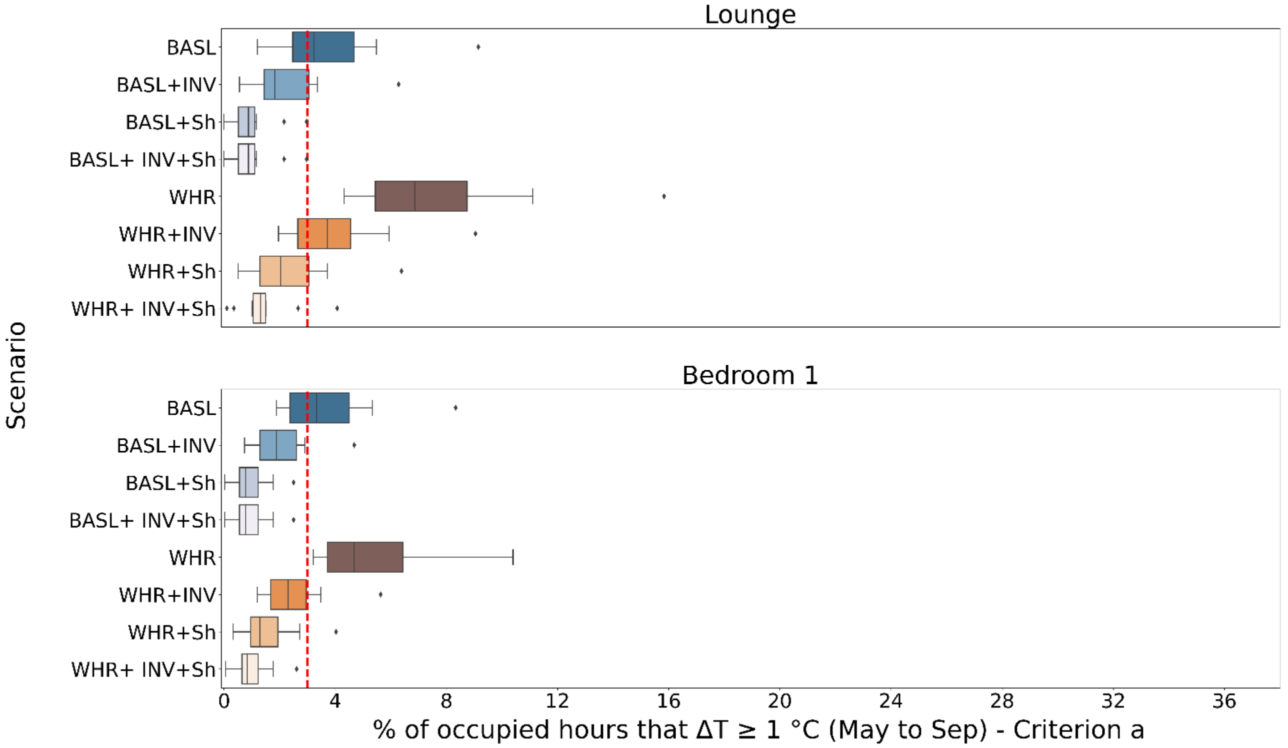
Figure 53: Overheating assessment for 17BG with London FWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
	Number of years that overheating occurs according to criterion b							
Bedroom 1	10/10	6/10	10/10	5/10	10/10	8/10	10/10	3/10

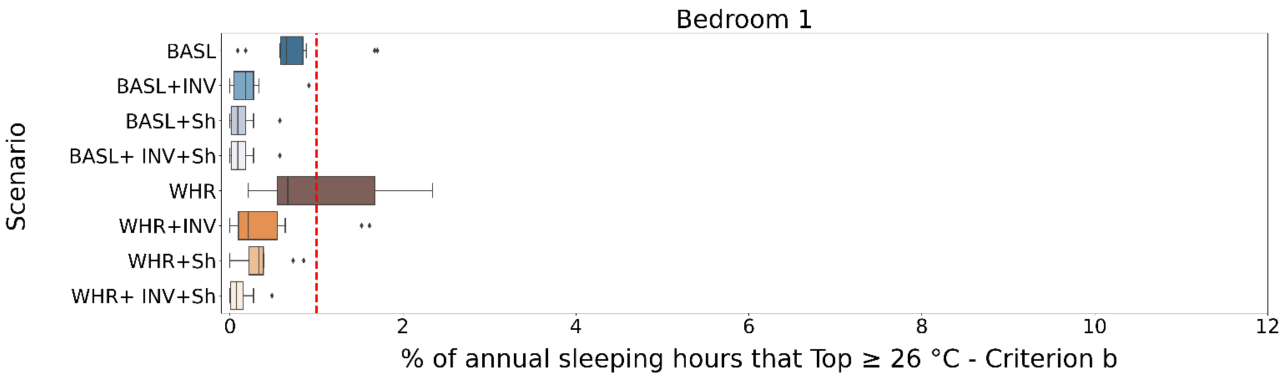
For the Manchester FWD, overheating was eliminated in the pre-retrofit house when ventilation was increased and external shutters used (strategy (INV + Sh), according to criterion a (Figure 54) and criterion b (Figure 55). The whole house retrofit did slightly increase overheating in the living room but overheating only occurred in one year and only according to criterion a. Otherwise, the median hours of exceedance for this house in Manchester were very similar when both the mitigation measures were applied.

Figure 54: Overheating assessment for 17BG with Manchester FWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Living room	6/10	3/10	0/10	0/10	10/10	6/10	3/10	1/10
Bedroom 1	6/10	1/10	1/10	0/10	10/10	3/10	1/10	0/10

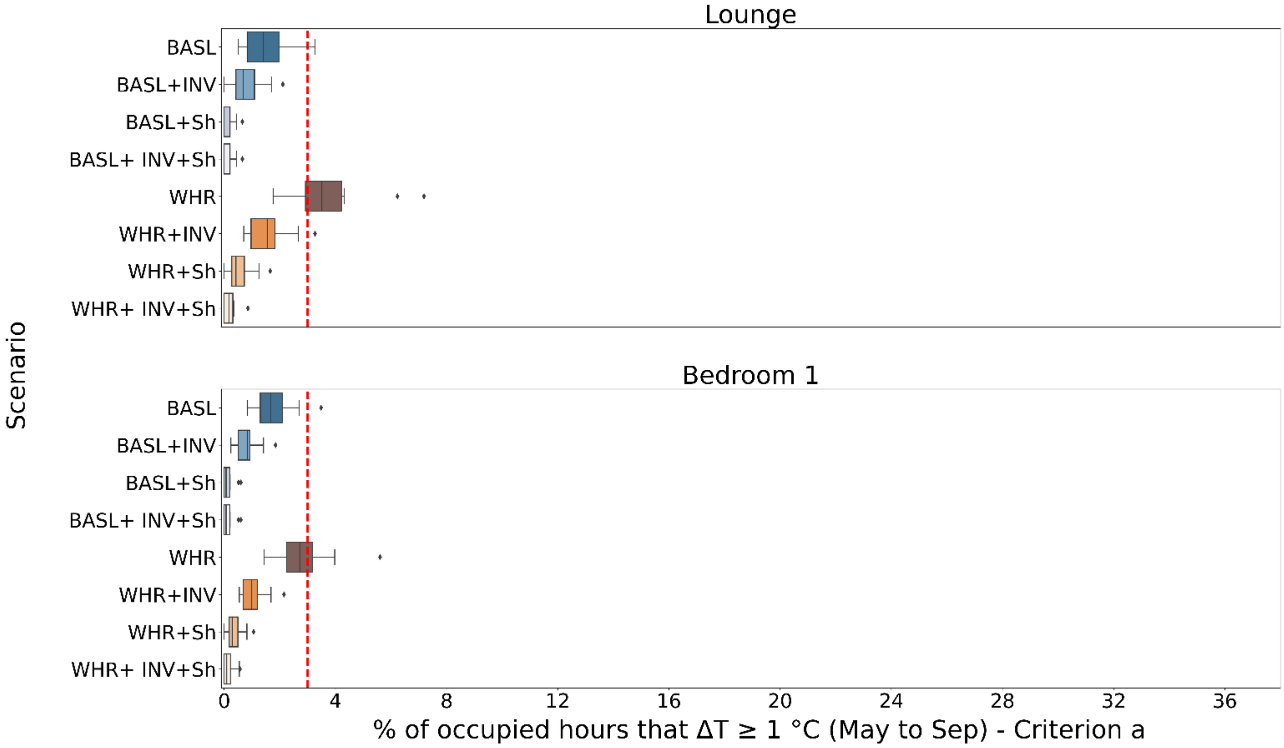
Figure 55: Overheating assessment for 17BG with Manchester FWD - comparing passive mitigation strategies - the red line shows the criterion b threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion b							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Bedroom 1	2/10	0/10	0/10	0/10	3/10	2/10	0/10	0/10

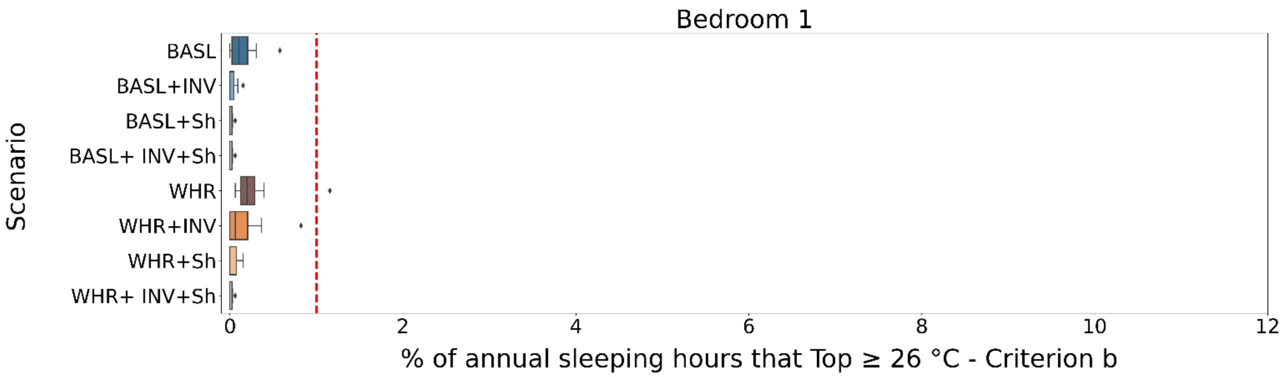
For the Glasgow FWD, overheating was eliminated using shading (strategy Sh) in both the pre-retrofit house and the whole house refurbishment house according to criterion a (Figures 56) and criterion b (Figure 57). Increased ventilation was effective in all but one year when overheating occurred in the living room of the house after retrofit according to criterion a. The whole house retrofit does not increase the risk of overheating compared to the pre-retrofit house when both of the mitigation strategies are applied as overheating was eliminated and the median hours of exceedance were very similar.

Figure 56: Overheating assessment for 17BG with Glasgow FWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion a							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Living room	1/10	0/10	0/10	0/10	6/10	1/10	0/10	0/10
Bedroom 1	1/10	0/10	0/10	0/10	3/10	0/10	0/10	0/10

Figure 57: Overheating assessment for 17BG with Glasgow FWD - comparing passive mitigation strategies - the red line shows the criterion a threshold, and the table shows the number of years that overheating occurs



	Number of years that overheating occurs according to criterion b							
Room	BASL	BASL+INV	BASL+Sh	BASL+INV+Sh	WHR	WHR+INV	WHR+Sh	WHR+INV+Sh
Bedroom 1	0/10	0/10	0/10	0/10	1/10	0/10	0/10	0/10

8. Discussion and conclusions

8.1 Summary of key findings

The two case-study houses were part of the DEEP field work and underwent sequential retrofit to individual thermal elements. House 56TR has windows on two opposite façades and so can be cross ventilated, while house 17BG only has windows on one façade and must rely on single-sided ventilation.

The risk of overheating was assessed for each of the case study houses before any retrofit work took place (baseline model) and at the end of each retrofit stage. The risk of overheating was then re-assessed with the application of simple mitigation measures (shading and increased ventilation) to each of the case study houses before any retrofit work took place, and after the whole house retrofit.

For house 56TR, which could be cross-ventilated, the retrofit had little impact on overheating. Under current weather (using the RWD), overheating occurred most years in London, some years in Manchester, and no years in Glasgow. The mitigation measures eliminated any overheating in all cases. Under future weather (using the FWD), overheating occurred every year in London and Manchester and most years in Glasgow. The mitigation measures were able to eliminate any overheating in Manchester and Glasgow. In London, the mitigation measures significantly reduced overheating according to criterion a, but the bedroom still overheated most years according to criterion b. Overall, the whole house retrofit did not increase the risk of overheating when the mitigation measures were applied, and even reduced the risk of overheating in some cases. Additional ventilation was the best mitigation for this house, but shading was also required in some cases.

For house 17BG, with only single-sided ventilation, the retrofit slightly increased the overheating risk in some cases. Under current weather (using the RWD), more overheating occurred after the whole house retrofit: every year in London, some years in Manchester, and no years in Glasgow. However, the mitigation measures were able to eliminate any overheating in all cases. Under future weather (using the FWD), more overheating occurred after the whole house retrofit: every year in London, every year in Manchester, and most years in Glasgow. The mitigation measures were able to eliminate any overheating in Glasgow and overheating only occurred after the whole house retrofit for one year in Manchester. For London, the whole house retrofit did increase overheating in the living room according to criterion a but reduced it in the bedroom according to criterion b, when the mitigation measures were applied. Overall, when mitigation measures were applied, whole house retrofit only slightly increased the risk of overheating. Shading was the best mitigation for this house, but increased ventilation was also required in some cases.

These results are logical, and it is quite clear that we should not be relying on poor fabric thermal efficiency to mitigate overheating. If a house can be adequately shaded to prevent solar gains, and ventilated to remove internal gains, then overheating is generally no worse after a whole house retrofit than before. In fact, retrofit can reduce overheating as the heat gains through the fabric are reduced. Houses (or flats) with single-sided ventilation are more at risk from overheating under future weather than those with cross-ventilation, as it is harder to get adequate ventilation. It is noted that under future conditions the average daily maximum temperature in London is expected to exceed 30 °C, see Table 7.

Table 7: Mean and average daily maximum temperature[1] in all considered locations.

	Current climate		Future climate	
City	Mean temperature (°C)	Average daily maximum temperature (°C)	Mean temperature (°C)	Average daily maximum temperature (°C)
London	16.4	26.0	20.0	31.3
Manchester	14,5	23.2	17.4	27.2
Glasgow	13.7	20.9	16.2	24.5

[1] These figures arise from the analysis of the weather files used in this work; see Section 4.1.

Taken together, these findings highlight the opportunity for holistic whole house retrofit that considers shading and ventilation. This also highlights the risk that piecemeal retrofit can increase the risk of overheating if shading and ventilation are not addressed. Two notable risk factors were floor insulation and internal wall insulation. Floor insulation noticeably increased the overheating risk for the house with single-sided ventilation and no mitigation. This was expected since for the rooms located on the ground floor, the floor represents the largest surface exposed to outdoors and the ground temperature during summers is significantly lower than that of the outdoor air. The results of the parametric analysis indicated that internal wall insulation can increase risk more than external wall insulation in some cases.

The TM59 method proved a useful tool for comparative overheating assessment. Applying the assessment over ten successive years of weather provided a better understanding of the overheating risk than an assessment using a single year of weather. Nevertheless, given that hot weather has occurred more frequently in recent years (as in the summers of 2019 and 2022) it would be advisable to update the RWD files frequently. Also, the FWD used here depicts one average future weather decade scenario. Similar to the CIBSE future weather files [24] where three future weather files are provided, three FWD files[14] could be used to depict low, medium and high conditions in terms of weather severity.

8.2 Limitations and future work

This work is based on the results of dynamic thermal simulation. The models were calibrated, but this did not include consideration of the building dynamics, i.e. rate of heating and cooling. There are many simplifications, such as the heat transfer between buildings and the heat transfer with the ground beneath the building. Furthermore, recent research indicates that thermal models may overestimate the impact of window operation on overheating (Roberts et al., 2019). Future work should verify these models, including the modelling of shading and ventilation mitigation strategies, using monitored data.

There are limitations to the deterministic overheating criteria in TM59. For example, the criterion b threshold temperature of 26°C originated from a small study [25] which is being challenged by ongoing research. Furthermore, both criteria ignore the magnitude of overheating, i.e. how high the temperature is above the threshold. Previous research has shown that overheating assessment is very sensitive to the kind of criteria used [26,27]. Future work should consider these thresholds.

[14] Twelve different weather files are generated, see DEEP Project Report 6.01 [14] for more details.

TM59 represents occupancy as a fixed schedule which is the same every day and does not differentiate between weekdays and weekends. Further work to understand the influence of occupancy on ventilation is required, given how importance of ventilation was shown here.

Further work is needed also with respect to ground heat transfer calculations. In reality, heat transfer between the floor and the ground below is a complex phenomenon and in building simulations it is simplified; ground transfer calculations are one-dimensional. Further to this, the difficulty to compute accurate ground temperatures increase the uncertainty regarding ground heat transfer. Hence, the significant impact of floor insulation shown in this report may not reflect reality accurately.

The overheating assessment did not consider RH, which is known to have an impact on thermal comfort when both temperature and RH are high. It is very difficult to quantify the effect of RH on overheating since 'increased discomfort that is commonly experienced at high humidity may not be entirely experienced as feeling hotter' [28]. The temperatures and RH experienced in the UK may not be high enough for this to be a concern. This should be explored further.

External shading and increased ventilation were shown to be effective mitigation strategies. However, there are considerable socio-technical barriers around aesthetics, noise, pollution, and security. Further work to improve the design of shutters and ventilation openings should be carried out to address these issues.

Finally, further work to map overheating risk across the UKs housing stock typologies and geographies is recommended.

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Appendix: Input data for simulations

The appendix contains the detailed input data used for the modelling work presented in this report: internal mass (A.1), airflow (A.2), heating temperature set-points (A.3) and internal gains due to occupancy, equipment, and lights (A.4) for both houses (56TR and 17BG). Input data are shown for the rooms that are assessed in the content of TM59 methodology (i.e., living rooms, kitchens, and bedrooms).

A.1: Internal mass

Table A.1 shows the surface area of furniture (see Section 4.2).

Table A.1 Surface area[1] (m^2) of furniture assumed in the assessed rooms

	House	
Room	56TR	17BG
Living room	32.7	33.0
Kitchen	13.8	11.4
Bedroom	24.8	29.6

A.2: Airflow

Tables A.2 - A.5 show the values of air mass flow coefficient and air mass flow exponent at the pre-retrofit and each retrofit stage (see Section 4.3).

Table A.2 Air mass flow coefficient (kg/s) in 56TR house at the pre-retrofit and each retrofit stage

	Retrofit stage				
Element	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Exterior walls	0.00013	0.00013	0.00013	0.00013	0.00014
Interior walls	0.00360	0.00356	0.00368	0.00360	0.00374
Roofs	0.00012	0.00011	0.00012	0.00011	0.00012
Ceilings	0.00123	0.00121	0.00127	0.00123	0.00131
Exterior windows	0.00040	0.00038	0.00043	0.00040	0.00046
Exterior doors	0.00152	0.00151	0.00154	0.00152	0.00155
Interior doors	0.02000	0.02000	0.02000	0.02000	0.02000

Table A.3 Air mass flow exponent (-) in 56TR house at the pre-retrofit and each retrofit stage

	Retrofit stage				
Element	BASL	BASL + Roof	BASL_R + Floor	BASL_R_F + Walls	WHR
Exterior walls	0.70	0.70	0.70	0.70	0.70
Interior walls	0.75	0.75	0.75	0.75	0.75
Roofs	0.70	0.70	0.70	0.70	0.70
Ceilings	0.70	0.70	0.70	0.70	0.70
Exterior windows	0.64	0.64	0.63	0.64	0.63
Exterior doors	0.65	0.65	0.65	0.65	0.65
Interior doors	0.60	0.60	0.60	0.60	0.60

Table A.4 Air mass flow coefficient (kg/s) in 17BG house at the pre-retrofit and each retrofit stage

	Retrofit stage					
Element	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Exterior walls	0.00024	0.00017	0.00019	0.00017	0.00018	0.00016
Interior walls	0.00752	0.00430	0.00470	0.00440	0.00460	0.00420
Roofs	0.00016	0.00013	0.00014	0.00014	0.00014	0.00013
Ceilings	0.00218	0.00162	0.00184	0.00167	0.00178	0.00156
Exterior windows	0.00136	0.00070	0.00087	0.00074	0.00083	0.00066
Exterior doors	0.00202	0.00166	0.00174	0.00168	0.00172	0.00164
Interior doors	0.02000	0.02000	0.02000	0.02000	0.02000	0.02000

Table A.5 Air mass flow exponent (-) in 17BG house at the pre-retrofit and each retrofit stage

	Retrofit stage					
Element	BASL	BASL + Airtightness	BASL_A + Dormer	BASL_A_D + Floor	BASL_A_D_F + Walls	WHR
Exterior walls	0.70	0.70	0.70	0.70	0.70	0.70
Interior walls	0.75	0.75	0.75	0.75	0.75	0.75
Roofs	0.70	0.70	0.70	0.70	0.70	0.70
Ceilings	0.70	0.70	0.70	0.70	0.70	0.70
Exterior windows	0.60	0.62	0.61	0.62	0.61	0.62
Exterior doors	0.66	0.66	0.66	0.66	0.66	0.66
Interior doors	0.60	0.60	0.60	0.60	0.60	0.60

A.3: Heating temperature set-points

Table A.6 displays heating temperature set-points (°C) (see Section 4.4); heating is provided outside the summer period as defined in TM59 (i.e., 1 May to 30 September inclusive).

Table A.6 Heating temperature (°C) setpoints

Hour	Living room	Kitchen	Bedroom
0 to 1	12	12	18
1 to 2	12	12	18
2 to 3	12	12	18
3 to 4	12	12	18
4 to 5	12	12	18
5 to 6	12	12	18
6 to 7	12	18	18
7 to 8	12	18	12
8 to 9	12	18	12
9 to 10	12	18	12
10 to 11	12	12	12
11 to 12	12	12	12
12 to 13	12	12	12
13 to 14	12	12	12
14 to 15	21	12	12
15 to 16	21	12	12
16 to 17	21	12	12
17 to 18	21	18	12
18 to 19	21	18	12
19 to 20	21	18	12
20 to 21	21	12	12
21 to 22	21	12	12
22 to 23	21	12	18
23 to 24	12	12	18

A.4: Internal gains

Tables A7 - A.9 show the internal gains due to occupancy, equipment and lights (see Section 4.4).

For the winter period, the density (people per floor area) was 0.018756303, 0.023703704, 0.022938776 in the living room, kitchen and bedrooms respectively. Gains (W/person) were 110, 160 and 90 in the living room, kitchen and bedrooms respectively. For the summer period, three people were assumed in 56 TR house (3-bedroom house) and two people in 17BG house (2-bedroom house). Gains were 130 W/person but reduced by 30% during sleeping hours.

For the winter period, the equipment load per floor area (W/m^2) was 3.9, 30.28 and 3.58 in the living room, kitchen and bedrooms respectively. For the summer period, the equipment load (W) was 150, 300 and 80 in the living room, kitchen and bedrooms respectively.

For the winter period, the lights load per floor area (W/m^2) was 7.5, 15 and 15 in the living room, kitchen and bedrooms respectively. For the summer period, the lights load was 2 W/m^2 in all assessed rooms.

Table A.7 Occupancy fractions in winter and summer period

	Winter period			Summer period		
Hour	Living room	Kitchen	Bedroom	Living room	Kitchen	Bedroom
0 to 1	0	0	1	0	0	1
1 to 2	0	0	1	0	0	1
2 to 3	0	0	1	0	0	1
3 to 4	0	0	1	0	0	1
4 to 5	0	0	1	0	0	1
5 to 6	0	0	1	0	0	1
6 to 7	0	0	1	0	0	1
7 to 8	0	1	0.5	0	0	1
8 to 9	0	1	0.25	0	0	1
9 to 10	0	1	0	0.75	0.25	1
10 to 11	0	0	0	0.75	0.25	1
11 to 12	0	0	0	0.75	0.25	1
12 to 13	0	0	0	0.75	0.25	1
13 to 14	0	0	0	0.75	0.25	1
14 to 15	0	0	0	0.75	0.25	1
15 to 16	0	0	0	0.75	0.25	1
16 to 17	0.5	0	0	0.75	0.25	1
17 to 18	0.5	0	0	0.75	0.25	1
18 to 19	1	0	0	0.75	0.25	1
19 to 20	1	0.2	0	0.75	0.25	1
20 to 21	1	0.2	0.25	0.75	0.25	1
21 to 22	1	0.2	0.25	0.75	0.25	1
22 to 23	0	0.2	0.25	0	0	1
23 to 24	0	0	0.75	0	0	1

Table A.8 Equipment fractions in winter and summer period

	Winter period			Summer period		
Hour	Living room	Kitchen	Bedroom	Living room	Kitchen	Bedroom
0 to 1	0.06413	0.06605	0.06993	0.23	0.17	0.13
1 to 2	0.06413	0.06605	0.06993	0.23	0.17	0.13
2 to 3	0.06413	0.06605	0.06993	0.23	0.17	0.13
3 to 4	0.06413	0.06605	0.06993	0.23	0.17	0.13
4 to 5	0.06413	0.06605	0.06993	0.23	0.17	0.13
5 to 6	0.06413	0.06605	0.06993	0.23	0.17	0.13
6 to 7	0.06413	0.06605	0.06993	0.23	0.17	0.13
7 to 8	0.06413	1	0.53497	0.23	0.17	0.13
8 to 9	0.06413	1	1	0.23	0.17	1
9 to 10	0.06413	1	0.53497	0.4	0.17	1
10 to 11	0.06413	0.06605	0.06993	0.4	0.17	1
11 to 12	0.06413	0.06605	0.06993	0.4	0.17	1
12 to 13	0.06413	0.06605	0.06993	0.4	0.17	1
13 to 14	0.06413	0.06605	0.06993	0.4	0.17	1
14 to 15	0.06413	0.06605	0.06993	0.4	0.17	1
15 to 16	0.06413	0.06605	0.06993	0.4	0.17	1
16 to 17	0.53206	0.06605	0.06993	0.4	0.17	1
17 to 18	0.53206	0.06605	0.30245	0.4	0.17	1
18 to 19	1	0.06605	0.53497	1	1	1
19 to 20	1	0.25284	0.76748	1	1	1
20 to 21	1	0.25284	1	1	0.17	1
21 to 22	1	0.25284	1	1	0.17	1
22 to 23	0.68804	0.25284	0.76748	0.4	0.17	1
23 to 24	0.06413	0.06605	0.30245	0.4	0.17	0.13

Table A.9 Lights fractions in winter and summer period

	Winter period			**Summer period**		
Hour	Living room	Kitchen	Bedroom	Living room	Kitchen	Bedroom
0 to 1	0	0	0	0	0	0
1 to 2	0	1	0	0	0	0
2 to 3	0	1	0	0	0	0
3 to 4	0	1	0	0	0	0
4 to 5	0	1	0	0	0	0
5 to 6	0	1	0	0	0	0
6 to 7	0	1	0	0	0	0
7 to 8	0	1	1	0	0	0
8 to 9	0	1	1	0	0	0
9 to 10	0	1	1	0	0	0
10 to 11	0	0	0	0	0	0
11 to 12	0	0	0	0	0	0
12 to 13	0	0	0	0	0	0
13 to 14	0	0	0	0	0	0
14 to 15	0	0	0	0	0	0
15 to 16	0	0	0	0	0	0
16 to 17	1	0	0	0	0	0
17 to 18	1	0	0	0	0	0
18 to 19	1	0	0	1	1	1
19 to 20	1	1	0.2	1	1	1
20 to 21	1	1	0.2	1	1	1
21 to 22	1	1	0.2	1	1	1
22 to 23	1	1	0.2	1	1	1
23 to 24	0	0	0	0	0	0

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