Indoor thermal environmental assessment of the UK's first Passivhaus-certified extra care scheme under current and projected future climate scenarios.

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Abstract

This paper examines the thermal performance of the UK's first Passivhaus-certified extra care home, assessing its resilience under current and projected climate scenarios. A mixed-methods approach—comprising environmental monitoring, dynamic thermal modelling, and semi-structured stakeholder interviews—evaluates indoor dry bulb temperature, relative humidity, and CO_2 levels across key spaces. A month's monitoring in summer indicates stable indoor temperatures between 23°C and 25°C, though high-traffic zones show variability of up to 0.5°C due to frequent door use. Dynamic thermal modelling across future climate scenarios indicates that, while the building meets comfort thresholds under current and near-term conditions, extreme cases, such as the 2080s high-emissions 90th percentile scenario, reveal a 4.6°C increase in median outdoor temperatures, leading to thermal comfort threshold exceedance in 12.3% of occupied hours. Stakeholder insights emphasise the need for adaptable cooling mechanisms and suggest enhancing passive strategies, such as adding external shading, to support occupant comfort as climate conditions evolve.

Keywords: Passivhaus, Extra care, Residential care, Thermal performance, Climate resilience.

1.0 Introduction

Climate change and an ageing population present critical challenges for care home environments, particularly for older residents and individuals with pre-existing health conditions who are highly vulnerable to temperature fluctuations and extreme weather events (1–4). As global temperatures continue to rise, ensuring stable and comfortable indoor thermal environments in care settings has become a top priority, especially since older adults experience heightened sensitivity to heat due to physiological and pre-existing health conditions (5–7). Studies have shown that prolonged exposure to elevated indoor temperatures can significantly impact the health and wellbeing of older residents, underscoring the need for robust thermal management strategies to mitigate these risks (5,8,9). Overheating risk is often exacerbated in care settings, where continuous occupancy, dense use, and the heightened thermal vulnerability of residents add layers of complexity to managing internal temperatures (5,9).

The Passivhaus standard is an internationally recognised building certification that emphasises energy efficiency and occupant comfort and has emerged as a leading framework for ultra-low energy and zero-carbon buildings (10). It achieves this by implementing rigorous criteria for insulation, airtightness, and mechanical ventilation, thereby minimising energy consumption for heating and cooling (11–14). However, recent studies indicate that, during periods of high external temperatures, such as heatwaves, Passivhaus buildings may be susceptible to overheating (6,15,16). This is particularly concerning in care environments, where residents are more vulnerable to temperature fluctuations (17,18).

Thermal comfort models, such as Fanger's Predicted Mean Vote (PMV) model, are widely used in building design to predict the average thermal sensation of occupants based on factors like air temperature, humidity, air velocity, clothing insulation, and metabolic rate (19,20). However, these models often assume a standard adult population and may not fully account for the specific thermal comfort needs of older adults in care settings. Older individuals often have different physiological responses and comfort preferences, which can lead to discrepancies between predicted comfort levels and actual occupant satisfaction. For instance, while some older residents may find warmer indoor conditions acceptable, care staff working in the same environment might experience discomfort at these temperatures, highlighting the challenge of balancing thermal comfort for diverse occupant groups (5,9).

In this context, sustainable thermal technologies, including heat generation methods like biomass boilers and ground-source heat pumps, heat distribution through underfloor systems, and heat retention via insulation and air sealing, have garnered interest as potential solutions (21). Despite their potential to enhance thermal comfort while minimising environmental impact, adoption in the care sector remains cautious due to concerns about operational reliability and perceived risks (21). Additionally, studies have shown that effective passive cooling methods, such as external shading, night ventilation and high thermal mass, can positively impact indoor temperatures but may require more extensive integration into building designs tailored to vulnerable populations (5,15).

Given these challenges, this paper explores the thermal environment within a Passivhaus-certified extra care home in the UK, focusing on overheating risks under current and projected future climate conditions. This study aims to contribute to the ongoing discourse on sustainable building design by evaluating whether Passivhaus standards, as currently applied, can meet the unique thermal needs of older residents in care settings. This pilot study, while preliminary, provides insights to inform the design, management, and potential adaptation of Passivhaus principles in climate-sensitive care environments.

2.0 Background

2.1 Overview of potential health issues for older people

The global shift towards an ageing population presents substantial health challenges, particularly for older adults in care settings who are at increased risk of chronic diseases, mental health disorders, and other age-related health issues. By 2050, individuals aged 60 and over are projected to represent 22% of the global population, surpassing 2 billion (17). This demographic shift highlights the urgency of addressing the unique health vulnerabilities of this population, as nearly 80% of older adults live with at least one chronic condition, and 68% suffer from two or more (7). Cardiovascular diseases, including hypertension and heart disease, affect approximately 30% of older adults, significantly contributing to morbidity and mortality, while conditions such as diabetes and chronic respiratory diseases, such as chronic obstructive pulmonary disease (COPD), impact an additional 25% and 10%, respectively, underscoring the widespread prevalence of chronic illness within this age group (7,22).

Mental health issues further compound these challenges. Studies (23) show that 15-20% of older adults experience depressive symptoms, with rates even higher among those in institutional care. Cognitive decline is also prevalent, with approximately 7% of individuals over 60 affected by dementia—a figure that rises sharply to 30-50% among those aged 85 and over and is projected to impact 1.7 million individuals in the UK by 2050 (7,23). Physical health limitations, including mobility restrictions and malnutrition, further hinder quality of life, contributing to falls and other injury risks, with an estimated 30% of older adults experiencing such falls annually. Malnutrition affects 10-15% of this population, particularly in care settings, leading to weakened immune systems and increased hospitalisation rates (7).

Environmental factors play a critical role in exacerbating these health issues. Older adults are especially vulnerable to temperature extremes due to diminished physiological thermoregulation, resulting in higher rates of heat-related mortality, particularly during heatwaves, where mortality can increase by up to 42% in care settings (24). Indoor air quality also significantly affects respiratory health, with poor ventilation and high pollutant levels in care homes further increasing the risks for residents (22). Given these vulnerabilities, it is essential to develop care environments that mitigate these risks and prioritise the health, comfort, and well-being of older adults.

2.2 Care and extra care settings

As the global population ages, the need for specialised living arrangements for older adults has grown substantially. A report (7) projects that public spending in the UK will rise from 33.6% to 37.8% of GDP by 2064, driven largely by healthcare and social services for older adults, with care homes and extra care settings emerging as primary models to meet these needs.

Care homes, also known as residential care facilities, offer 24-hour support and personal care for individuals with substantial health requirements or limited mobility, assisting with daily activities like bathing, dressing, and medication management (8,25). There are approximately 17,000 care homes in the UK, housing around 400,000 residents with an average age of 84 years (26). Notably, nearly 70% of these residents have some form of dementia, highlighting the importance of environments tailored to support cognitive health (27,28).

Care homes are classified into two main categories: residential care homes, which provide personal care without nursing supervision, and nursing homes, which offer both medical and personal care, with registered nurses on-site to manage complex health needs (5). This distinction ensures that older adults receive support levels appropriate to their individual needs, whether recovering from surgery, managing chronic conditions, or dealing with frailty associated with advanced age.

In contrast, extra care settings—also referred to as assisted living or very sheltered housing—are designed to foster independence while providing access to support services as needed. These settings typically comprise self-contained apartments or bungalows, with communal facilities such as dining areas, lounges, and gardens to promote social engagement (18,29). Extra care facilities support around 60,000 residents across more than 1,500 schemes in the UK, emphasising a flexible care approach where assistance can adjust to evolving health conditions, such as dementia (7,8).

Studies indicate that residents in extra care settings report higher levels of satisfaction due to the autonomy and privacy afforded by self-contained living spaces, along with the benefits of community engagement in shared spaces (7,30). By prioritising independence and adaptable care, extra care settings offer a supportive environment that enables residents to exercise control over their daily lives while fostering connections with others, which is essential for their mental and social well-being.

2.3 The 'Passivhaus' standard

The 'Passivhaus standard, developed by the Passive House Institute in Germany, is widely recognised as one of the most rigorous building standards for energy efficiency and occupant comfort, with particular relevance as global construction shifts towards sustainable and low-carbon practices (10). This standard adopts a "fabric-first" approach, focusing on optimising building elements before adding mechanical systems, which minimises heat loss and maximises thermal comfort. Key principles include superinsulation, airtight construction, high-performance glazing, thermal bridge-free design, and mechanical ventilation with heat recovery (MVHR), all contributing to a building's ability to maintain a stable and comfortable environment with minimal energy input (11,12,14,31). The principles of Passivhaus are tightly defined and measurable, including airtightness standards of 0.6 air changes per hour at 50 Pascals (Pa) pressure and U-values of ≤ 0.15 W/m²K for walls and ≤ 0.8 W/m²K for windows (32). With MVHR systems designed to recover a minimum of 75% of exhaust air heat, Passivhaus buildings maintain stable, thermally comfortable environments with significantly reduced reliance on mechanical systems (32).

Originally developed for cold European climates, the standard has proven adaptable to a wide range of climates worldwide, including warmer regions like Mexico, Chile, and China, showcasing its versatility in varied geographic contexts (33–36). In the UK, over 1,300 buildings have achieved Passivhaus certification, with more than 65,000 certified globally, underlining the standard's growing role in achieving near-zero energy design goals (37–39).

2.4 Application in the care and extra care settings

The adoption of the Passivhaus standard in care and extra care settings has strong potential to address the unique health challenges faced by older adults in such environments. Given the heightened susceptibility of older residents to environmental conditions, Passivhaus-designed buildings promise to offer a stable indoor climate conducive to health and well-being, even during extreme weather events. Studies have demonstrated that Passivhaus care homes maintain indoor temperatures effectively, reducing the discomfort associated with temperature fluctuations. For example, during heatwaves, Passivhaus buildings in the UK allowed residents to remain comfortable while other building types struggled to mitigate excessive indoor heat, underscoring the adaptability of this standard to cater to both staff and resident needs, especially for older adults with compromised thermal tolerance (24).

Additionally, the economic benefits of Passivhaus construction in the care sector are substantial. The energy demands of UK care homes, where heating and cooling needs are constant, currently result in annual operational costs of approximately £468.5 million and emissions totalling around 2.3 million tonnes of CO_2 (40). Passivhaus standards, by significantly reducing energy consumption, can achieve up to 11% savings, a crucial economic advantage that also aligns with climate goals. Lower energy costs allow facilities to allocate additional resources to resident care and services, enhancing quality of life while contributing to broader sustainability targets (41).

Empirical research has documented the benefits of Passivhaus residential buildings regarding their energy consumption and indoor environments. Studies consistently show that Passivhaus-certified homes provide superior IAQ compared to conventional dwellings, with marked reductions in indoor radon levels, CO_2, tVOC, and $PM_{2.5}$ concentrations (33,42–44). These buildings are also recognised for their enhanced thermal performance and energy efficiency, evidenced by reduced indoor temperature fluctuations and lower heating and cooling energy requirements (45,46) However, challenges such as overheating and the need for optimised ventilation strategies to maintain adequate IAQ without compromising energy efficiency have also been identified, particularly under future climate projections with medium to high emission scenarios. In these scenarios, the risk of indoor overheating is expected to increase due to higher external temperatures and prolonged heatwaves, which could challenge the ability of Passivhaus buildings to maintain comfort without active cooling systems (47–49).

Despite the wealth of knowledge on Passivhaus residential buildings, research on the standard's application in non-domestic and particularly hybrid buildings such as care and extra care settings remains sparse. By coupling supportive care with high-quality living environments, Passivhaus principles can potentially offer a promising pathway toward meeting the complex needs of an ageing demographic in the UK and beyond, setting a new standard for climate-adaptive, health-promoting housing solutions (41,50). By exploring the application of Passivhaus principles in these hybrid buildings, this study fills a critical gap in our understanding of designing and operating buildings that cater to complex and diverse needs.

3.0 Methodology

This study examines a recently constructed, Passivhaus-certified extra care facility located in a cold-temperate climate zone in southwest UK. This building was purposefully selected due to its recent completion, Passivhaus certification, and its suitability for evaluating energy-efficient design's impact on indoor thermal environments for vulnerable populations.

The case study building, with a net floor area of 3,596 m^2, comprises five storeys, oriented east/west, with 53 apartments configured as one- and two-bedroom units available for social rent or part-ownership. In addition to residential units, the building includes multiple communal areas, such as a café, a library, and a dining room, providing a broad spectrum of indoor spaces for monitoring. It employs centralised mechanical ventilation with a heat recovery (MVHR) system and a central gas boiler for hot water and under-floor heating, supported by a well-insulated precast concrete frame and masonry façade.

3.1 Methods

A mixed-methods approach was employed as shown in Figure 1, integrating environmental monitoring, semi-structured interviews, and dynamic thermal modelling. This approach aimed to capture a comprehensive picture of the indoor thermal environment, stakeholder perspectives, and thermal resilience under projected future climate conditions.

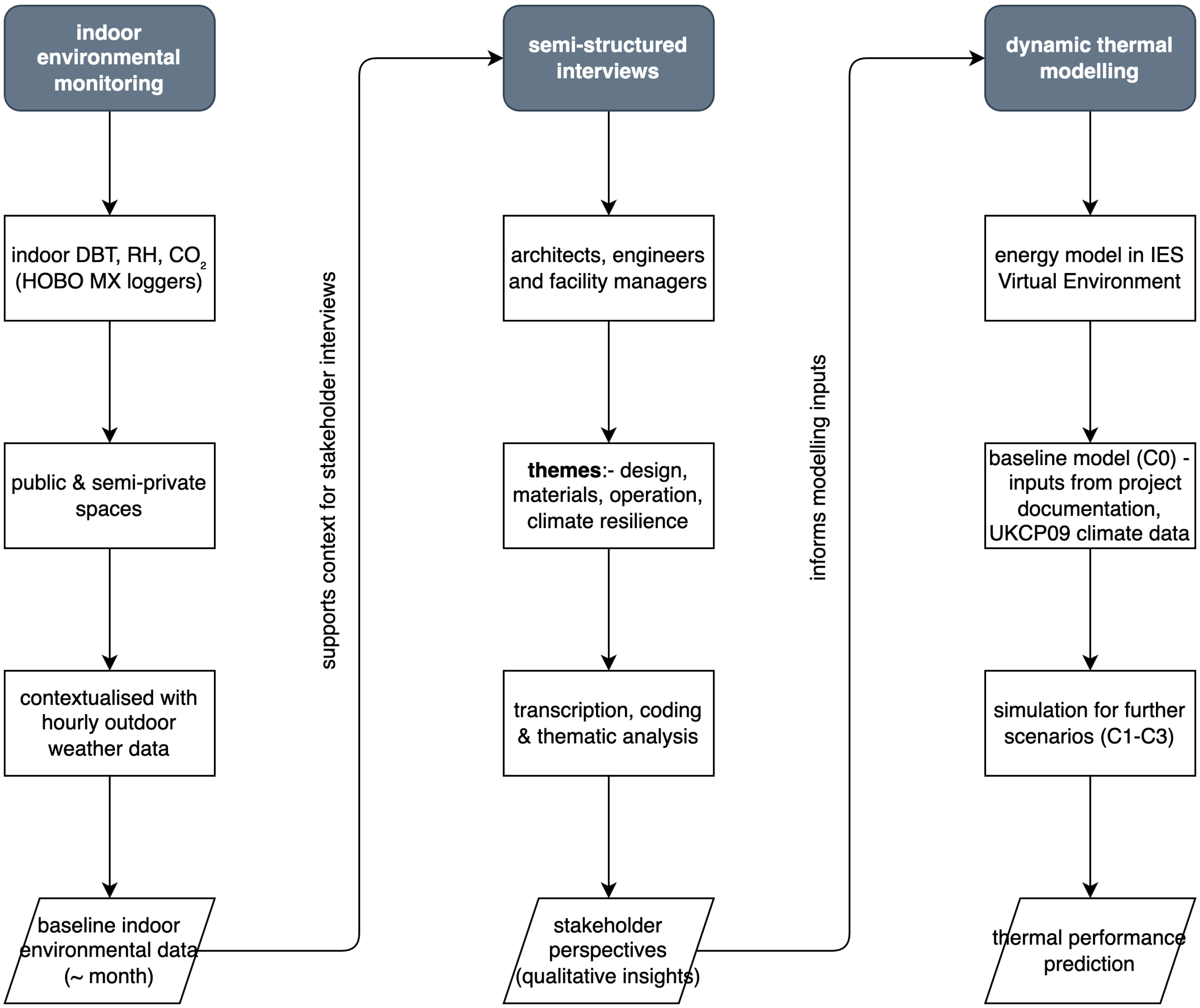

Figure 1 Methodology for assessing indoor thermal environment of the case study extra care setting

3.1.1 Environmental monitoring

Real-time environmental monitoring was conducted for about a month, from 13 August to 9 September 2024. Three HOBO MX CO_2 loggers (MX1102A) (51) were deployed to measure indoor dry bulb temperature, relative humidity (RH), and CO_2 concentrations in the manager's cabin, staff room, and entrance lobby, as shown in Figure 2, representing semi-private and public spaces. Due to access limitations, residential apartments were not included in this phase. The loggers were set to record data at 10-minute intervals. Hourly outdoor temperature and RH data were obtained from an online weather application (52) to contextualise indoor environmental variations.

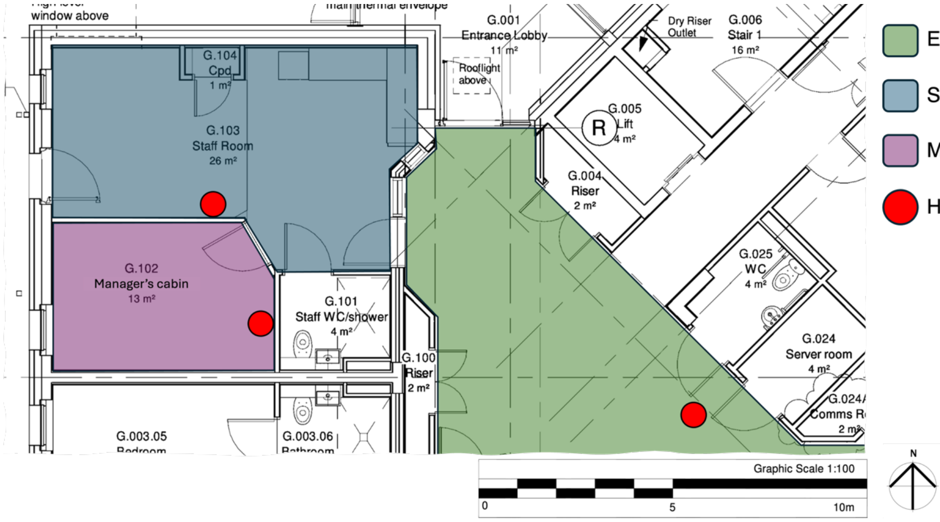

Figure 2 Sensor placement in the case study building

The sensors were positioned at 1.1 to 1.5 meters above floor level to reflect the conditions in the occupants' breathing zone, adhering to best practices to avoid direct sunlight and other heat sources. To ensure accurate readings, the loggers were calibrated in the UCL environmental chamber before deployment, and the auto-calibration feature was disabled to prevent any unintended adjustments during monitoring. The displays of the monitoring equipment were disabled to prevent any behavioural bias (53–55).

3.1.2 Semi-structured interviews

Qualitative data were collected through semi-structured interviews with stakeholders (n=4) in the design, construction, and management of the building, selected through purposive sampling. Given the ethical considerations, residents were excluded from the pilot interview phase. The stakeholders interviewed included three members from the design and engineering teams and one facility manager. The interview protocol covered four main themes as mentioned in Table 1 below.

Design philosophy	Assessing sustainability and well-being objectives.
Material and construction choices	Understanding the impact of construction materials on thermal and environmental performance.
Operational challenges	Practical issues in maintaining IEQ and resident feedback.
Climate resilience	Exploring future climate considerations and adaptability.

Table 1 Semi-structured interview themes

The interviews were audio-recorded with consent, transcribed, and coded using thematic analysis. This qualitative data offered insights into operational challenges and adaptive behaviours, supplementing quantitative data.

3.1.3 Dynamic thermal modelling

The building's thermal performance under current and projected climate scenarios was modelled with simulations run hourly using IES Virtual Environment (version 2022.4.1.0) (56). While the study initially intended to adhere to the CIBSE TM59 methodology (57) for overheating risk assessment, it deviates slightly by using the PROMETHEUS dataset (60), based on UK Climate Projections 2009 (UKCP09), for the climate files. The TM59 overheating criteria (57), however, were followed to ensure the robustness of the overheating risk assessment.

Five representative units, as shown in Figure 3, were purposively sampled for assessment: two two-bedroom apartments on the third floor (northeast and southwest orientations), one one-bedroom apartment on the third floor (south orientation), one one-bedroom apartment on the fourth floor (north orientation), and a staff office on the ground floor (north orientation). These units were selected due to their heightened exposure to potential overheating risks based on factors such as external orientation, roof exposure, and occupancy type (58,59). Within each unit, individual rooms, including kitchens, living rooms, bedrooms, and bathrooms, were modelled separately to accurately represent occupancy and usage patterns, following CIBSE TM59's zoning recommendations (57).

Figure 3 Selected units for thermal performance analysis

The baseline model, C0, was developed using project documentation for building geometry and specifications. The thermal comfort category I assumed for the analysis was suitable for spaces occupied by vulnerable populations requiring a higher standard of comfort (57,61). Some key input parameters for the baseline model (C0) are described in Table 2 below.

Input parameter	Value	Source
Weather file	Historic climate data	PROMETHEUS UKCP09 weather data (60)
External walls	U-value: 0.15 W/m²K	Project documentation
Internal walls	U-values: 0.46 W/m²K (load-bearing); 1.59 W/m²K (non-load bearing)	
Floors	U-value: 0.16 W/m²K (ground floor); 0.66 W/m²K (internal floor)	
Roof	U-value: 0.11 W/m²K	
Glazing	U-value: 1.50 W/m²K G-value: 0.47 Transmittance: 0.71	
MVHR	ON 24X7 + heat recovery	Project documentation
Mechanical ventilation rates	8 l/s for bathrooms; 11 l/s for bedrooms and lounges; 14 l/s for kitchens.	Project documentation
Infiltration rates	0.5 ac/h	Project documentation
Profiles: occupancy, lighting and equipment	As defined in section 5 and 6 of CIBSE TM 59: 2017	(57)

Table 2 Key input parameters for baseline model (C0)

Following the establishment of the baseline model, three additional design cases (C1-C3), as described in Table 3, were created to evaluate the impact of projected climate change on the building's thermal performance. Each case maintained the baseline parameters but altered the weather file to reflect future climate scenarios.

Category	ID	Test case description	Parameter altered
Baseline	C0	As described in 3.1.3	None
Climate scenarios	C1	Projected climate data for the 2030s under a high emissions scenario (50th percentile).	Weather file
	C2	Projected climate data for the 2050s under a high emissions scenario (50th percentile).	Weather file
	C3	Projected climate data for the 2080s under a high emissions scenario (50th percentile).	Weather file

Table 3 Description of test cases

Each case was analysed using CIBSE TM59's overheating criteria (Criterion a and b) to identify potential overheating risks (57). The results provide insights into the impact of climate change on the extra-care home's thermal environment, potentially informing recommendations for strategies to mitigate overheating risks.

4.0 Results

The time series and distribution of indoor and outdoor temperatures (Figure 4) reveal variability in thermal stability across monitored spaces. The Entrance Lobby exhibited the highest variability, with temperatures ranging from 18.4°C to 24.1°C (mean = 21.4°C, SD = 0.96), likely influenced by frequent door use and external air exchange. In contrast, the Manager's Cabin and Staff Room showed greater temperature stability, with mean values of 22.6°C (SD = 0.66) and 23.4°C (SD = 0.66), respectively, highlighting effective insulation and limited external influence. This stability is essential for maintaining occupant comfort, especially in care settings.

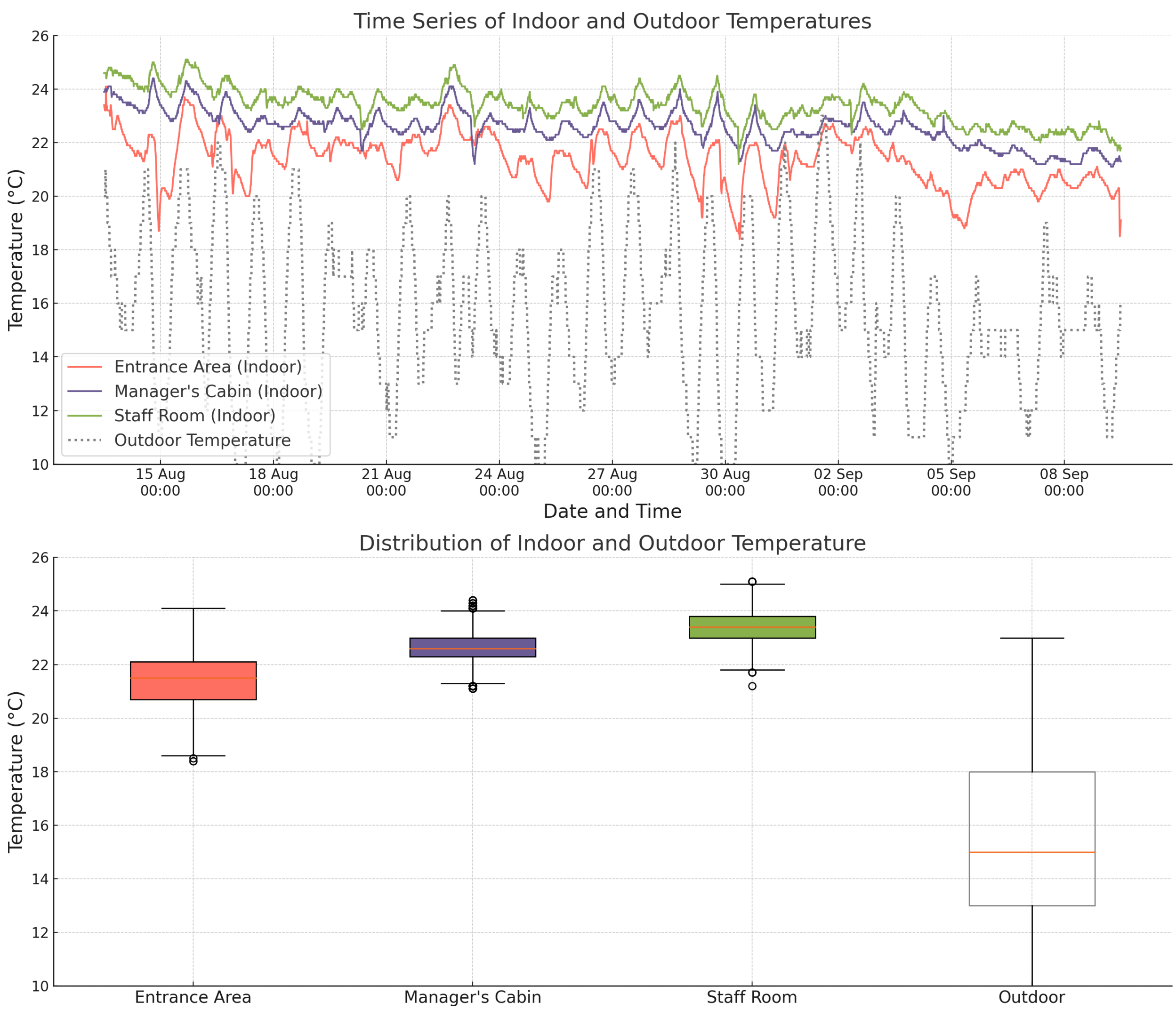

Figure 4 Monitored dry bulb temperature: time-series and distribution

The regression analysis (Figure 5) supports these observations, showing a moderate positive correlation between indoor and outdoor temperatures in the Entrance Lobby ($R^2 = 0.305$, $p < 0.001$), with a slope of 0.17. In comparison, the Manager's Cabin and Staff Room had lower slopes (0.057 and 0.049) and weaker correlations ($R^2 = 0.072$ and $R^2 = 0.053$, respectively), indicating that these spaces are better insulated from outdoor fluctuations.

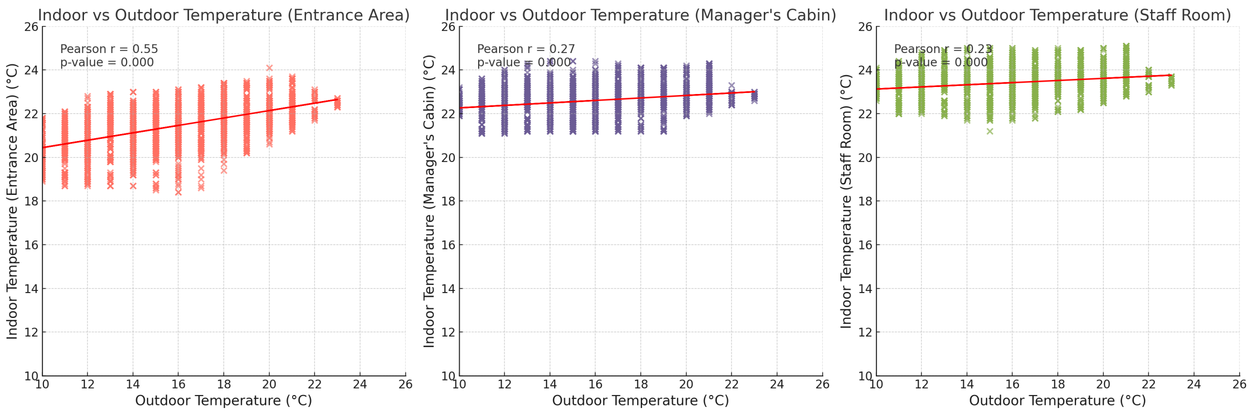

Figure 5 Regression analysis: dry bulb temperature (indoor v outdoor)

The RH levels in the three indoor spaces showed distinct patterns, as illustrated in the time series and distribution plots (Figure 6). The entrance area exhibited higher variability, with RH values ranging from 43% to 78%, likely due to frequent interaction with outdoor air through door openings. In contrast, the manager's cabin and staff room maintained lower and more stable RH levels, with ranges of 45%–75% and 43%–72%, respectively. The mean RH in the entrance area (60%) was higher than in the manager's cabin (57%) and the staff room (55%), but all indoor locations were significantly lower than the outdoor average RH of 79%.

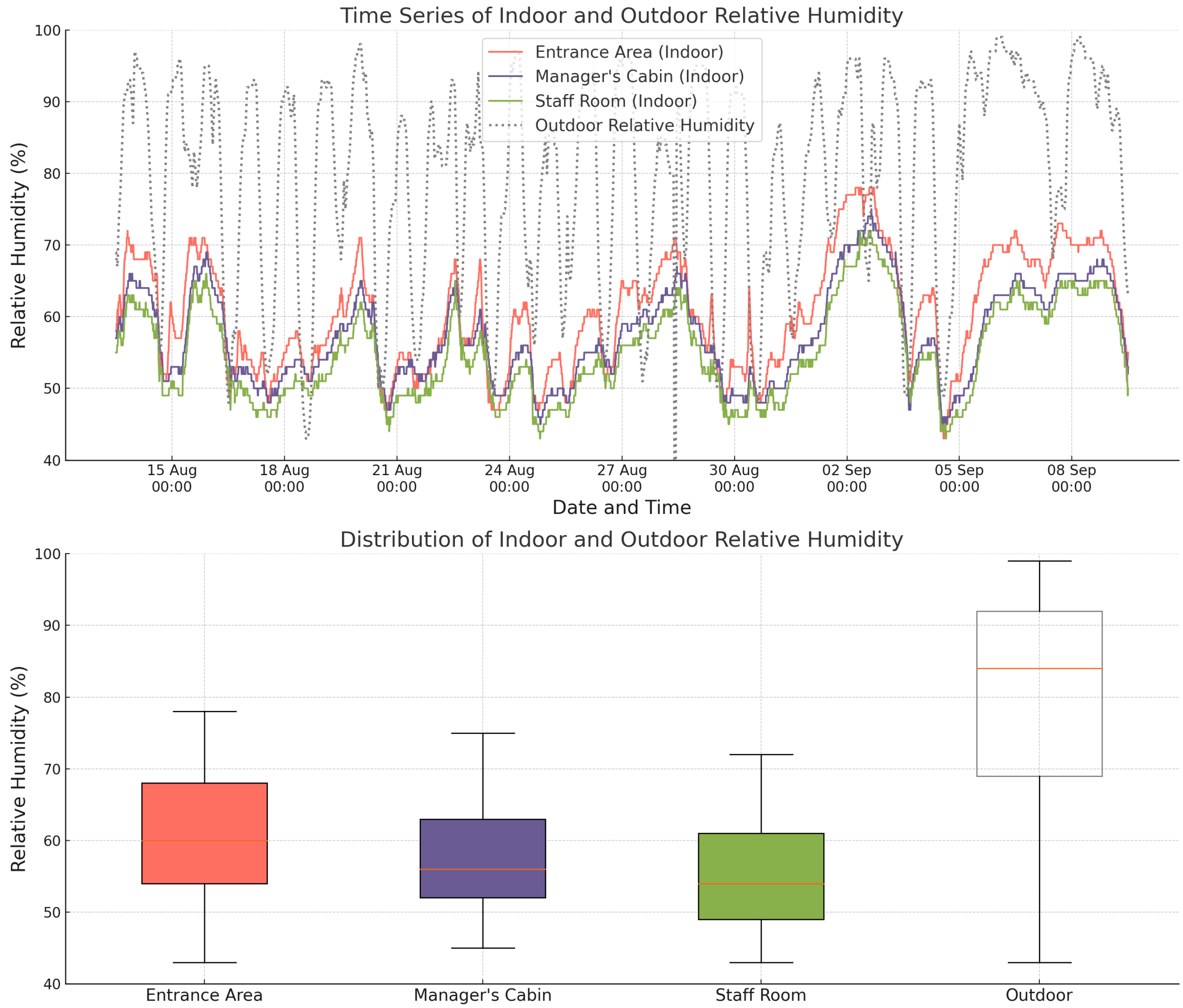

Figure 6 Monitored RH: time-series and distribution

The regression analysis (Figure 7) highlights the correlation between indoor and outdoor RH. The entrance area showed the strongest correlation with outdoor RH ($R^2 = 0.28$, $p < 0.001$), followed by the manager's cabin ($R^2 = 0.17$, $p < 0.001$) and the staff room ($R^2 = 0.16$, $p < 0.001$). These values suggest that while indoor RH in all three spaces is influenced by outdoor conditions, the entrance area, with its higher slope (0.28), is more susceptible to external RH variations, reflecting its greater exposure to outdoor air.

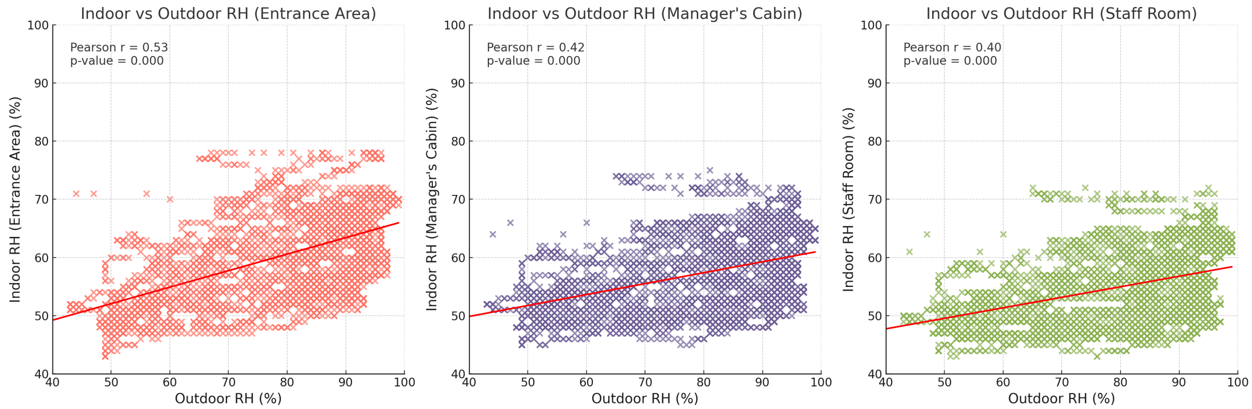

Figure 7 Regression analysis: RH (indoor v outdoor)

The CO_2 concentration levels across the monitored spaces are depicted in Figure 8. The entrance area maintained the lowest mean CO_2 concentration at 464 ppm, reflecting effective natural ventilation due to frequent door openings. In contrast, the manager's cabin showed the highest mean concentration at 611 ppm, with occasional peaks reaching up to 1,452 ppm, indicating a potential buildup of CO_2 and limitations of CO_2 management from ventilation alone. The staff room had a mean concentration of 576 ppm, with occasional spikes up to 1,175 ppm. The distribution analysis (Figure 8) further highlights that the manager's cabin has the highest variability, as indicated by the wider interquartile range and the presence of multiple outliers. The entrance area shows the narrowest distribution, confirming its stable and lower CO_2 levels due to continuous air exchange.

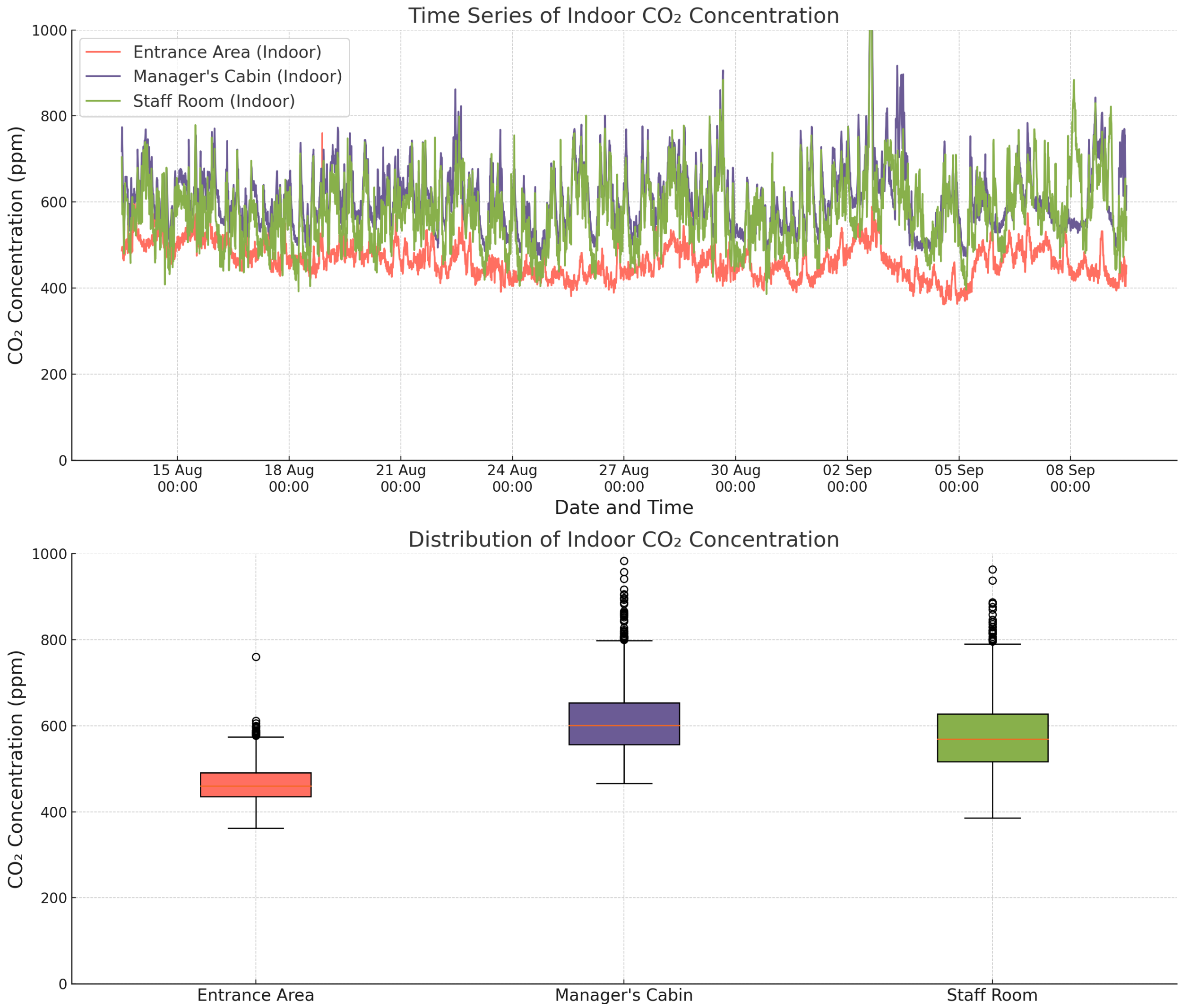

Figure 8 Monitored CO_2 concentrations: time-series and distribution

Dynamic thermal modelling assessed the indoor thermal environment of the case study building under four climate scenarios: historical baseline (C0), 2030s high emissions scenario-50%(C1), 2050s high emissions scenario-50% (C2), and 2080s high emissions scenario-50%(C3).

Median outdoor DBT increased by approximately 43% from 10.2°C (C0) to 14.6°C (C3), with the interquartile range (IQR) expanding from 8.1°C to 9.5°C. This indicates greater temperature variability and an increased prevalence of extreme conditions under future climate scenarios (see Figure 9).

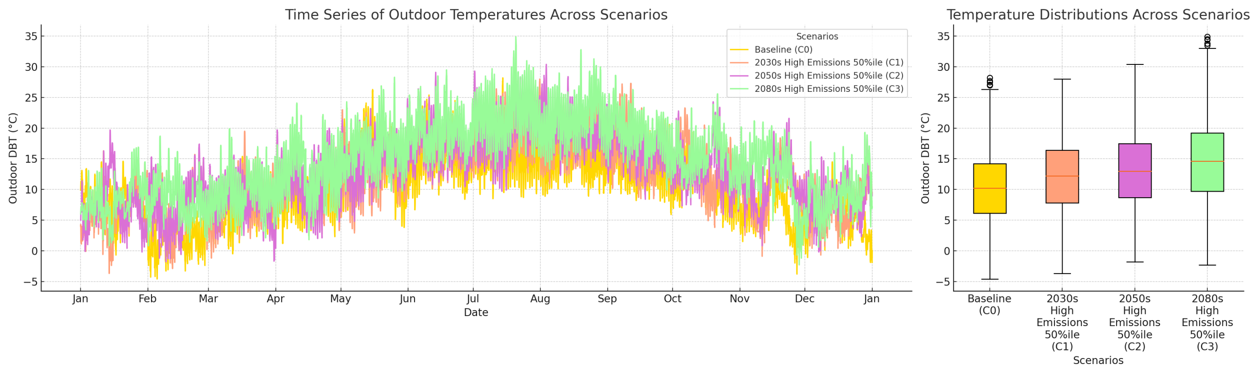

Figure 9 Outdoor DBT: time series and distribution

Heatwave analysis, defined as three or more consecutive days above 28°C, showed no heatwaves in the baseline scenario (C0). In contrast, under C3, 21 heatwaves were recorded, with the maximum duration reaching 11 days. This emphasises the growing risk of prolonged heatwave events in high-emissions scenarios (see Figure 10).

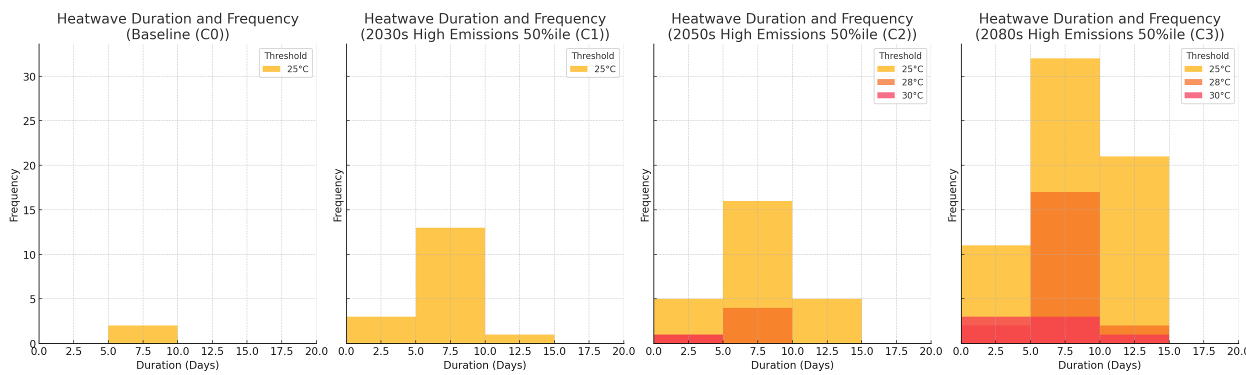

Figure 10 Heatwaves duration and frequency across climate scenarios

The first CIBSE overheating criterion limits occupied hours with operative temperatures exceeding the threshold by more than 1K to 3% during the non-heating season. In all scenarios, including the baseline (C0) and future climate scenarios (C1, C2, and C3), none of the assessed rooms exceeded the 3% threshold, indicating compliance with the criterion even under projected high emissions scenarios. This suggests that the building's current design offers resilience against overheating under future climate projections (see Figure 11).

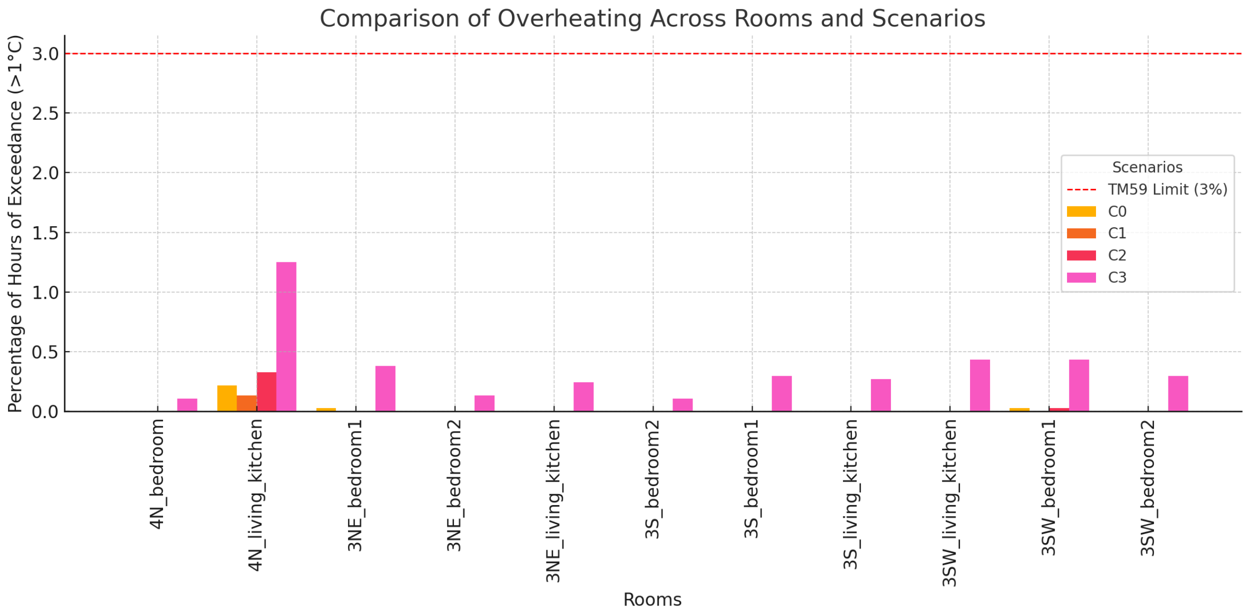

Figure 11 Comparison of overheating across rooms and scenarios

The cumulative distribution function (CDF) analysis in Figure 12 shows that 50% of exceedance hours occur by mid-July in C3, compared to August in C0, reflecting a substantial forward shift in overheating onset. The area under the CDF curve for C3 is significantly larger than for C0 ($p < 0.01$, Mann-Whitney U test), further confirming the heightened overheating risk.

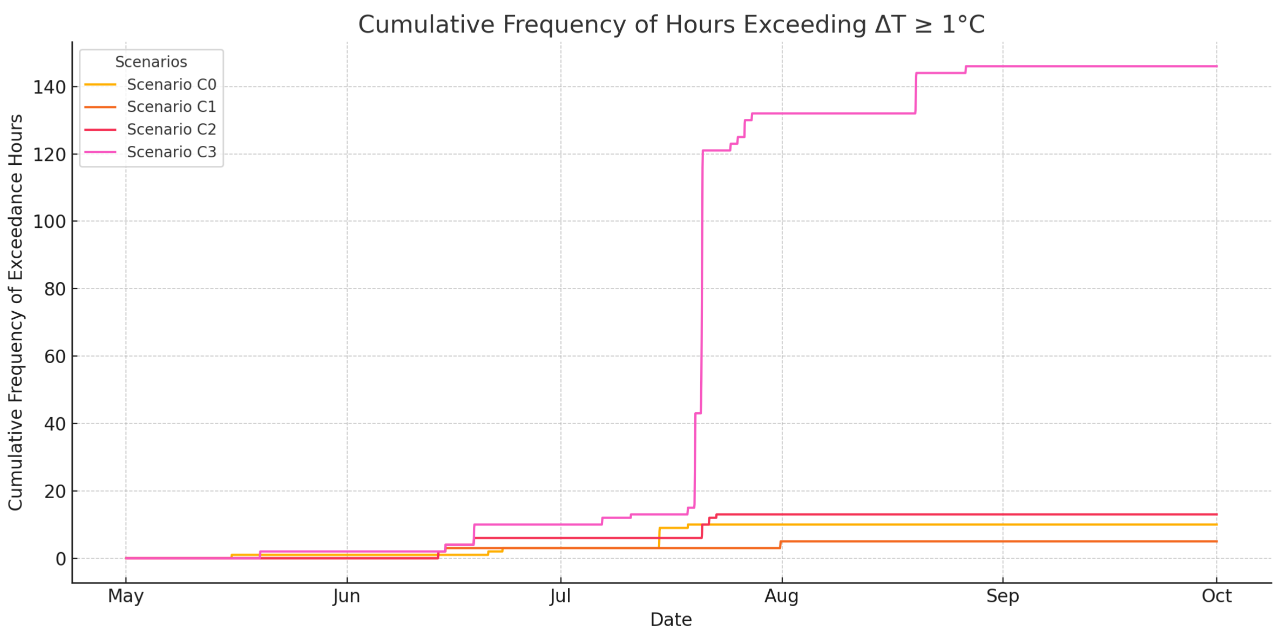

Figure 12 Cumulative frequency of hours of exceedance (He)

The second CIBSE criterion limits bedroom temperatures above 26°C during sleeping hours (22:00–07:00) to 1% annually (approximately 32 hours). In the baseline scenario (C0), bedrooms met this criterion with negligible exceedances. However, in the future climate scenario C3, exceedance hours significantly increased, with a mean of 15 hours across all bedrooms. None of the bedrooms exceeded the 32-hour threshold in any scenario, indicating resilience to overheating under the evaluated sleeping conditions (see Figure 13)

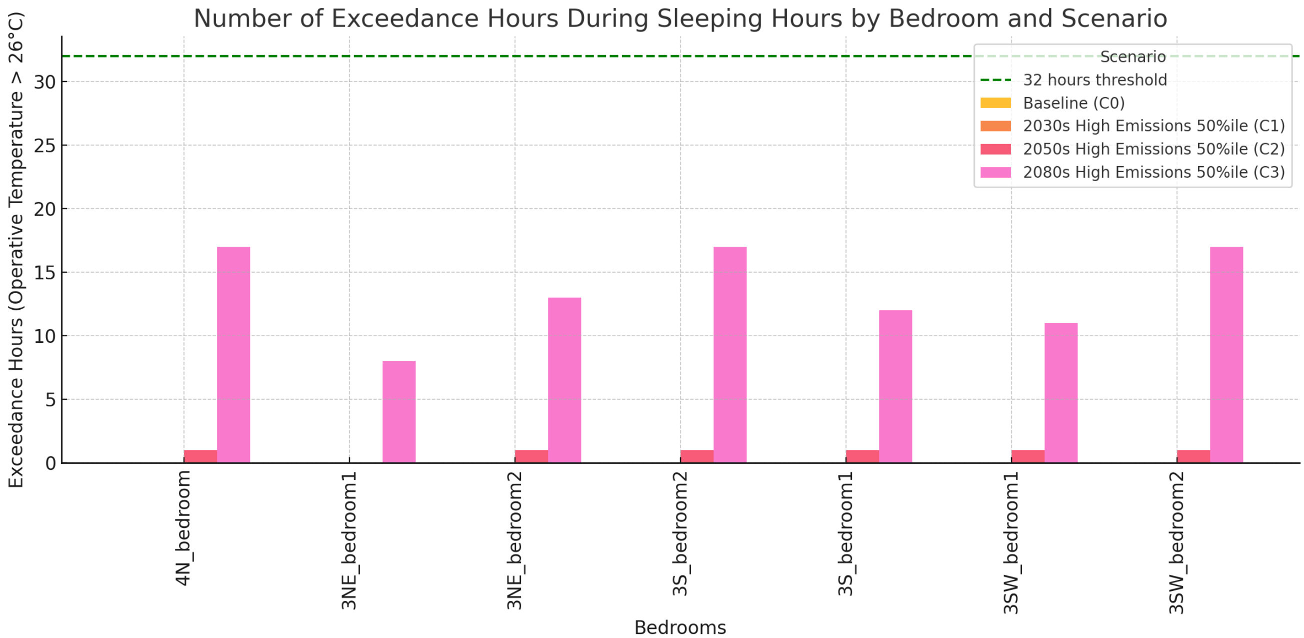

Figure 13 Number of nighttime exceedance hours across bedrooms

Regression analysis between indoor and outdoor temperatures indicated a strong correlation in the 2080s (C3), with a coefficient ranging from 0.41 to 0.47 ($p < 0.01$), suggesting that each 1°C rise in outdoor temperature corresponds to a 0.4°C increase indoors. Nighttime cooling effectiveness declined significantly across future climate scenarios, with the average nighttime temperature drop decreasing from 7.8°C in the baseline (C0) to 5.0°C in the 2080s (C3), reflecting reduced passive cooling potential. This trend highlights the growing challenge of maintaining indoor comfort under future warming conditions, where passive cooling alone may not suffice.

5.0 Discussion

This pilot study offers initial insights into the performance of a Passivhaus-certified extra care setting under current conditions, highlighting areas of potential resilience while identifying specific challenges, particularly under projected future climate scenarios. With its focus on environmental monitoring, dynamic thermal modelling, and stakeholder perspectives, this study adds to the existing literature on Passivhaus performance in vulnerable settings, though findings are necessarily tempered by the limited scope of the pilot, including only a one-month monitoring period during a cooler-than-typical summer and some ventilation commissioning issues.

Consistent with prior research on Passivhaus's performance, this study observed that enclosed spaces, such as the manager's cabin and staff room, exhibited stable indoor temperatures throughout the one-month monitoring period, indicating effective insulation and controlled indoor conditions (42,62). The entrance lobby, however, displayed greater variability, likely due to frequent door openings and the associated air exchange with cooler outdoor air, a phenomenon also noted by Ridley et al. (14) in high-traffic areas, highlighting an area where the Passivhaus standard may benefit from design modifications in similar communal settings to maintain consistent thermal conditions. Localised strategies, such as vestibules or air curtains, could be explored in future studies to mitigate these effects (18,63), and further research on occupant behaviours and usage patterns across seasons would clarify these preliminary observations.

CO_2 levels observed in the manager's cabin highlight potential ventilation limitations under certain conditions. However, without occupancy data, it is challenging to quantify the exact ventilation requirements and adequacy of airflow based solely on these measurements. Similar challenges have been observed in other Passivhaus studies, where CO_2 concentrations can sometimes exceed expectations in high-use rooms due to usage and occupant density (64). Given that some CO_2 patterns in this study may have been influenced by MVHR commissioning adjustments during the monitoring period, the study results underscore the need for further calibrated monitoring to fully understand the ventilation dynamics in high-occupancy areas. The entrance lobby's relatively low CO_2 concentrations, on the other hand, may reflect its large volume and continuous air exchange due to frequent door use. These observations align with Guerra-Santin & Tweed (15), who discuss the importance of spatial design and occupancy in understanding IAQ dynamics in Passivhaus buildings. Future research should incorporate more extensive monitoring, ideally with direct occupancy tracking, to refine the interpretation of ventilation efficacy across varying room types.

Dynamic thermal modelling across future climate scenarios indicates that, while the building meets comfort thresholds under current and near-term conditions, extreme cases, such as the 2080s high-emissions 50th percentile scenario (C3), reveal an increment in the hours of exceedance. This aligns with findings by Fletcher et al. (6) in Passivhaus residential settings, which also demonstrated performance challenges under intense heat conditions. Literature on passive cooling strategies (24,65) suggests that while night ventilation may help alleviate some overheating, future research should test additional adaptive measures, such as shading devices, as well as the adequacy and effectiveness of the designed cooling systems in future scenarios.

Interviews with the architects revealed that analyses of the case study building's design considered future climate resilience, incorporating provisions for retrofitting shading devices and cooling coils within the MVHR system if needed, reflecting an approach aligned with the adaptive design strategies in the literature (49). As noted by Santin et al. (15), flexibility in building systems, even within a Passivhaus framework, can be essential for meeting the changing demands of climate conditions.

5.1 Future research directions

While this study provides preliminary insights, a longer and more comprehensive monitoring period across varied seasonal conditions would strengthen the understanding of Passivhaus's performance in extra care settings. Additionally, testing passive cooling interventions, such as shading devices, alongside active cooling under high-emission climate scenarios would help build a more comprehensive understanding of the adaptive capacity of Passivhaus standards in extra care settings. Further, as updated climate datasets (e.g., UKCP18) become available, integrating these into thermal models will allow for refined, regionally accurate simulations that account for the latest climate predictions.

The current design, which includes future provisions for shading and MVHR cooling coil installations, demonstrates a proactive approach that aligns with the building's original design analysis for overheating risks. Further studies evaluating these adaptive features post-installation would provide practical insights for refining Passivhaus applications in extra care settings.

6.0 Conclusions

This study demonstrates that while the Passivhaus standard offers a robust foundation for stabilising indoor temperatures and air quality in extra care settings, its adaptability under extreme future climate conditions may require enhancements. By testing performance under projected climate scenarios, the findings indicate that, despite the building's stable conditions in enclosed spaces, communal and high-traffic areas experience temperature and CO_2 variability due to external air exchange and user interactions. The preliminary findings underscore the importance of integrating adaptive features to manage thermal comfort and IAQ effectively, especially as climate conditions become more intense.

This pilot study reveals that achieving climate resilience in Passivhaus extra care settings may involve both passive and active strategies. Existing provisions, such as the building's potential for future external shading and MVHR cooling upgrades, exemplify proactive planning, yet further investigation is needed to test the operational impact of these features. Enhanced occupancy-driven ventilation and individualised control options for residents may also address gaps between technical performance and occupant satisfaction.

Looking forward, this research suggests that Passivhaus buildings may benefit from incorporating adaptive cooling mechanisms tailored to occupant-specific needs in care and extra care settings. While Passivhaus principles provide a low-energy framework, the broader climate resilience of such buildings will rely on dynamic strategies capable of addressing the multifaceted needs of vulnerable populations. The implications for policy and practice extend beyond the pilot's immediate findings, recommending that future updates to Passivhaus and extra care facility standards prioritise adaptive features that anticipate long-term climatic shifts. By fostering environments that balance energy efficiency, comfort, and flexibility, these buildings can better support the well-being of their occupants in the face of a changing climate.

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