

Monitoring and modelling the risk of summertime overheating and passive solutions to avoid active cooling in London care homes

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ABSTRACT

Summertime overheating in care settings has been identified as a key risk and research priority for the health and social care system. This paper examines the current and future risk of summertime overheating in two London-based care homes occupying modern and older buildings. Continuous monitoring of outdoor and indoor temperature in bedrooms, communal areas and offices in summer 2019 helped to establish the prevalence and intensity of overheating. Dynamic thermal simulation (EnergyPlusV8.9) of the two care settings assessed the potential for avoiding active cooling in future climate using passive solutions. In both care settings, indoor temperatures were observed to exceed 30 °C during daytime hours, significantly higher than the recommended 26 °C threshold of Public Health England. Although severity of overheating was lower in the older building, overheating was found to be prevalent and prolonged across both care settings with bedroom temperatures higher than lounges especially at night. Thermal simulation analysis showed that, with regards to temperature reduction and cooling load, night-time ventilation was the single most effective passive solution for both buildings for the current climate, while a combination of night ventilation, external shading and high-albedo external walls was the most effective package solution. By the 2080s, air-conditioning was the most effective solution for reducing temperature, but also had the highest cooling load, highlighting the importance of balancing passive with active measures to improve thermal comfort and reduce cooling loads.

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1. Introduction

In 2019 about 9% of the world's population was over 65 years old. By 2050 this is projected to be 16% [51]. In the UK, 18.5% of the population was aged 65 and over in 2019 [49], placing it 24th in the world for countries with the largest populations of 65 + year olds [42]. The proportion of 85 + year olds in the UK is predicted to increase by 36% between 2015 and 2025 [11]. All of these predictions indicate that the UK care home population – 410,000 in 2017 [11] – will also increase significantly, with demand on state and privately funded care home services also increasing.

In parallel with the aging population, climate predictions indicate that temperatures will continue to rise. Significantly, this will mean an increase in the frequency and severity of heatwaves. Research has shown that heatwave periods coincide with increased levels of mortality, particularly within the elderly population [29]

and those in nursing and care homes [24]. Excessive heat has been linked to several medical conditions, in particular an increased risk of cardiovascular and respiratory disease, heat stroke and dehydration [41,2]. In turn, heat stroke can lead to cell, organ and brain damage, and dehydration to urinary tract infections (UTI's), blood-stream infections, and dizziness, increasing the risk of falls. All of these risks are exacerbated in the elderly. Sleep quality and duration can also be affected by high temperatures, with studies finding that at least half of over-65-year-olds experience difficulty in sleeping [35], and those with dementia can experience 40% of their bedtime hours awake [16].

In 2003, a ten-day heatwave in England and Wales resulted in a 33% increase in mortality in those aged 75 and over, and a 42% increase in mortality for those in nursing homes – compared to a 13.5% increase in mortality in the under-75's [29]. This increased vulnerability amongst the elderly population to the effects of excessive heat has been found in several studies from around the world [41,46,12,3]. By 2050, heat-related mortality could increase by more than 250%, with vulnerable groups such as the elderly

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being responsible for the majority of this [26]. With this in mind, the UK Government's 2017 Climate Change Risk Assessment report and the 2018 National Adaptation Programme identified summertime overheating in care homes as a key risk, and as a research priority for the health and social care setting [13,14].

Historically, given the temperate climate of the UK, a key focus in the design of care homes in the UK has been keeping residents warm. The buildings often have distinct features such as heated corridors – rarely found in dwellings other than those designed for the elderly [30]. Heating systems are routinely designed to operate all year round. Evidence of the 'keep the residents warm' mindset is also found in the inspection criteria of the Care Quality Commission – the independent regulator of all health and social services in England. Inspections include checking room temperatures and questioning staff on how they deal with residents feeling cold, but not on how they deal with residents feeling hot [39]. With this in-built historical bias, many care homes can find themselves ill-prepared to deal with high indoor temperatures caused by prolonged periods of high outdoor temperatures.

In this context, and with limited research on summertime performance of care homes in the UK, this study combined continuous environmental monitoring (indoor and outdoor temperatures) with dynamic thermal simulation to examine the current and future prevalence and severity of summertime overheating in two contrasting case study care homes occupying modern and older buildings. Dynamic thermal simulation (EnergyPlusV8.9) of the two care settings was used to explore the potential for avoiding active cooling in the future using passive solutions under current climate conditions and projected future climates.

2. Evidence to date

The relationship between high temperatures and an increase in mortality and morbidity has been established in many studies, particularly using data from 21st century national and international heatwave events, such as the Europe-wide heatwave of 2003. In the UK, over 2000 deaths were attributed to the 2003 heatwave in England and Wales, with excess mortality less than 14% in the under-75's and 33% in those age 75 and over [28]. In this age group, excess was greatest in nursing homes (a 42% increase) during the heatwave, compared to a 33% increase in deaths at home [29]. In response to this heatwave, public authorities have proposed action plans to better anticipate and coordinate the response to future heatwave events [46], including improving the performance of buildings and installing sustainable air-cooling systems. A further UK-based study by Hajat in 2007 found that elderly people, especially those in nursing and care homes were most vulnerable to heat mortality [24]. The study recommended specific interventions for people in nursing and care homes.

As well as high daily average temperatures, high nighttime temperatures have been linked to increases in mortality, particularly amongst the elderly. Looking at London-based data from 1993 to 2015, Murage found, compared to daytime exposure to high temperatures, nighttime exposure had a higher mortality risk on stroke, whereas respiratory mortality was most sensitive to daytime temperatures [38]. Hot days followed by hot nights had a greater mortality risk than hot days followed by cool nights. As in other studies, older adults were found to be most vulnerable to the effects of hot nights. A study in 10 care homes in south east England found that residents' bedtimes and getting-up times were often determined by the shift patterns of the staff: residents spending around 11 h in bed at night but sleeping for significantly less than this [34]: the most dependent residents were particularly affected by this, but even those who were more independent were found to shift their bedtimes to fit with the social norm in the homes. Many medications taken by elderly residents have side

effects which include insomnia, and sleep disorders related to breathing and periodic limb movement are known to increase with age, along with an advancement of the circadian rhythm which causes older people to awaken earlier in the morning [35]. High nighttime temperatures would therefore be exacerbating a problem which already exists in many of the residents.

Thermal perception has been shown to change with age: young children with high metabolic rates seemingly not feeling the cold, wearing shorts throughout the winter and shedding their coats when out on walks with their parents; older people with much slower metabolic rates keeping their heating on throughout the summer and wrapping up with cardigans even on the hottest of days. A review of studies investigating the thermal comfort, health and energetic properties of the elderly found that their perceptions of thermal comfort tended to differ from the common comfort indexes such as Predicted Mean Vote and Predicted Percentage of Dissatisfied [47]. This study focussed more on the need to provide the elderly with higher comfort temperatures during winter months, but the differing thermal perceptions of the elderly remains a concern during the hotter summer months.

Looking to the future based on climate and population predictions, heat-related mortality in the UK has been projected to rise by over 250% by the 2050's compared to a 2000-deaths baseline in 2014, with the elderly contributing to this most significantly [25]. This corroborates research by Gasparrini which predicted central and southern parts of Europe experiencing a sharp surge in heat related mortality from a 1990 baseline through to the end of the 21st Century [18].

A summary of key literature on the prevalence of overheating in care homes in the UK is shown in Table 1 which illustrates the risks to the elderly, particularly in the context of the anticipated increase in frequency, duration and intensity of heatwaves. A number of studies have focussed their attention on thermal comfort and heat vulnerability amongst care home residents using monitoring, modelling and interviews with staff and residents. An epidemiologically focused literature review concluded that indoor overheating in care homes arises from an interaction between occupants' susceptibility to heat, their behaviour and the building's location and characteristics [9]. The interrelation of these factors is expected to vary over time with demographic and climate changes. A recent study of a Passivhaus care home in the UK found that residents described themselves as thermally comfortable, whereas staff found themselves uncomfortably warm [48]. Furthermore, it was found that energy calculations in the design of the care home did not consider the typical behaviours and activities of the residents and staff, resulting in energy usage being much higher than predicted by the models.

Care home staff identified the design of care homes as creating challenges to keeping the indoor environment cool, including heating and cooling controls which were difficult to interact with [8]. Research into potential retrofit measures to help care settings cope better with high outdoor temperatures found a key challenge to be the fact that the buildings are in constant use and any works would be constrained by this fact [39]. Nevertheless, researchers have identified some measures which could help. Ground source heat pumps powering underfloor heating would facilitate the removal of radiators (often problematic due to their high temperatures and danger to residents) and provide more stable thermal environments at lower cost [39]. Air-conditioning has been suggested, but energy demand and cost of installation make this prohibitive [7]. Furthermore, whether residents would find the cool air-conditioned air acceptable is questionable. Instead, adaptive behaviours – changing clothing, adapting food and drink intake, opening windows – are seen as being both low tech and low cost, making them more feasible to implement.

Thermal simulation models have been used to investigate the effectiveness of different measures to mitigate against the effects

Table 1
Studies investigating overheating in care homes in the UK.

No	Study	Methods	Key findings
1	[7]	One residential care building (UK). Observation of care and conversations with residents and carers. Outdoor environment also monitored.	Understanding how heat vulnerability is constructed through everyday routines and practice helps identify alternative ways to manage heat.
2	[1]	Interviews with older people and their carers (not in care homes) (London, UK). Themes included perception of vulnerability in relation to heat-related risks, likely actions in extreme heat.	Some acknowledged that older people might be adversely affected by the heat, but they did not perceive themselves to be particularly vulnerable. Most reported making 'common sense' behaviour changes during previous heatwaves.
3	[8]	An ethnographic approach: observation and interviews to investigate heatwave vulnerability in 4 London care homes.	Vulnerability to heat in care homes is produced in a number of ways: (1) design of care homes makes them hard to keep cool; (2) staff/residents unable to interact with heating/cooling controls; (3) perception of cold as dangerous, shaping heat management and normalising excessively warm indoor temperatures; and (4) timetables introducing inflexibility, making adapting to the needs hot weather extremely difficult.
4	[34]	Diary data collected over 14 days from 125 residents in 10 care homes in South East England.	Residents spent nearly 11 h in bed at night, significantly more time than was spent sleeping. Bedtimes and getting-up times for dependent residents influenced by the staff's shift patterns. Staff's 12-hour night shifts promoted an overly long 'nighttime', curbing residents' choices about bedtimes and get up times.
5	[4]	Five focus groups conducted with residents in four extra-care schemes in England. One focus group with relatives of residents from a fifth scheme.	Independent living was compromised by building elements that did not take account of reduced physical ability. The buildings were too hot, too brightly lit and poorly ventilated.
6	[43]	Dynamic thermal simulation modelled the effect of passive heatwave mitigating interventions for UK dwellings.	Internal wall insulation was less effective and in some cases increased the overheating problem. Solar gains controlled through glazing, using shutters and fixed shading. Combinations of interventions can eliminate overheating and reduce space heating energy use.
7	[19]	One care home (UK). Summer environmental and energy monitoring in various locations. 14 interviews (staff, not residents) concerning staff and resident comfort and the operation of the building.	Most staff considered the building to be too warm and reported to be (thermally) uncomfortable most of the time.
8	[31]	13 interviews with those involved in the design, development and management of extra-care housing (UK).	Typical occupants characterised as vulnerable to cold, at risk from fuel poverty, being burned by hot surfaces or falling from high windows – ideas inscribed into the design of extra-care housing schemes.
9	[37]	Three case study social housing dwellings (London, UK) occupied by vulnerable individuals (elderly/ill health/mobility impairment). Environmental monitoring informed modelling for future climates.	Temperature monitoring showed overheating in the current climate. Modelling suggested that improved natural ventilation strategies could help to reduce overheating in future climates. Night cooling and shading more effective than all-day rapid ventilation.
10	[39]	Qualitative research in six case study homes, focused on management and staff perspectives and experiences. Explored potential of sustainable thermal technologies in care homes.	Despite potential benefits, infrastructure changes are limited as buildings are in constant use.
11	[50]	Five extra-care homes and six care homes (UK): Interviews investigated influence of thermal conditions on use of space, preferred thermal environments and spaces.	When conditions were not considered extreme, preferences for spaces were not usually determined by thermal conditions. However, thermal environment was often cited as an important factor in interviews.
12	[52]	Six care homes (UK): Interviews with care home owners, managers and staff.	Respondents saw care homes' core function to provide thermal comfort. Much more emphasis was placed on keeping residents warm than cool. Consequently, carers routinely overheated, particularly when doing more physical work.
13	[21]	Two care and two extra-care homes (UK). Dynamic thermal simulation. Interviews with design team.	Simulation results demonstrated the magnitude of projected summertime overheating in care settings, yet there was little awareness amongst designers about overheating risks and long-term adaptation approaches such as external shading or cross-ventilation.
14	[20]	Two care and two extra-care homes (UK). Temperature monitoring, building surveys, interviews with design and management teams.	Summertime overheating was prevalent, yet little awareness or preparedness existed to implement suitable adaptation strategies. Interviewees perceived cold to represent a bigger threat to occupants' health than excessive heat.
15	[48]	One Passivhaus care home (UK). Environmental and building energy monitoring, and thermal comfort survey.	Staff found the care home uncomfortably warm whereas residents were comfortable. Energy use was higher than expected due to design models which did not consider the in-practice activities of the care home.

of heatwaves. Interestingly, internal wall insulation was found to be less effective and in some cases increased the overheating problem. More effective measures in limiting solar gains included using shutters and fixed shading such as brise soleil [43]. Natural ventilation strategies and night-cooling strategies have also been found to help reduce overheating in models, but the effectiveness of these measures is diminished in projected future climate scenarios [37].

As the evidence from literature shows, historically, care homes have been designed and built with the aim of keeping residents comfortably warm all year round, with heating systems designed accordingly. Frontline carers and managers are trained to view cold as a danger: an effective strategy during the cold winter months, but when warmer weather arrives, many residents and staff become more vulnerable [22].

The research presented in this paper aims to deepen understanding about the prevalence and severity of overheating within newer

and older care home buildings in London. The environmental data is used to validate thermal simulations to investigate physical adaptations which could be made to care homes to mitigate against the risk of overheating in current and future climatic conditions.

3. Methods

The research methodology combined continuous monitoring of indoor and outdoor temperature with dynamic thermal simulation.

3.1. Environmental monitoring

Temperature was recorded using Hobo UX100, iButton and Hobo MX2301 data loggers (logging at 5-minute intervals), with device specifications provided in Table 2.

Table 2
Specification, accuracy and resolution of logging devices.

Purpose	Device	Measures and details	Specification		
			Range	Accuracy	Resolution
Continuous monitoring – 5-minute intervals	Hobo UX100	Indoor air temperature	–20 to + 70 °C	±0.21 °C	0.024 °C at 25 °C
	iButton DS1922L	Indoor air temperature	–40 to + 85 °C	±0.5 °C	0.0625 °C
	Hobo MX2301	Outdoor temperature	–40 to + 70 °C	±0.2 °C	0.04 °C

The loggers were distributed throughout the two care homes, with locations categorised as ‘offices’ (staff-only locations), ‘lounge/dining rooms’ (communal areas for residents and staff), and ‘bedrooms’ (Table 3). The nomenclature for locations in each home consists of care home i.d. (PA or VI) followed by room type (O = office, L = lounge, B = bedroom) and number, followed by floor (G, 1st, etc.) and orientation (N, S, E, W, int = internal). For monitoring purposes, occupied hours for these location types were defined as 09:00–18:00 for offices and 08:00–21:00 for lounges and dining rooms. Bedrooms were more difficult to define in terms of occupancy: some were occupied only at night for sleeping whereas others were occupied almost 24–7, either through personal preference or necessity due to the resident being bedbound. Bedrooms were therefore differentiated by day – 07:00–21:00 – when any occupants were more likely to be awake and conscious of their immediate environmental conditions, and night – 21:00–07:00 – when occupants were more likely to be asleep and therefore unable to make changes to their immediate environmental conditions. An outdoor logger was deployed in the garden of each of the two care homes to record localised outdoor temperature. These loggers were placed in shaded locations to protect them from precipitation and direct sunlight.

This form of temperature measurement is used because it is practically challenging to measure dry-bulb or mean radiant temperature in occupied buildings. In reality, the Hobo temperature

loggers are likely to be recording some (undefined) mix of air and radiant temperature with a component of surface temperature from conduction through the mounting surface [45]. Moreover, this set-up may actually record a temperature closer to that experienced by the occupants than pure dry bulb temperature [33]. Previous overheating monitoring studies using such wall-mounted sensors have previously delivered insights into overheating, such as the dwelling types most at risk [5,32], and building characteristics that can make dwellings more susceptible to overheating [36].

Overheating analysis was conducted on the recorded temperature data. Both static and dynamic (adaptive) metrics were used to identify the prevalence and concentration of overheating within the two case study buildings (Table 4). For static overheating from CIBSE Guide A, ‘living areas’ in the care homes covered lounges/dining rooms and offices (i.e. all spaces that were not bedrooms). Temperature thresholds were also considered from the Heatwave Plan for England [44]. The static method allows simple calculations to be performed when judging the overheating of a building as it is based on fixed maximum temperature thresholds.

The static method does not account for occupants’ ability to adapt to their environment – including external temperatures. Therefore, adaptive overheating criteria were also investigated. This method, developed by Humphreys and Nicol [40], is relevant to free-running buildings such as the two case study care homes. It should be noted that the adaptive method was developed from research into non-domestic buildings, and more research is needed to establish how applicable it is to hybrid buildings such as care homes. Furthermore, the ability of elderly residents, many with underlying health concerns, to adapt to their local environmental conditions may be reduced. The adaptive model derives threshold comfort temperatures on outdoor temperatures. However, the vast majority of residents spend most if not all of their time indoors. Outdoor temperatures may therefore have less influence on the comfort temperatures of the residents than it has on the staff who come and go from the building much more often. Nevertheless, adaptive overheating criteria have been considered, as defined by CIBSE Guide A, and overheating is deemed to have occurred if at least two of the three criteria are met (Table 4).

Overheating has also been considered using CIBSE TM59, which uses a combination of dynamic and static criteria. Criterion A is dynamic, the same as CIBSE TM52 Criterion 1: Hours of exceedance from May to September; criterion B is static, for nighttime hours – 10 pm to 7 am in bedrooms only, annually. In addition, TM59 states that for care homes, Type I occupancy (sedentary residents) should be assumed (as defined in CIBSE TM52). The case study care homes were not mechanically ventilated, but they did have restricted window openings, and therefore a third criterion, C, is applicable. If any of these criteria are failed, the space is deemed to be overheating. TM59 is intended for design and modelling of buildings using annual data rather than measured data from the limited period presented here (17th June to 31st August 2019). However, the percentage thresholds for annual occupied hours can be converted to actual hours. The analysis therefore considers these threshold number of hours. Although some locations may not have met the overheating criteria in the monitored period, it is not known whether they would have met the criteria had annual data been

Table 3
Location characteristics for data loggers.

Case study	Location type	Location code	Notes
PA	Office	PA01-G-S	Manager’s office.
	Lounge/dining room	PAL1-1st-S	High-ceilinged lounge with tall sash windows. High occupancy.
		PAL2-G-N	Lounge connected to main dining room. High occupancy.
		PAL3-G-S	Lounge next to main entrance. Low occupancy.
	Bedroom	PAB1-1st-S	Residents spent most of daytime in lounges.
		PAB2-2-S	
		PAB3-G-S	Bedbound resident – occupied 24–7.
		PAB4-2nd-E	Resident chose to spend most of daytime in chair in room.
		PAB5-2nd-S	Resident spent most of daytime in lounge.
	outdoor	PA-out	
VI	Office	VIO1-G-int	Finance manager’s office adjacent to reception desk and bistro. No natural light or ventilation.
	Lounge/dining room	VIL1-1st-NE	TV lounge with kitchenette and double doors leading to enclosed outdoor area
		VIL2-2nd-NE	TV lounge with kitchenette, directly above VIL1-1st-NE
	Bedroom	VIB1-1st-NE	Resident spent most of days in room, though not bedbound
		VIB2-4th-SW	Bedbound resident, but able to leave the room with assistance
		VI-out	
	outdoor		

Table 4
Metrics considered for overheating.

Metric	Overheating criterion	Definition
1	CIBSE Guide A: Static	No more than 1% of occupied hours over 28 °C in living areas. No more than 1% or more of occupied hours over 26 °C in bedrooms.
2	Public Health England	A cool room/area within the building to be available where temperatures are kept below 26 °C.
3	CIBSE TM52: Dynamic	Threshold comfort temperature: $T_{\text{threshold}} = 0.33 (T_{\text{acr}}) + 21.8$ °C (where T_{acr} is the running mean of outdoor temperatures)
	Criterion 1	Temperatures are at least 1 °C above the threshold comfort temperature for no more than 3% of occupied hours from May to September.
	Criterion 2	Daily weighted exceedance (W_e) < 6. $W_e = S(DT \times H_{DT})$ where DT is the temperature difference above $T_{\text{threshold}}$ and H_{DT} is the number of hours spent at DT
	Criterion 3	Maximum indoor temperature is no more than 4 °C above $T_{\text{threshold}}$.
4	CIBSE TM59 Criterion A	For living rooms and bedrooms, no more than 3% of occupied hours ≥ 1 °C above threshold temperature from May to September – equivalent to 42 h in offices, 60 h in lounges and dining rooms, 41 h in bedrooms (day) and 69 h in bedrooms (night).
	Criterion B	No more than 1% of overnight hours in bedrooms (10 pm–7am) over 26 °C annually – equivalent to 33 h.
	Criterion C	All occupied rooms greater than 26 °C for no more than 3% of annual occupied hours – equivalent to 99 h in offices, 143 h in lounges and dining rooms, 99 h in bedrooms (day) and 164 h in bedrooms (night).

available. The analysis provides indicative results for TM59 rather than definitive results.

3.2. Thermal simulation approach

Thermal simulation models of the two care home settings were developed using DesignBuilder V6 [15], a graphical user interface for the EnergyPlus V8.9 simulation engine [17]. Since a heatwave is considered to be a period with at least a three-day moving average of external temperatures above 21.5 °C [23], thermal analysis was conducted for a five-day heatwave period (22nd–26th July) for two weather scenarios:

- Current climate using 2019 weather files obtained from the nearest weather stations: London Weather Centre (WMO:37780) for VI and London Heathrow (WMO: 37720) for PA.
- Future climate using Design Summer Year 1 (DSY1) 2080's high emissions scenario weather data from CIBSE (UKCP09).

Inputs for the thermal simulation models were primarily based on site visits and observations, and on physical, technical and occupancy surveys conducted by the research team. Additional inputs, such as building age and construction characteristics, were derived from Reduced SAP (RdSAP) (DECC, 2017). The key baseline simulation inputs and their sources for both case studies are outlined in Table 5.

To ensure modelling robustness, temperatures from the baseline model (using 2019 actual weather data) from typical zones of each type (office, lounge and bedroom) were compared to the monitored data for the heatwave period (Fig. 1 and Fig. 2). The validation checks suggested that the modelled data was a close enough match to the monitored data that it could therefore be

Table 5
Inputs for thermal simulation models.

Input	Specifications
Occupancy	Bedrooms: 1 occupant; Schedule: All day (with diversity) Offices: 1 occupant; Schedule: 08:00–18:00 Lounges: up to 10 occupants: 09:00–22:00 (with diversity – max. in evenings) Source: site observations
Lighting and small power	Power density: 8–10 W/m ² Operation: linked to occupancy Source: site observations and RdSAP
Ventilation	Window openable area PA: 12.5% VI: 5% All zones are naturally ventilated by operable windows. Windows are open when the space is occupied and when indoor temperature exceeds 22 °C and is higher than the outdoor temperature. Source: site observations and CIBSE TM59
Construction	Source: design documents and RdSAP

used to assess the future risk of overheating and the potential for reductions through passive building adaptation strategies.

Both monitored and modelled average temperatures were close to or exceeded the 26 °C threshold. Temperature values and trends between the two datasets were closely aligned, while temperature differences were within an acceptable 2 °C range [27]. A higher deviation was observed in the bedrooms of both care homes, where differences could be attributed to the uncertainty of night-time window operation assumption (for the particular bedroom) specified in the thermal models. Since daytime peak temperatures were closely matched, and the objective was to analyse overheating risks, further fitting of the models was not deemed necessary.

Baseline models were then used to assess future overheating risk and to run a set of simulation scenarios in order to evaluate the potential reduction of overheating in current (2019) and future (2080) climates through the use of passive and active strategies (Table 6). These strategies can also be defined as 'hard' (structural) and 'soft' (behavioural) adaptations, the former being inherently more expensive and fixed regardless of the future climate scenario experienced, the latter being relatively low cost and flexible, possible to implement relatively quickly and adapt depending on the climatic circumstances [10]. Baseline scenario S1 used only window operation as a means of thermal regulation. Scenario S2 considered the use of air-conditioning (AC) in the care homes, used around the clock. Scenarios S3, S4 and S5 used different passive design strategies – night ventilation, shading and reflective surfaces – in conjunction with AC. The final scenario (S6) assessed the cumulative effect of each of the passive strategies. For these simulations (depending on simulation specifications) two results were calculated:

1. Area-weighted hourly average internal temperatures for different zone types over the 5-day heatwave period, and
2. Area-weighted hourly peak cooling loads for each care home over the 5-day heatwave period.

4. Overview of the case study care homes

The location of the care homes is shown in Fig. 3 with Table 7 providing key characteristics of the two homes. Both homes were privately owned and operated. Case study PA was one of 12 care homes in the southwest of England managed by a company operating since 2006. The original building was constructed during the

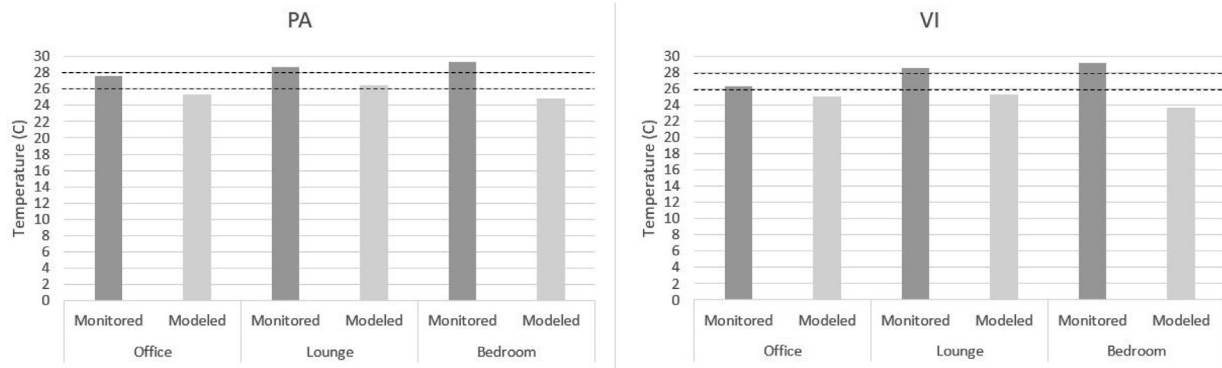


Fig. 1. Monitored vs modelled average temperatures for office, lounge and bedroom during the 5-day heatwave period.

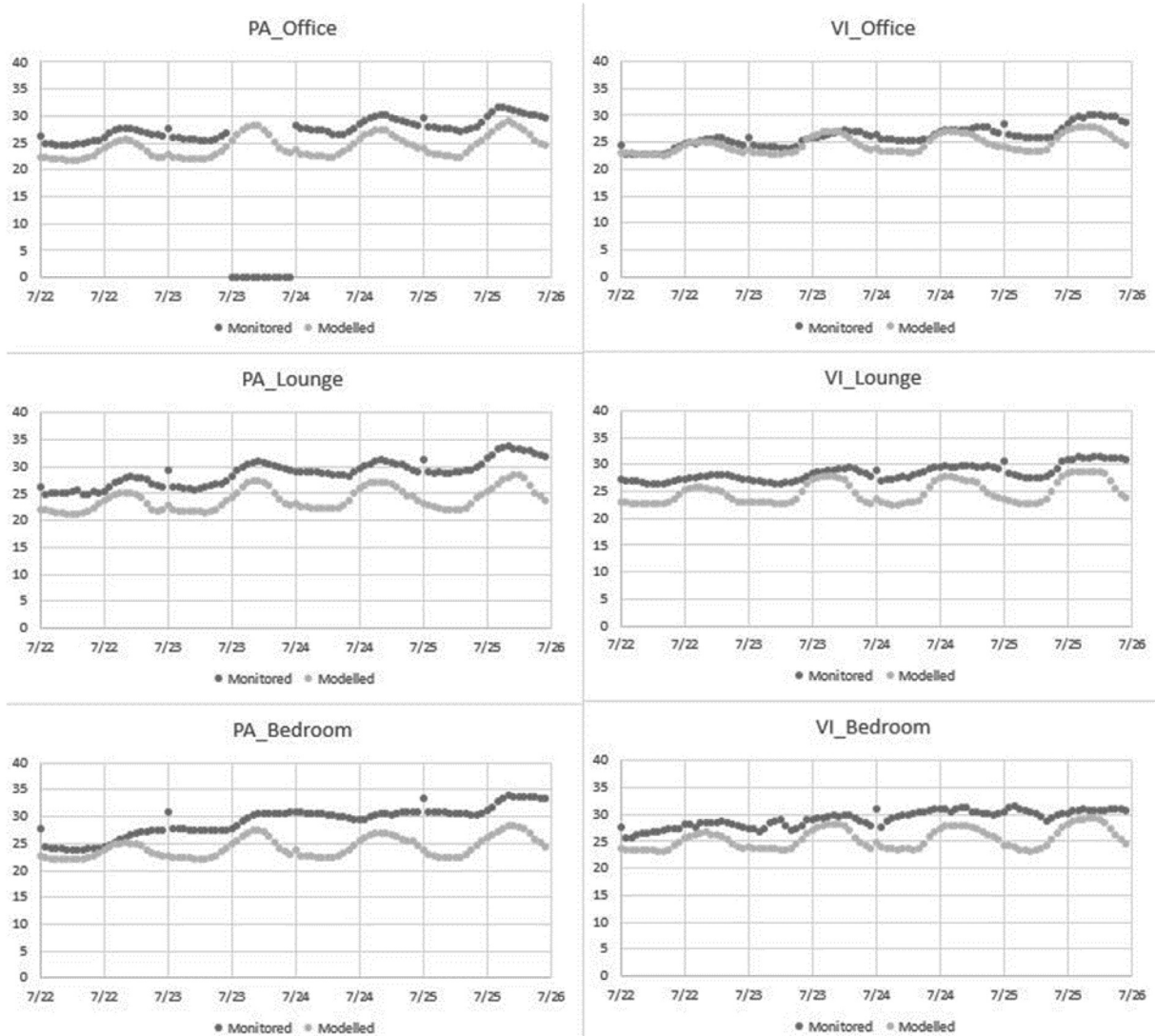


Fig. 2. Monitored vs. modelled temperatures for office, lounge and bedroom during the five-day heatwave period.

Georgian period (1714–1830), and has been added to over the years, serving as a private residence until the 1980's when it was sold and converted into a nursing care home. The building has a south-facing front and entrance, with the majority of residents' rooms also south-facing, and only around ten north facing. At the front of the home, bordering the small visitor/staff car park is a

grassed garden area with a pagoda and shade provided by large trees. The home is surrounded by residential dwellings.

Case study VI, located in west-central London, was purpose-built in 2013 as the first and only care home managed by a company operating since the same year. It is a large, five-storey building situated next to a hospital and near a large supermarket in a

Table 6
Building adaptation scenarios for thermal simulations based on passive strategies.

ID	Category	Adaptation	Specifications
S1	Baseline	–	
S2	AC	Hard	AC: open during day (07:00–21:00) and night (21:00–07:00)
S3	AC combined with ventilation	Hard/soft	AC: open during day Ventilation: windows open during night
S4	AC combined with shading	Hard/hard	AC: open during day Shading: window louvres/side fins (0.5 m projection)
S5	AC combined with reflective surfaces	Hard/hard	AC: open during day. Reflective surfaces: high wall albedo
S6	AC combined with ventilation, shading and reflective surfaces	Hard/soft/hard	AC: open during day Ventilation: windows open during night Shading: window louvres/side fins (0.5 m projection) Reflective surfaces: high wall albedo

semi-industrial area. The building's main entrance is to the south-east. The ground floor is home to staff offices, a bistro, a hair salon, cinema, plant room, kitchen and staff rooms. Residents' rooms on the 1st to 4th floors are located either side of corridors which run three sides of a square. From the main stairwell and lift in the southern corner, corridors run to the north-east and north-west, and from the end of the north-west corridor, turning right to another north-east corridor. Lounges and dining rooms are located on each floor. On the first floor, an outdoor 'garden' area is boxed in on 3 sides by bedrooms and lounges, and on the fourth side to the north-east by a high wall.

Both homes catered for a variety of residents, many of whom were suffering from a range of dementia-related issues. Care home VI was a significantly larger care home than PA. Around two-thirds of the bedrooms in PA were south-facing, the rest north or east-facing. Case study VI was at an approximately 45° angle to south, with rooms orientated in all possible directions from this: north-east, north-west, south-east, south-west.

5. Results

Guided by the definitions used for overheating analysis in CIBSE Guide A, TM52 and TM59, occupied hours were defined as 09:00–18:00 in the offices and 08:00–21:00 in the lounges. Bedroom occupancy was more difficult to categorise as it varied so much. Some bedrooms were occupied 24–7, either because the resident was bedbound or because they preferred to stay in their room. Other bedrooms were only occupied for sleeping, with the residents spending their waking hours in the lounges and dining rooms. Environmental analysis for bedrooms was therefore cate-

gorised by day – 07:00–21:00, when any occupants were more likely to be awake and conscious of their immediate environmental conditions, and night – 21:00–07:00, when occupants were more likely to be asleep and unable to change their immediate environmental conditions.

5.1. Indoor and outdoor temperature in case study care homes

Monitored outdoor temperatures were observed to reach as high as 35.1 °C (PA) and 38.0 °C (VI) during the hottest days of the summer. In PA, indoor temperatures reached as high as 34.7 °C in PAB2-2nd-S and 33.8 °C in PAL1-1st-S. Within the monitored spaces, temperatures were in the 24–28 °C range for the majority of the time (interquartile range for all rooms, all hours was 24.8–27.0 °C). In no monitored space did the temperature fall below 20 °C (Fig. 4 and Table 8), even during unoccupied hours. Peaks in outdoor temperatures corresponded to peaks in indoor temperatures, particularly around 23rd–27th July 2019 and 24th–29th August 2019 when outdoor temperatures were high during the day and remained relatively high overnight, preventing the building from cooling significantly during 'unoccupied' hours. It is particularly notable that in three of the five monitored bedrooms, mean and median temperatures at night were higher than during the day, and in one room they were the same. Only one of the five bedrooms was cooler at night (PAB3-G-S), and that was only by 0.1 °C. This suggests that the bedrooms did not make use of nighttime cooling strategies such as opening windows, or if they did, these strategies were mitigated by other factors such as residents radiating heat and devices such as televisions or fans generating heat.



Fig. 3. Location of the two case study care homes.

Table 7
Key characteristics of case study care homes.

	Care home PA	Care home VI
Location	Suburban	Urban
Ownership	Privately company	Private company
Type of facility	Residential care home	Residential care home
Care provided	Includes dementia, mental health condition, old age, physical disability, sensory impairment	Includes nursing, dementia, learning disabilities, mental health, sensory impairments, disease/injury
Age of occupants	65+	Mainly 65+, with some 18 + residents with acute needs.
CQC rating	Good	Good
Occupancy/max capacity	36/44	115/115
Gross internal area (m ²)	1195	3196
Year constructed/converted		18th century (manor house) – converted to care home in 1980's.
2013 (purpose-built).		
No. of storeys/no. of rooms	3 storeys, 40 rooms	5 storeys, 110 rooms
Typology and construction	Converted, 3-storey, partly pitched/partly flat roof, brick built	Purpose built, 5-storey modern building, flat roof, block and beam built
Ventilation and/or cooling scheme	Natural ventilation	Natural ventilation
Single or multi-aspect bedrooms	Single	Single
Approximate U-values (based on age)	Wall: 2.15 Ground Floor: 1.5 Roof: 2.0	Wall: 0.35 Ground Floor: 0.25 Roof: 0.20
Exceptional design standards or certification	Listed building (Grade II)	N/A

By comparison, monitored indoor temperatures in VI only reached as high as 32.5 °C in bedroom VIB2-4th-SW and 31.2 °C in lounge VIL2-2nd-NE (more than 2 °C lower than the peak temperatures in PA). Temperatures in the monitored spaces remained in the 24–29 °C range for the majority of the time, with an overall interquartile range of 25.3–27.7 °C for all monitored spaces during the entire monitored period. Indoor temperatures did not fall below 21 °C in any of the monitored spaces, even overnight.

The distribution of indoor temperatures in monitored locations are given in Fig. 5, with the office and lounges showing results for occupied hours and bedrooms showing both day and night results. Of PA's three lounges, PAL1-1st-S stands out as being the warmest by far – median temperature at more than 2 °C warmer than the other two lounges. Its large south-facing sash windows allowed great solar gains, and it did not have PAL2-G-N's benefit of being north facing nor PAL3-G-S's benefits of shading from trees and being next to the main entrance, allowing significantly more cross-ventilation. Bedroom PAB3-G-S stands out from the other bedrooms as having significantly lower median temperatures, day and night, and a lower and narrow IQR. This room also benefited from being on the ground floor, and had shade from nearby trees from the early afternoon into the evening.

In VI, the office VIO1-G-int stood out as having a much lower distribution of temperatures compared to the other monitored locations, with 87% of readings during working hours being between 22 and 26 °C. As with the bedrooms in PA, the day and night temperature distributions in were very similar, but with nighttime temperatures being slightly higher than those during the day.

Plots of the average diurnal temperature profiles for each location type (Fig. 6) showed that in both care homes, the office and lounge temperatures rose during the day and fell overnight in response to the rising and falling of outdoor temperatures. Office and lounge lines ran almost parallel with lounges an average of 0.9 °C warmer in PA and 2.3 °C warmer in VI. Bedroom temperatures in both care homes followed a different trend, changing much less throughout the day and remaining high overnight.

5.2. Current risk of overheating

Overheating analysis using the static criteria revealed that all of the monitored locations within both care homes exceeded the 28 °C or 26 °C thresholds for at least 1% of occupied hours (Fig. 7 and Table 9). In PA, lounge PAL1-1st-S, with the disadvantage of being on the 1st floor and south facing, was over 28 °C for 18.5% of occupied hours, compared to only 1.6% of occupied hours in the north-facing ground floor lounge PAL2-G-N. Internal ground floor office VIO1-G-int came closest to passing this threshold, exceeding 28 °C for only 1.5% of occupied hours. Of the communal areas, VIL2-2nd-NE exceeded 28 °C for the longest – 29.1% of occupied hours, despite having the same north-east orientation as VIL1-1st-NE, directly below. Although being on a lower floor may have helped, VIL1-1st-NE's main advantage was having two pairs of doors which opened out onto the first floor 'garden' area, allowing significantly more cross-ventilation – when the residents did not complain of the 'draught' and ask for the doors to be closed.

All of the monitored bedrooms failed the static criteria. Three of PA's five monitored bedrooms (PAB2-2nd-S, PAB4-2nd-E and PAB5-2nd-S) exceeded the 26 °C threshold for more than 50% of the monitored hours. Notably, these three bedrooms were all on the 2nd (top) floor. Both VI's monitored bedrooms failed the static overheating criteria with significantly more day and night hours over 26 °C than any of the monitored PA bedrooms. Bedroom VIB2-4th-SW spent almost 90% of day and night hours above 26 °C, the higher floor and orientation both being a disadvantage when trying to prevent high temperatures.

Public Health England's threshold temperature of 26 °C was exceeded for 70.1% of hours in lounge PAL1-1st-S (Table 10). VI's two lounges exceeded 26 °C for 69–88% of occupied hours. The two locations which exceeded 26 °C the least were the two ground floor lounges PAL2-G-N and PAL3-G-S. (Note: this temperature threshold was the same as CIBSE Guide A's for bedrooms).

Dynamic overheating metric CIBSE TM52 had threshold comfort temperatures (T_{acr}) which varied according to the rolling mean of daily average outdoor temperatures. Consequently, following warmer periods of weather T_{acr} tended to be higher, but was generally within the 26–28 °C range. With regards to TM52's first criterion – failed if at least 3% of occupied hours are at least 1 °C above T_{acr} – all monitored space except VIO1-G-int failed (Fig. 8 and Table 11). Bedroom PAB3-G-S failed this criterion for slightly less than 3% of nighttime hours, but for 7.6% of daytime hours.

In the bedrooms, an interesting dichotomy appeared between daytime and night-time overheating according to this criterion 1: Five of the seven monitored bedrooms failed for a higher proportion of nighttime hours than daytime hours. This concurs with the monitored temperature profiles, which saw the same five bedrooms experience slightly higher temperatures overnight than during the day. The bedroom which failed criterion 1 the least (i.e. spent the fewest amount of time at least 1 °C above T_{acr}) was PAB3-G-S, which received a good deal of shading from outside during the day and kept the window open at night.

Dynamic criterion 2 – daily weighted exceedance greater than 6 – was failed in all fourteen monitored spaces (Table 12). The worst offenders were the lounges PAL1-1st-S (38 days) and VIL2-2nd-NE

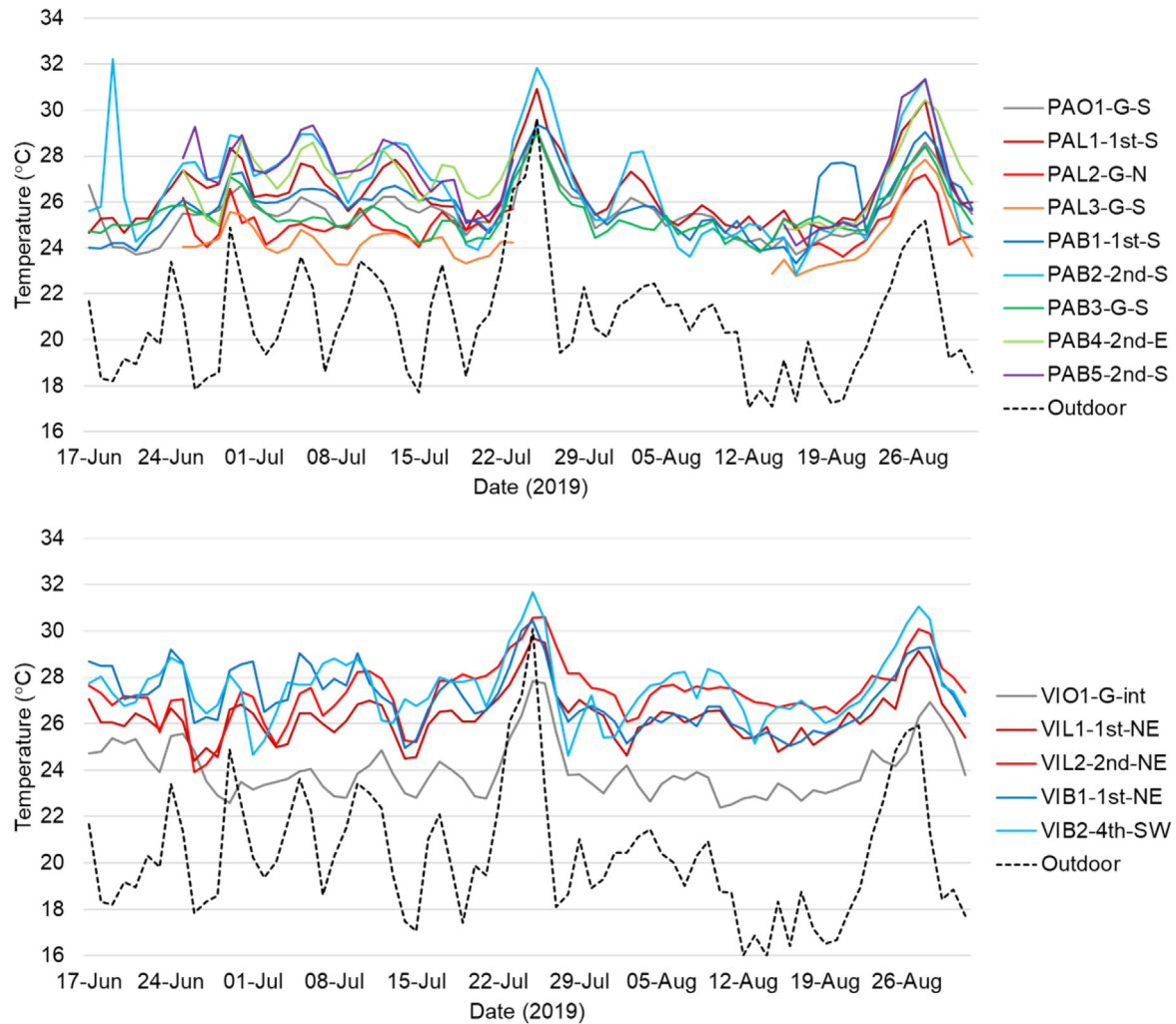


Fig. 4. Monitored temperatures (daily averages) for case studies PA (top) and VI (bottom): office and lounge averages for occupied hours, bedroom averages covering day and night.

Table 8
Descriptive statistics for monitored locations in PA and VI.

Care home	Location type	Room	Hours	N	Mean (°C)	Median (°C)	Min (°C)	Max (°C)
PA	Office Lounges	PAO1-G-S	Occupied	8098	25.9	25.8	21.8	31.9
		PAL1-1st-S		11,808	26.9	26.8	22.5	33.8
		PAL2-G-N		3534	25.0	24.8	23.1	28.5
		PAL3-G-S		3534	24.8	24.5	22.2	30.1
	Bedroom	PAB1-1st-S	Day	13,620	25.9	25.8	22.4	30.7
			Night	8124	26.0	26.0	23.2	30.2
		PAB2-2nd-S	Day	13,620	26.5	26.5	20.4	34.7
			Night	8124	27.0	27.0	22.5	33.4
		PAB3-G-S	Day	13,620	25.5	25.3	21.8	32.1
			Night	8124	25.4	25.2	23.0	29.9
		PAB4-2nd-E	Day	4084	27.0	27.1	24.2	31.2
			Night	2455	27.0	27.1	24.3	31.1
		PAB5-2nd-S	Day	4083	27.0	27.1	21.3	33.7
			Night	2457	27.5	27.5	23.4	32.1
			All	21,744	20.9	20.6	11.8	35.1
	Outdoor							
VI	Office Lounge	VIO1-G-int	Occupied	8208	24.2	24	21.7	30.2
		VIL1-1st-NE		11,856	26.5	26.5	23.0	31.4
		VIL2-2nd-NE		11,856	27.5	27.6	22.3	32.1
	Bedrooms	VIB1-1st-NE	Day	13,679	27.0	26.8	20.6	31.2
			Night	8208	27.2	26.9	23.0	31.5
		VIB2-4th-SW	Day	13,680	27.5	27.3	22.8	32.5
			Night	8208	27.5	27.4	23.2	32.4
			All	14,493	20.1	19.4	11.4	38.0
	Outdoor							

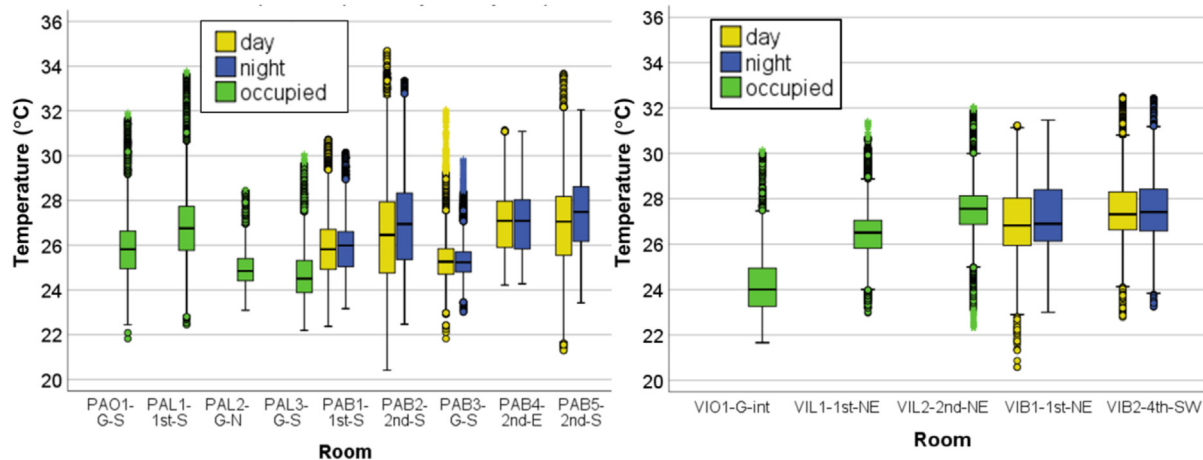


Fig. 5. Boxplot showing distribution of temperatures in selected PA (left) and VI (right) locations.

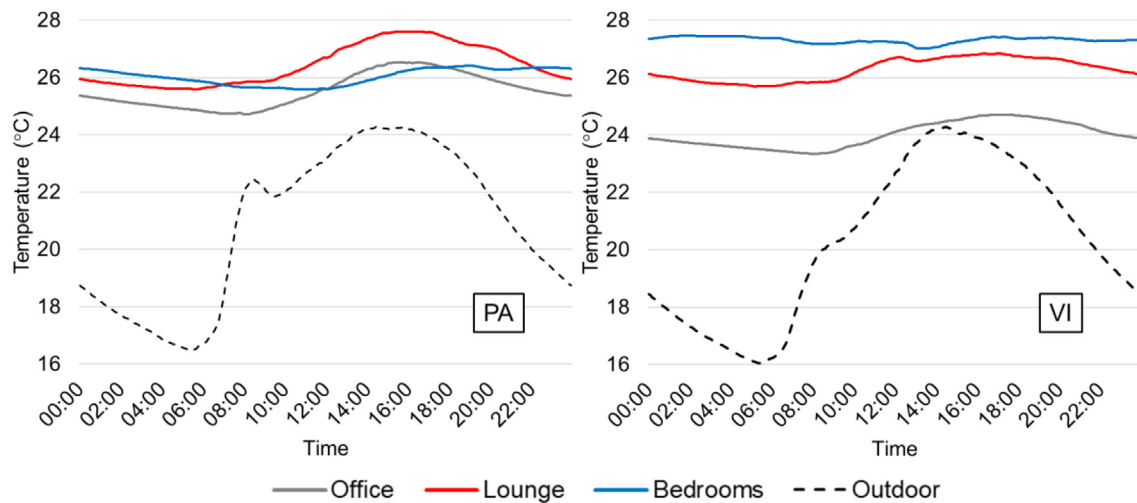


Fig. 6. Average diurnal temperature profiles for PA (left) and VI (right), grouped by offices (PAO1-G-S and VIO1-G-int), lounges (PAL1-1st-S and VIL1-1st-NE), and bedrooms (averages of PAB1-1st-S, PAB2-2nd-S and PAB3-G-S, and of VIB1-1st-NE and VIB2-4th-SW).

(58 days), and the bedrooms PAB2-2nd-S (30 days), VIB1-1st-NE (48 days) and VIB2-4th-SW (59 days).

The third criterion for dynamic overheating was met in ten monitored spaces. Ground floor office VIO1-G-int and ground floor lounges PAL2-G-N and PAL3-G-S did not fail this criterion. The only bedroom not to fail was PAB1-1st-S. Monitored second-floor bedrooms in PA exceeded T_{ac} by 6.5 °C and 7.4 °C, more than any other monitored location other than PA's first floor lounge PAL1-1st-S (6.6 °C).

In summary, thirteen of the fourteen monitored spaces fail at least two of the three TM52 criteria. The only space not to fail was ground floor internal office VIO1-G-int (Table 13). Ground floor spaces were less likely to fail criterion 3 than spaces on other floors.

The fourth overheating metric, TM59, combined static (fixed threshold temperature) criteria and dynamic (variable) overheating criteria. Criterion A, as with CIBSE TM52's Criterion 1, was failed office PAO1-G-S and lounges PAL1-1st-S, VIL1-1st-NE and VIL2-2nd-NE. All monitored bedrooms failed during daytime hours, PAB3-G-S the only bedroom to not fail during nighttime hours (Table 14). Criterion B, only applicable to bedrooms at night, was failed by all bedrooms, being over 26 °C for between 124 and 588 of the monitored 675 night-time

hours – the maximum allowed being 33 h. Criterion C's fixed-temperature threshold of 26 °C exceeded for at least 3% of occupied hours in all but three locations – lounges PAL2-G-N and PAL3-G-S and office VIO1-G-int. Although bedroom PAB3-G-S had fewer than 164 night-time hours over 26 °C, during the day it had nearly 229 h over 26 °C, far more than the maximum 99 h allowed. Compared to the lounges and bedrooms of PA, those in VI failed criterion C for many more hours during the monitored period. Since a location had to fail only one criterion to fail the whole metric, eleven of the monitored spaces failed TM59. Those which passed were office VIO1-G-int and lounges PAL2-G-N and PAL2-G-S – notably all ground floor locations.

A summary of the four overheating metrics shows that all monitored locations failed at least two of the four (Table 15). All seven monitored bedrooms failed all four metrics. The two fixed-temperature threshold metrics, CIBSE Guide A and PHE, found overheating in all monitored locations. CIBSE TM59 allowed more locations to pass than any other metric, but with the caveat that its thresholds to fail were based on a full non-heating season or year whereas monitoring data were only available for 76 days and were more data available, these locations may not have fared so well.

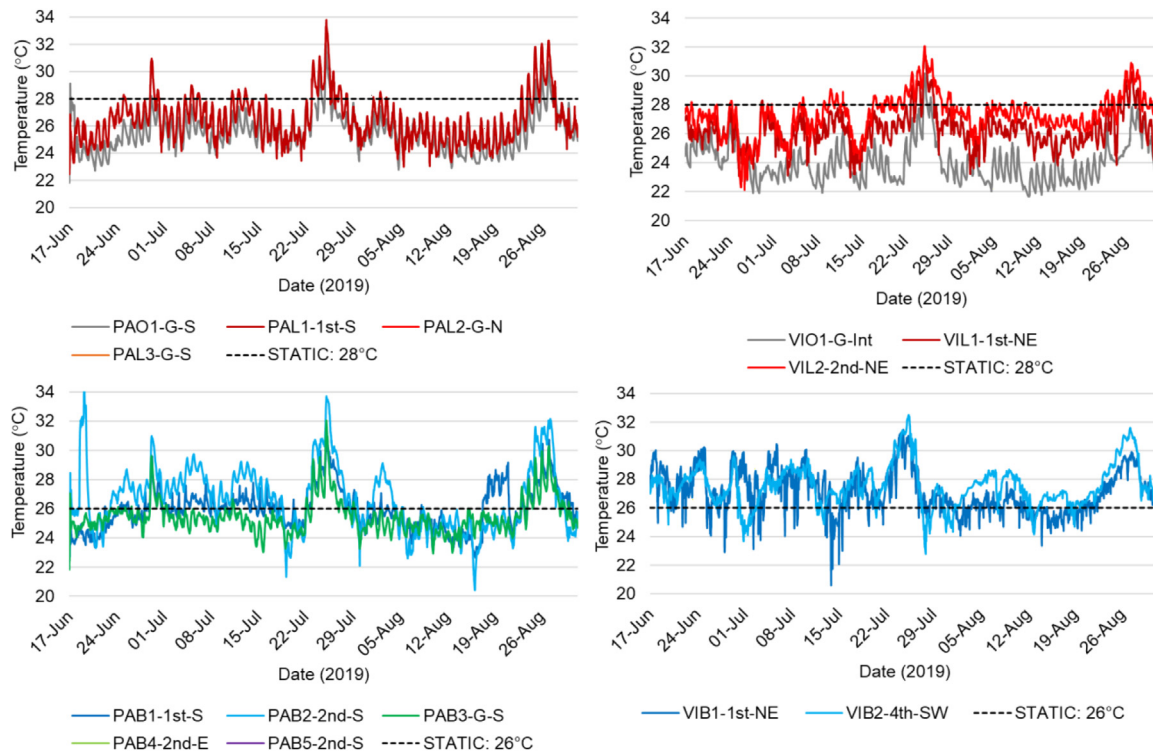


Fig. 7. Temperatures in selected office and lounge spaces (top) and bedrooms (bottom) in PA (left) and VI (right) during the monitored period, showing static overheating threshold temperature.

Table 9

Percentage of occupied/day/night hours over threshold temperatures in monitored locations.

Care home	Location type	Room	Percent of occupied hours over 28 °C	Percent of daytime hours over 26 °C	Percent of night-time hours over 26 °C
PA	Office	PAO1-G-S	7.5		
		PAL1-1st-S	18.5		
		PAL2-G-N	1.6		
		PAL3-G-S	3.3		
	Bedroom	PAB1-1st-S		40.4	47.9
		PAB2-2nd-S		49.3	54.5
		PAB3-G-S		17.8	16.0
		PAB4-2nd -E		59.8	59.3
VI	Office	PAB5-2nd -S		56.3	63.2
		VIO1-G-int	1.5		
		VIL1-1st-NE	9.9		
		VIL2-2nd -NE	29.1		
	Bedroom	VIB1-1st-NE		72.4	78.7
		VIB2-4th-SW		88.8	86.2

Table 10

Percentage of occupied hours temperatures exceeded the 26 °C threshold for PHE's overheating criterion in offices and lounges in PA and VI.

Care home	Location type	Room	Percent of occupied hours over 26 °C
PA	Office	PAO1-G-S	43.9
		PAL1-1st-S	70.1
		PAL2-G-N	14.0
		PAL3-G-S	13.6
VI	Office	VIO1-G-int	10.7
		VIL1-1st-NE	69.1
		VIL2-2nd -NE	88.2

5.3. Thermal simulation

5.3.1. Future risk of overheating

For the thermal simulations, a sample office (PAO1-G-S and VIO1-G-int), lounge (PAO1-1st-S and VIO1-1st-S) and bedroom (PAB2-2nd-S and VIB1-1st-NE) were used. Using the projected climate data for 2080, simulations were run for a five-day heatwave period. Average temperatures in all of the locations were found to be greater than 32 °C, reaching as high as 36 °C in VIB1-1st-NE (Fig. 9 and Table 16), with maximum predicted temperatures between 35.8 and 39.2 °C. Even minimum predicted temperatures exceeded the CIBSE Guide A static thresholds of 28 °C (offices and lounges) and 26 °C (bedrooms).

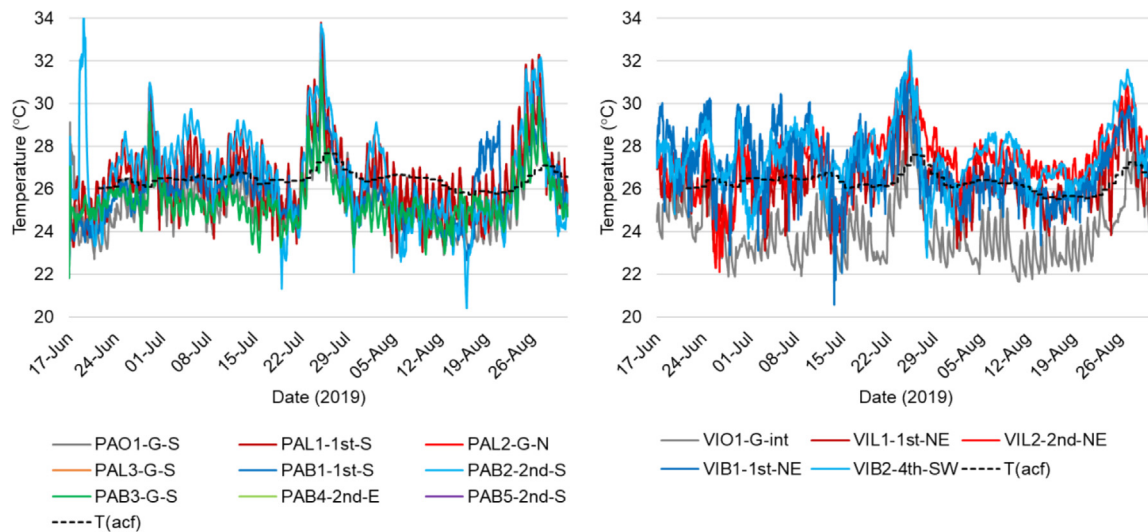


Fig. 8. Temperatures in selected offices, lounges and bedrooms in PA (left) and VI (right), with adaptive threshold comfort temperatures shown.

Table 11

Percentage of occupied/day/night temperatures exceeded the threshold comfort temperature by at least 1 °C in offices, lounges and bedrooms in PA and VI.

Care home	Location type	Room	Percent of hours ≥ 1 °C above threshold comfort temperature		
			Occupied	Daytime	Night-time
PA	Office	PAO1-G-S	9.4		
		PAL1-1st-S	32.3		
		PAL2-G-N	4.0		
	Bedroom	PAL3-G-S	5.5		
		PAB1-1st-S		16.0	13.4
		PAB2-2nd-S		33.2	41.2
		PAB3-G-S		7.6	3.0
		PAB4-2nd -E		37.4	40.4
		PAB5-2nd -S		41.0	49.2
VI	Office	VIO1-G-int	1.0		
		VIL1-1st-NE	18.7		
		VIL2-2nd -NE	65.1		
	Bedroom	VIB1-1st-NE		36.3	38.4
		VIB2-4th-SW		54.8	58.0

Again, considering a simulated five-day heatwave period in 2080, boxplots showing the projected temperature ranges in the sample offices, lounges and bedrooms revealed the majority of temperatures to be in the 30–36 °C range in PA and 31–39 °C range in VI (Fig. 10). The distribution of temperatures was clearly higher and had wider ranges in VI than in PA. Both care homes saw a similar decrease in temperatures over the five day period from the hot-test day (22nd Jul) to the least hot day (26th Jul) (Fig. 11).

Diurnal temperature variations averaged over the five-day heatwave period showed both care homes having their least hot periods between 07:00 and 09:00. From then on, indoor temperatures rose in both care homes (Fig. 12). Interestingly, indoor temperatures in PA rose more gradually, not reaching their peak until around 16:00, and beginning to decrease again from around 20:00. By contrast, in care home VI indoor temperatures increased more rapidly throughout the morning, reaching their peak earlier in the day, from around 13:00. As with PA, VI's indoor temperatures remained high until around 20:00, meaning they were at their peak for significantly longer than in PA.

It was clear that projected temperatures for 2080 (future climate) followed a similar trend with the monitored temperature data for 2019 (current climate). The risk of overheating increased considerably in the future compared to the current climatic scenarios; almost all projected temperature ranges during the five-day

heatwave period failed to meet the static criteria in both care homes. Temperature averages for office, lounge and bedroom in PA and VI ranged from 31.5 to 35.9 °C, 3–7 °C higher than the threshold of 28 °C, while no temperatures fell below 27 °C. Temperature averages and ranges were notably higher in the newer care home (VI) compared to the older one (PA). Although office average temperatures and typical ranges were closely matched (in the 31–34 °C range), average temperature in VI's lounge exceeded that in PA's lounge by almost 3 °C, while the typical temperature range was 32–36 °C (VI) compared to 30–34 °C (PA). Similarly, the average temperature in VI's bedroom was more than 2 °C higher than in PA's bedroom.

5.3.2. Modelling of passive strategies

To avoid the risk of active cooling to bring down the indoor temperatures in current and future climate, six different building adaptation scenarios were investigated as outlined in Table 6. The simulations considered the current climate (using 2019 weather data) and future climate (2080 simulated data). With projected increases in global temperature, the cooling load needs in both care homes increased greatly in the future climate (Fig. 13): between 5 and 12 times in PA, and 2 and 22 times in VI.

Scenario 6 – using a combination of hard adaptations (daytime AC, external shading and reflective surfaces) and soft adaptations

Table 12

Descriptive statistics for criteria 2 and 3 in monitored PA and VI spaces.

Care home	Location type	Room	Criterion 2: No. of days when W_e greater than 6 h per day (no. of monitored days)	Percent of monitored days when W_e greater than 6 h per day	Criterion 3: Maximum temperature above T_{acr} (°C) during occupied hours (all hours in bedrooms)
PA	Office	PAO1-G-S	9 (71)	12.7	4.7
		PAL1-1st-S	38 (71)	53.5	6.6
	Lounge	PAL2-G-N	1 (48)	2.1	1.9
		PAL3-G-S	3 (48)	6.3	3.2
	Bedroom	PAB1-1st-S	16 (71)	22.5	3.9
		PAB2-2nd-S	39 (71)	54.9	6.5
		PAB3-G-S	11 (71)	15.5	4.8
		PAB4-2nd -E	27 (49)	55.1	4.3
		PAB5-2nd -S	30 (49)	61.2	7.4
VI	Office	VIO1-G-int	1 (71)	1.4	3.1
		VIL1-1st-NE	24 (71)	33.8	4.3
	Lounge	VIL2-2nd -NE	58 (71)	81.7	4.9
	Bedroom	VIB1-1st-NE	48 (71)	64.8	4.6
		VIB2-4th-SW	59 (71)	83.1	5.4

Table 13

Monitored spaces in PA and VI which failed the CIBSE TM52 dynamic overheating criteria.

Care home	Location type	Room	Criterion 1	Criterion 2	Criterion 3
PA	Office	PAO1-G-S	×	×	×
	Lounge	PAL1-1st-S	×	×	×
		PAL2-G-N	×	×	
	Bedroom	PAL3-G-S	×	×	
		PAB1-1st-S	×	×	
		PAB2-2nd-S	×	×	×
		PAB3-G-S	×	×	×
		PAB4-2nd -E	×	×	×
		PAB5-2nd -S	×	×	×
VI	Office	VIO1-G-int		×	
	Lounge	VIL1-1st-NE	×	×	×
		VIL2-2nd -NE	×	×	×
	Bedroom	VIB1-1st-NE	×	×	×
		VIB2-4th-SW	×	×	×

(nighttime window opening to purge heat) – was found to be the most beneficial for energy consumption in both the current and future climates in both care homes. Interestingly, in the current climate, Scenario 5 – daytime AC and reflective surfaces (both hard adaptations) – had the highest energy consumption in both care homes, whereas in the future scenario, Scenario 2 – using hard adaptation AC during the day and overnight – proved to be the least beneficial for energy consumption. In the current climate, the soft adaptation of nighttime ventilation to purge daytime heat gains (Scenario 3) appeared to be more effective than the use of the hard adaptation of external shading (Scenario 4). However, in the future climate, external shading appeared to be more effective: with higher projected outdoor temperatures, window opening became a less effective method of cooling.

The results from thermal simulation models suggested a high increase in cooling loads by 2080, for both the old and the new care homes, expected given the significant increase in outdoor temperatures under the future climate scenario. For both care homes and for both present and future climates, S6 (AC combined with ventilation, shading and reflective surfaces) was most effective. The application of high albedo materials on the exterior walls combined with the daily use of AC (S5), and the continuous use of AC (S2), appeared to have the smallest impact on reducing current and future cooling loads.

To understand the generalisability of the findings an indicative uncertainty and sensitivity assessment was undertaken for scenario 6 for current and future climate for the peak summer week.

The factors that were varied were occupancy rates, internal gains (lighting and equipment), operation of windows (opening area and operation schedule), thermal conductivity of envelope thermal mass and location (urban/sheltered and rural/unsheltered). The variation was assessed for half, single or double occupancy rate; for 10% deviation in other space loads and thermal properties, in line with the typical variations quoted in BS EN 15603–2008 [6]; operation of windows was tested for quarter, half or full opening area and the various operation times of window opening scenarios (always closed, day-time only, night-time only, always open); and geographically tested for urban and rural settings. Resultant uncertainty in cooling load was up to $\pm 21\%$ standard deviation and sensitivity results showed that the operation of windows, envelope thermal performance and occupancy rate were the most important parameters affecting the cooling loads. Window operations were 2–3 times more influential factor than envelope thermal properties and impact of any other internal gains or location was negligible.

Temperatures within the care homes were simulated using historic 2019 weather data files. In the baseline scenario 1, the three spaces in each home all had average temperatures below CIBSE Guide A's 26 and 28 °C temperature thresholds (Fig. 14, left). Interestingly, only scenario 3 (daytime AC and nighttime ventilation to purge heat gains) and scenario 6 (daytime AC, nighttime ventilation, external shading and reflective surfaces) were able to produce average temperatures lower than the baseline simulation, the other measures seemingly leading to higher temperatures.

Table 14

Evaluation of TM59 criteria for each monitored location in PA and VI, showing number of monitored hours criteria were failed, with threshold number of hours to fail criteria also shown.

Care home	Location type	Room	Criterion A			Criterion B	Criterion C		
			Occupied	Day	Night		Occupied	Day	Night
PA	Office Lounge	PAO1-G-S	59				296		
		PAL1-1st-S	298				687		
		PAL2-G-N	23				83		
		PAL3-G-S	33				80		
	Bedroom	PAB1-1st-S		170	86	337		492	337
		PAB2-2nd-S		351	265	422		639	422
		PAB3-G-S		81	19	124		229	124
		PAB4-2nd-E		252	168	306		497	306
		PAB5-2nd-S		276	204	315		468	315
VI	Office Lounge	VIO1-G-int	7				72		
		VIL1-1st-NE	172				676		
		VIL2-2nd-NE	598				1725		
	Bedroom	VIB1-1st-NE		384	248	536		1632	536
		VIB2-4th-SW		581	374	588		1002	588
Threshold to fail criterion (hours)			42 (offices) 60 (lounges)	41	69	33	99 (offices) 143 (lounges)	99	164

Table 15

Overheating metrics for each monitored location in PA and VI.

Care home	Location type	Room	CIBSE Guide A	PHE	CIBSE TM52	TM59
PA	Office Lounge	PAO1-G-S	×	×	×	×
		PAL1-1st-S	×	×	×	×
		PAL2-G-N	×	×	×	
		PAL3-G-S	×	×	×	
	Bedroom	PAB1-1st-S	×	×	×	×
		PAB2-2nd-S	×	×	×	×
		PAB3-G-S	×	×	×	×
		PAB4-2nd -E	×	×	×	×
		PAB5-2nd -S	×	×	×	×
VI	Office Lounge	VIO1-G-int	×	×		
		VIL1-1st-NE	×	×	×	×
		VIL2-2nd -NE	×	×	×	×
	Bedroom	VIB1-1st-NE	×	×	×	×
		VIB2-4th-SW	×	×	×	×

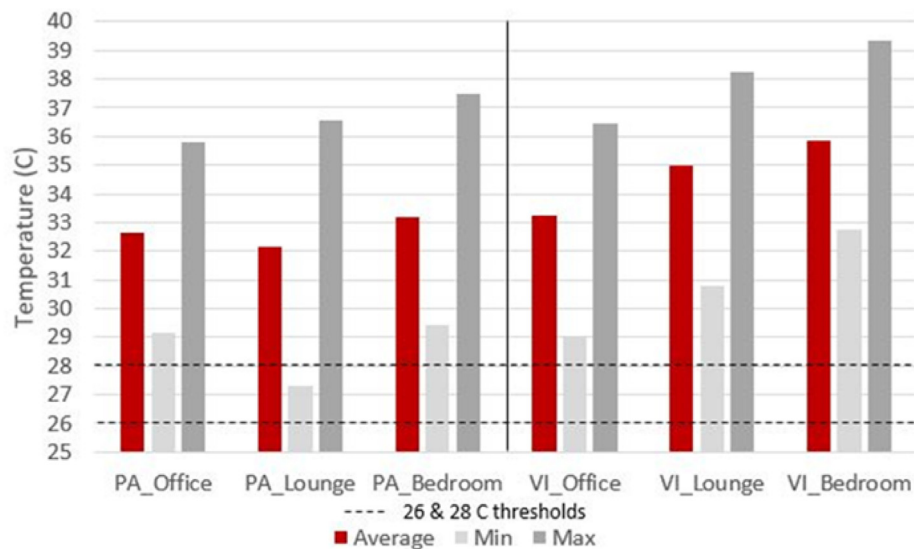
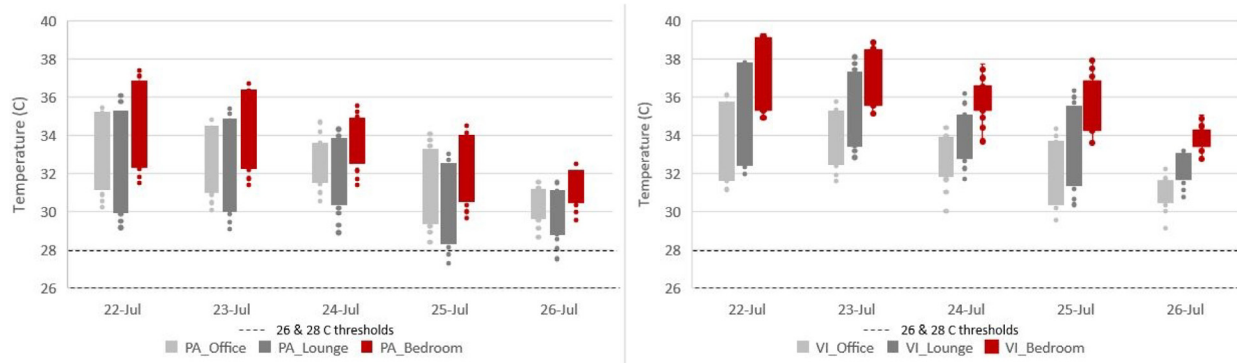
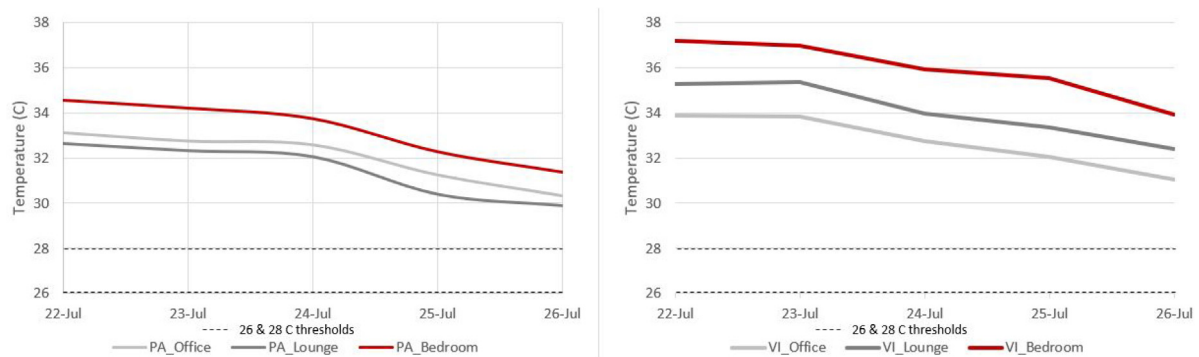
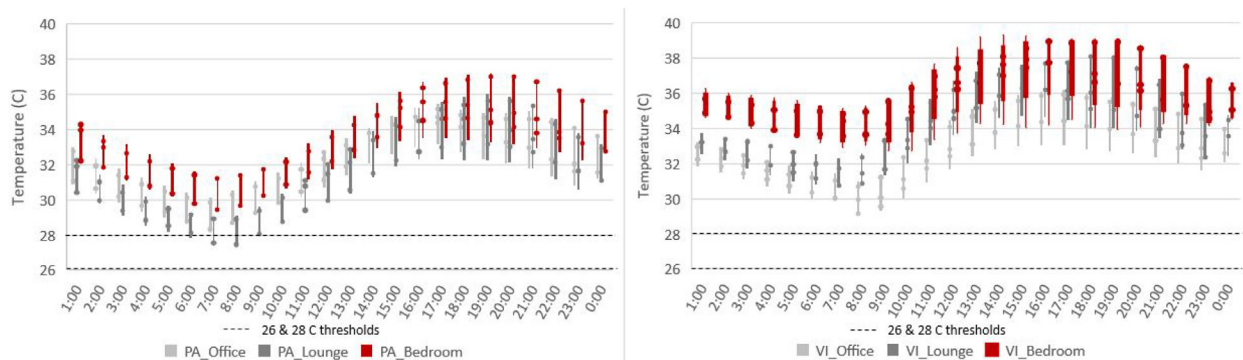


Fig. 9. Projected average, min and max temperatures during occupied hours by office, lounge and bedroom zone in PA (Left) and VI (right) for the 5-day heatwave period of 2080.

Table 16

Descriptive statistics of modelled temperatures in office, lounge and bedroom zones in PA and VI for the five-day heatwave period of 2080.

Hours	Modelled Temperatures (°C)	PA			VI		
		Office	Lounge	Bedroom	Office	Lounge	Bedroom
All	Average	32.01	31.46	33.23	32.70	34.06	35.89
	Min	28.16	27.18	29.40	29.07	30.34	32.73
	Max	35.82	36.54	37.48	36.47	38.23	39.33
Occupied Hours	Average	32.64	32.17	33.23	33.25	34.98	35.89
	Min	29.16	27.31	29.40	29.07	30.76	32.73
	Max	35.82	36.54	37.48	36.47	38.23	39.33

**Fig. 10.** Projected temperature range by office, lounge and bedroom zone in PA (Left) and VI (right) for the 5-day heatwave period of 2080.**Fig. 11.** Projected daily average temperatures of office, lounge and bedroom zones in PA (left) and VI (right) for the 5-day heat wave period of 2080.**Fig. 12.** Projected hourly variations of office, lounge and bedroom zone temperatures in PA (left) and VI (right) for the 5-day heatwave period of 2080.

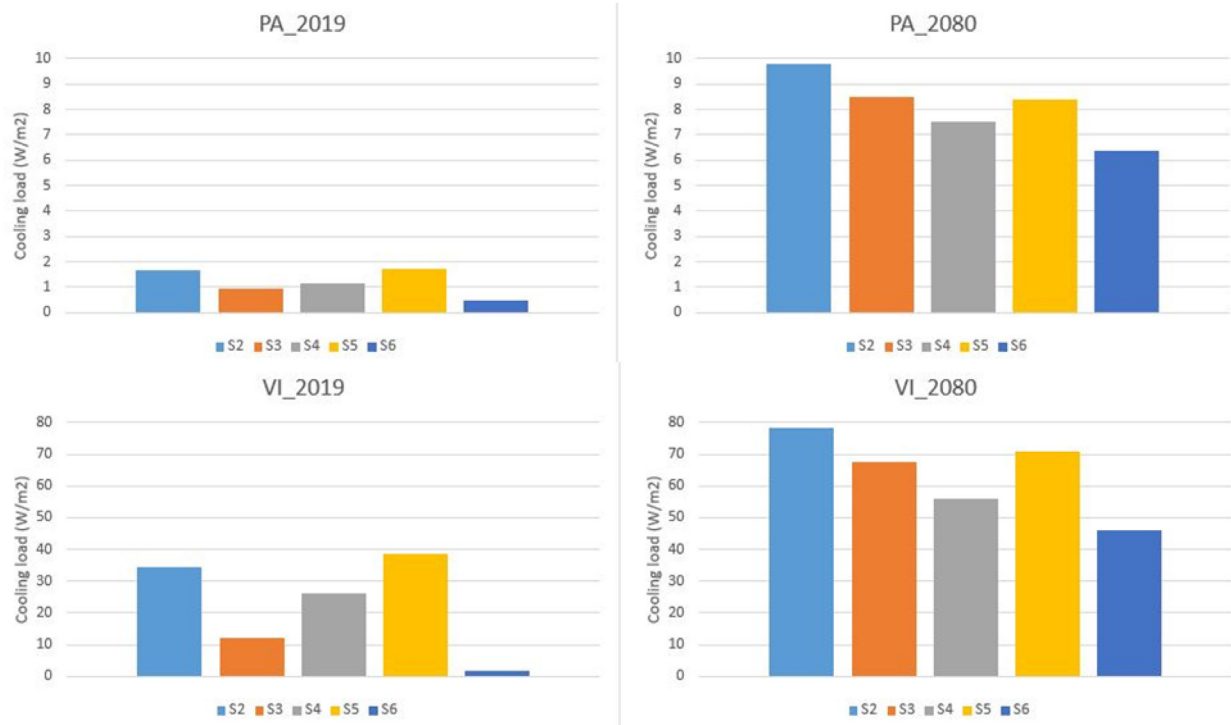


Fig. 13. Modelled building average cooling loads by simulation scenarios in PA (top) and VI (bottom) for the 5-day heatwave period of 2019 and 2080.

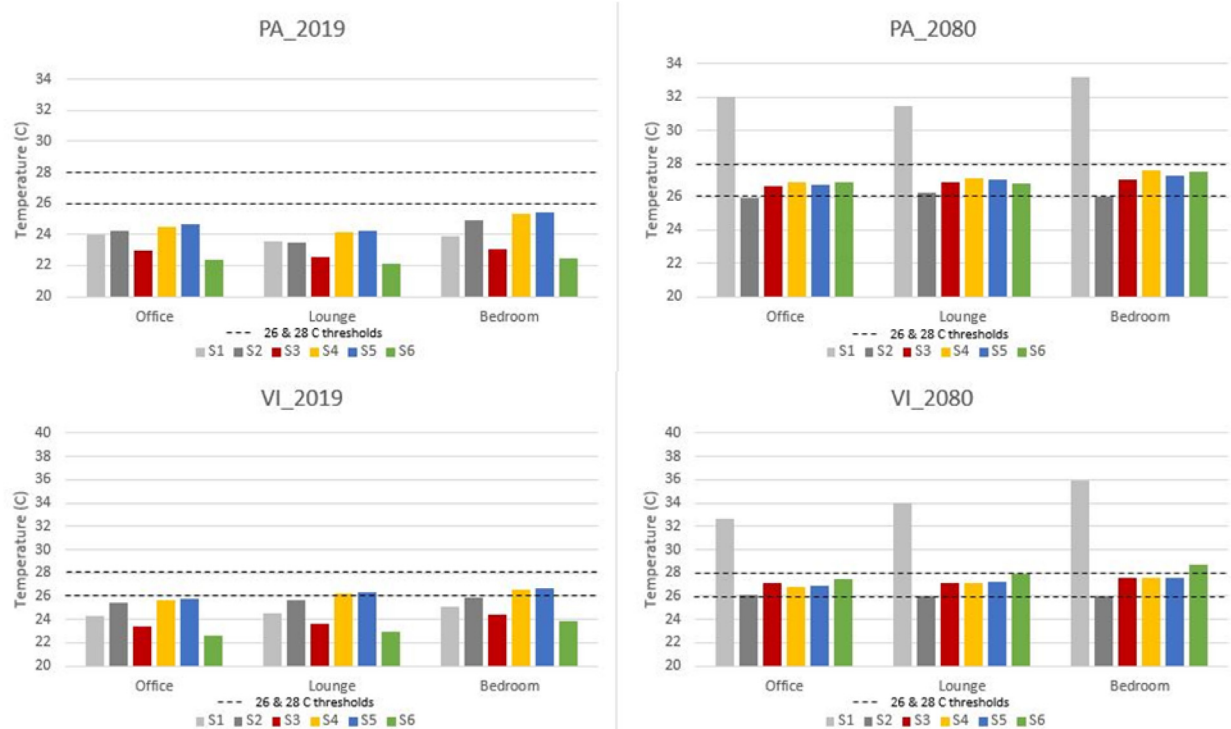


Fig. 14. Modelled zone average temperatures for all hours by simulation scenarios in PA (top) and VI (bottom) for the 5-day heatwave period of 2019 (left) and 2080 (right).

In the 2080 simulations, baseline scenario 1 average temperatures had increased significantly, to between 31 °C in lounge PAL1-1st-S and 36 °C in bedroom VIB1-1st-NE (Fig. 14, right). All five scenarios were able to bring temperatures down much lower than these baseline temperatures, and there was less of a difference between the different scenarios in terms of average

temperatures they produced compared to the 2019 simulations. In the 2080 simulations, scenario S2 (AC only, day and night) produced the lowest average temperatures at all six locations, with S6 the least effective on average, particularly in VI. For bedrooms, although S2 was the only scenario able to keep average temperatures below 26 °C, it was likely that at least 1% of hours would have

been above 26 °C, the threshold for overheating according to CIBSE Guide A. Indeed, with average temperatures in the 26–28 °C range for both offices and lounges, it is exceedingly likely that the 28 °C threshold would also have been exceeded for more than 1% of occupied hours regardless of the scenario adopted.

Thermal simulation affirmed that projected indoor temperatures in both care settings remained considerably lower than the 26 and 28 °C static thresholds under all scenarios, except for VI's bedroom. Under future climatic conditions, all zones in both settings had average temperatures 4–8 °C above the 28 °C threshold in baseline scenario S1. Simulations under current climatic conditions found the application of high albedo materials in external walls, combined with external shading, night ventilation and daily use of AC (S6) the most effective scenario in reducing overheating, lowering average temperatures by around 2 °C compared to baseline S1. Under future climatic conditions, continuous use of AC (S2) was found to be the most effective, bringing average temperatures down by almost 10 °C. Of the other scenarios, the highest temperature reduction was produced by S2 in the old care home (PA) and S4 in the new (VI).

6. Discussion

Continuous monitoring of indoor and outdoor temperature in summer 2019 revealed that overheating was a current risk that was prevalent, prolonged and severe across both care homes. However local differences in the magnitude of indoor temperature were observed in the two care homes buildings due to difference in the size and age of the buildings. Monitored rooms in care home PA reached higher temperatures than those in VI, with peak bedroom temperatures as high as 34.7 °C (PAB2-2nd-S) compared to 32.5 °C (VIB2-4th-SW) and peak lounge temperatures as high as 33.8 °C (PAL1-1st-S) compared to 31.2 °C (VIL2-2nd-NE).

This is why both buildings remained warm overnight, with indoor temperatures never falling below 20 °C in PA and 21 °C in VI. Although temperatures in the monitored offices and lounges fell slightly overnight, diurnal profiles indicated that, with windows and doors closed, the bedrooms temperatures actually increased overnight in both buildings. Nocturnal purging of heat can be one of the simplest, low-cost ways of keeping temperatures in a building within comfortable (and safe) levels during hot summer periods. But with the majority of rooms within both care homes being bedrooms, this becomes extremely challenging. Bedroom doors are routinely closed, both so as to minimise any disturbance to the residents while they sleep and for their safety. Windows are also routinely closed at night in the empty offices and lounges, and also in the occupied bedrooms. Bedrooms were the warmest monitored locations in both care homes.

Interestingly similar trends were observed in both care homes with regards to the four overheating metrics investigated. CIBSE Guide A's static 28 °C and 26 °C temperature thresholds for offices/lounges and bedrooms were exceeded for the maximum 1% of occupied hours in every monitored space. Some rooms came close to staying below the threshold, notably lounges PAL2-G-N (1.6%) and PAL3-G-S (3.3%) and office VIO1-G-int (1.5%). Interestingly these three spaces were all on the ground floors, as was bedroom PAB3-G-S, which exceeded 26 °C far less often than the other monitored bedrooms. The stricter PHE overheating metric was also failed in all monitored spaces, between 13 and 76% of occupied/day/night hours in PA's rooms and between 69 and 89% of occupied/day/night hours in VI's rooms.

The adaptive TM52 metric provided varying temperature thresholds generally somewhere in between the static limits of 26–28 °C, higher following warmer outdoor periods. This allowed one location – VIO1-G-int – to pass the metric, but all other loca-

tions still failed, the majority failing all three criteria. Metric TM59 was also failed in the majority of monitored spaces. Despite failing TM52's criterion 1, ground floor lounges PAL2-G-N and PAL3-G-S were not overheating according to TM59 criterion A since monitored data covered less than half of the May–Sept non-heating season considered by this criterion. VI's ground floor office VIO1-G-int also passed TM59. Criterion C's upper limit of 143 h was exceeded by up to 1580 h in monitored spaces. It was clear that regardless of the overheating metric applied to the case study care homes, they were found to be overheating in the current climate, particularly in the bedrooms and often at night.

Unsurprisingly the prevalence of overheating became more severe in the projected future climate of 2080. Over a simulated five-day summer heatwave period, the selected locations had average indoor temperatures of 32–36 °C, reaching highs of 36–39 °C. Care home VI fared worse in the 2080 scenario with significantly higher indoor temperatures than PA. Diurnal profiles also revealed VI to experience a more rapid rise in indoor temperatures throughout the morning, reaching a peak around three hours earlier than in PA and remaining there until mid-evening. The medium weight construction and lack of external shading likely contributed to VI's poorer performance.

The passive strategies investigated to mitigate against the high indoor temperatures and minimise active cooling highlighted the common pay-off that often occurs between energy intensity – cooling load per m² – and reduction in indoor temperature. The scenario most successful in reducing indoor temperatures was the most energy intense and vice versa. In a future scenario with a decarbonised energy grid and possible localised energy production, energy intensity factor in may be reduced depending upon the timing of energy demand. Given that even the most energy-intense scenario 2 – the hard adaptation of using AC around the clock – still resulted in high average indoor temperatures which may well have failed all of the overheating criteria investigated, it is likely that further measures may be necessary in order to bring indoor temperatures down to levels which are safe and comfortable for the residents and staff.

7. Conclusions

This research has systematically examined the *prevalence, intensity* and possible *solutions* for tackling summertime overheating during the summer of 2019 in two London care homes occupying modern and older buildings. Continuous monitoring of indoor temperature in different spaces of the two care homes along with outdoor temperature allowed detailed analysis of overheating using four distinct metrics. Thermal simulation helped to identify the current and future risk of overheating in a warming climate. The monitoring data was used to calibrate and validate the thermal models, which enabled the testing of passive solutions for avoiding cooling in the care homes under a set of representative climate change scenarios.

Both care homes were found to experience overheating regardless of the metrics used. Fixed-temperature-threshold metrics – CIBSE Guide A and PHE – identified all monitored locations to be overheating. Variable-temperature-threshold metrics – TM52 and TM59 – found the majority of monitored locations to be overheating, particularly bedrooms. Many of the bedrooms were found to be warmer at night than during the day due to windows and doors being closed. This practice means nighttime purging of heat is severely hampered throughout the buildings, making them particularly vulnerable to consecutive days of high temperatures. This is also particularly interesting since thermal simulation confirmed night ventilation as the single most impactful passive technique for both buildings. This is also particularly

interesting since thermal simulation confirmed nighttime ventilation as the single most impactful passive technique for both buildings under current climate. The combination of all of the investigated passive measures - nighttime ventilation, external shading and high-albedo materials on external walls proved to be the most effective passive technique, but implementing all of these measures would be more expensive. However for 2080 s, the higher outdoor temperatures made nighttime ventilation much less effective. The most effective solution, continuous use of air-conditioning, was also, naturally, the most energy intensive, highlighting the importance of finding the most appropriate balance between indoor temperature reduction and cooling load on a case-by-case basis. Where the implementation of passive measures alone is not sufficient, their combination with active cooling is likely to enable care homes that remain comfortable for longer and require less cooling.

Care homes are by their very nature hybrid buildings, serving both as living spaces for the residents and offices/workspaces for the staff. It is vital to provide adequate comfort to both residents and staff occupying these buildings particularly during periods of hot weather. The need for an overheating metric tailored for care homes is clearly evident. It is recommended that further research is conducted to gather empirical data - both objective measures of the indoor environments and subjective occupant feedback on perceptions of thermal comfort and preference - which can be used to support the development of a bespoke metric for these vulnerable settings.

CRediT authorship contribution statement

Rajat Gupta: Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Supervision, Funding acquisition. **Alastair Howard:** Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Mike Davies:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Supervision, Funding acquisition. **Anna Mavrogianni:** Conceptualization, Formal analysis, Writing - review & editing, Supervision, Funding acquisition. **Ioanna Tsoulou:** Software, Writing - original draft, Writing - review & editing. **Nishesh Jain:** Software, Writing - original draft, Writing - review & editing. **Eleni Oikonomou:** Software, Writing - original draft, Writing - review & editing. **Paul Wilkinson:** Conceptualization, Methodology, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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