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RESEARCH PAPER

Urban social housing resilience to excess summer heat

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The potential levels of exposure to indoor overheating in an urban environment are assessed for vulnerable social housing residents. Particular focus is given to the synergistic effects between summertime ventilation behaviour, indoor temperature and air pollutant concentration in relation to energy retrofit and climate change. Three different types of social housing are investigated (1900s' low-rise, 1950s' mid-rise and 1960s' high-rise). The case study dwellings are located in Central London and occupied by vulnerable individuals (elderly and/or people suffering from ill-health or mobility impairment). Indoor temperature monitoring suggests that occupants are already exposed to some degree of overheating; the highest levels of overheating occur in 1960s' high-rise tower blocks. The thermal and airflow performance simulation of a mid-floor flat in the 1960s' block under the current and projected future climate indicates that improved natural ventilation strategies may reduce overheating risk to a certain extent, with night cooling and shading being slightly more effective than all-day rapid ventilation. However, their potential may be limited in future due to high external temperatures and the undesired ingress of outdoor pollutants. This highlights the need for the development of combined strategies aiming to achieve both indoor thermal comfort and air quality.

Keywords adaptation, climate change, indoor air quality, heat stress, housing, overheating, public health, resilience, thermal comfort

Introduction and background

Comfort and health impacts of urban warming trends

Anthropogenic climate change is predicted to increase the frequency and severity of heatwave events (IPCC, 2014a). Whilst developing countries are likely to be harder hit by global warming effects (World Bank, 2008), the low-income groups of inner cities in temperate climates are also vulnerable to extreme weather events (IPCC, 2014b). As population exposure to unprecedentedly high temperatures is becoming more frequent, heat related morbidity and mortality is an increasing concern in climates that were previously predominated by space heating. In terms of mortality, the 2003 heatwave resulted in an estimated 70 000 excess deaths across Europe (Robine, Cheung, Le Roy, Van Oyen, & Herrmann, 2007), of which approximately 2000 occurred in the UK (Johnson et al., 2005) and around 600 in London alone (Mayor of London (MoL), 2006).

Mean summer temperatures are projected to increase by up to 4°C in the South of England by the 2080s under a medium emissions scenario (Jenkins et al., 2009). Average winter air temperatures are also likely to rise by between 2 and 3°C, with slightly higher increases projected for the South East of England. Numerous studies and programmes have investigated the impacts of climate change in the UK, *e.g.* the Department for Environment, Food and Rural Affairs (DEFRA) National Adaptation Programme (NAP) outlined the UK government's plans for becoming more climate ready (DEFRA, 2013).

The need to adapt to ongoing climate change has been highlighted by the National Health Service (NHS) Heatwave Plan for England (NHS England & PHE, 2014) and the recently published report by the UK's Committee on Climate Change (CCC) Adaptation Sub-Committee (ASC) on the potential climate change risks to population well-being and the economy (CCC ASC, 2014).

The heat-related health risks faced by vulnerable populations residing in unsuitable building properties in urban environments have been referred to as a 'triple jeopardy' phenomenon (MoL, 2011; Wolf & McGregor, 2013). The determinant factors of risk are further analysed below at the citywide, building and occupant level.

Determinant factors of urban heat and pollution vulnerability

Whilst the use of active cooling systems could be beneficial for human health in the short-term (Keatinge et al., 2000), these will lead to negative environmental, financial and social consequences for households. For example, an increase in the uptake of air-conditioning in the housing sector will result in a rise in household electricity consumption, especially peak demand, which could potentially put a strain on the grid. It will also be accompanied by an increase in associated carbon emissions, which will create a negative feedback loop between cooling needs and increased temperatures. In addition, it is likely that low-income households may not be able to afford the higher summer fuel costs, thus leading to summer fuel poverty (Hills, 2012). Active cooling equipment in residential environments is currently rare in England, with fewer than 3% of households currently operating a fixed or portable air-conditioning unit during the summer period (BRE, 2013). However, it is expected that an increasing percentage of household spaces in England will be equipped with mechanical cooling systems in future based on climate change projections (Collins, Natarajan, & Levermore, 2010), thus resulting in an additional 100 000 tonnes CO_2 per year by 2030 (Day et al., 2009). Hence, it is essential to reverse this trend through the adoption of alternative passive cooling solutions across the UK housing stock.

A number of studies have indicated that heat-related mortality risk increases in urban environments due to the exacerbation of hot spells by the urban heat island phenomenon (Hajat, Kovats, & Lachowycz, 2006; Kovats & Kristie, 2006), *i.e.* the inadvertent local urban climate modification caused by urbanization processes that result in a systematic positive temperature differential between urban and surrounding rural areas (Oke, 1982). This is of particular importance as future urban growth and human response to heatwaves, *e.g.* the installation of air-conditioning and associated waste heat to urban street canyons, could potentially lead to a further intensification of warming trends (Gupta & Gregg, 2012; Peacock, Jenkins, & Kane, 2010).

There is currently a wealth of modelling and monitoring studies assessing the impact of energy efficient retrofit interventions and climate change-induced rises in ambient temperature on indoor overheating and air quality (Crump, Dengel, & Swainson, 2009; Mavrogianni, Wilkinson, Davies, Biddulph, & Oikonomou, 2012; Porritt, Cropper, Shao, & Goodier, 2012; Shrubsole, Macmillan, Davies, & May, 2014). Recent studies have also indicated that indoor overheating may be an issue in newly built homes that are constructed to high energy efficiency standards not only during the summer but also in winter (NHBC Foundation, 2012). These issues are, nevertheless, usually examined in isolation and synergistic effects between summertime ventilation behaviour, indoor temperature and air pollutant concentration have been under-investigated to date. This is an issue of critical importance in urban areas characterized by high levels of outdoor air pollution.

Determinant factors of building heat and pollution vulnerability

People in the UK tend to spend more than 90% of their time indoors (Schweizer et al., 2007), a percentage that is likely to be even higher among elderly and low-mobility individuals. This suggests that enhancing our understanding of the indoor climate in dwellings occupied by vulnerable people is vital in order to estimate exposure to heat and pollutants.

A series of recent modelling and monitoring studies have quantified the relative impact of building fabric characteristics on indoor overheating risk, the majority of which are reviewed in detail elsewhere (DCLG, 2011; NHBC Foundation, 2012; ZCH, 2014). One of the recommendations of the DCLG review is that councils should ensure that vulnerable individuals are not housed in the most at-risk properties for overheating.

A consistent finding among various modelling studies is that mid- and top-floor purpose-built flats that are located in core urban areas and lack sufficient solar protection and/or ventilation are more prone to overheating (CIBSE, 2005; Hacker, Belcher, & Connell, 2005; Mavrogianni et al., 2012; Oikonomou et al., 2011; Orme & Palmer, 2003; Salagnac, 2007; Vandentorren et al., 2006). In particular, the relative risk of overheating in top-floor 1960s' flats is six times that of ground-floor flats in the same block (depending on orientation) and around nine times that of Victorian terraces (DCLG, 2011). Notably, a large proportion of high-rise housing developments in the UK belong to the social housing sector; it is estimated that 64%

of households living on or above the fifth floor of a residential building are social tenants (ONS, 2001). Taking this into account, it is suggested that adaptation studies should give particular emphasis to this dwelling type.

A number of monitoring studies have also sought to address the relative overheating risk inside dwellings. For example, temperatures were recorded in 62 dwellings in Leicester during the 2006 heatwave; it was found that purpose-built flats and post-1990 houses were at highest risk of overheating (Firth & Wright, 2008). These findings are in accordance with the analysis of monitored summer temperatures in 207 dwellings across England that also indicated that there is an increased risk of overheating in post-1990 houses and flats (Beizaee, Lomas, & Firth, 2013).

As highlighted by the recent London Climate Change Partnership's (LCCP) report *Your Social Housing in a Changing Climate* (LCCP, 2013), most of the social housing in London was not constructed with climate change in mind and, thus, its widespread climate proofing is an emergent need. In addition, social housing residents, in particular, may not have the economic or physical means and/or the knowledge to adapt their homes to a changing climate by themselves. The negative impacts of climate change on social housing are likely to have repercussions to entire communities. A high uptake of building fabric retrofits is, however, observed in low-income areas, likely driven by councilled retrofit programmes, and this is likely to increase summer overheating risk (Hamilton et al., 2012).

It has been suggested that occupant behaviour can have a measurable impact on indoor overheating (Mavrogianni et al., 2014; Porritt et al., 2012), with increased ventilation and window shading having a significant potential to mitigate excess temperatures. Unfortunately, as indicated in a recent review by Fabi et al. (2012), actual data on the way people operate their homes during the summer period are scarce, as most relevant research on window-opening patterns is focused on office buildings. There is, nevertheless, some evidence of a correlation between window opening frequency/duration and external temperature, as well as indoor activities in dwellings (IEA Annex 8, Dubrul 1988).

The majority of UK dwellings are naturally ventilated, and while increasing ventilation through window opening may act to reduce indoor temperatures, it also causes an increase in the infiltration of outdoor pollution into the internal air (Taylor et al., 2014b). In urban centres, levels of outdoor pollutants such as fine particulate matter with a diameter of 2.5 μm or less ($PM_{2.5}$), nitrogen dioxide (NO_2), and sulphur dioxide (SO_2) can be high due to high volumes of traffic, dense road networks and industry. Pollutants may also be generated from indoor activities, *e.g.* cooking, smoking and cleaning (Shrubsole et al., 2012). Air quality has an important impact on population health; $PM_{2.5}$, for example, has been associated with health problems such as respiratory and cardiovascular disease (Brunekreef & Holgate, 2002); and $PM_{2.5}$ from outdoor sources is estimated to cause a 7.2% fraction of mortality in London (PHE, 2013). Ventilation is a key determinant of indoor pollution exposure, and the temperature-dependent window-opening behaviour of dwelling occupants can influence the degree of exposure, particularly to pollution from outdoor sources.

Determinant factors of individual heat vulnerability

Individual heat vulnerability comprises of the following factors: sensitivity; exposure; and inability to adapt or access treatment. There are a number of epidemiological studies investigating individual determinant factors for heatwave sensitivity and inability to adapt, summarized in a literature review by Kovats and Hajat (2008). Such factors include age (elderly above 65 years and children), health status (people suffering from heart or blood pressure conditions, diabetes, depression, low mobility, and/or other chronic diseases) and social isolation.

Study focus and aims

Taking the above into consideration, there is an urgent need to study the summertime thermal performance of council flats in core urban areas due to the increased overheating risk in certain dwelling types, the urban heat island effect and the high concentration of vulnerable individuals in social housing. Assessing current and future heat vulnerability is a necessary step towards the creation of climate resilient urban social housing. 'Resilience' in the context of climate change is defined as:

> the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.
>
> (IPCC, 2014b)

The current paper presents the findings of a monitoring and modelling study designed as a follow-up to the DEFRA-funded Climate Resilience Islington South Project (CRISP).

The main aim of CRISP was to interview vulnerable Central London residents in order to explore their attitudes towards, and preparedness for, climate change-induced risks, such as heatwaves and flooding; the results of the main study have been presented in detail elsewhere (Kolm-Murray, Smith, & Clarke, 2013). The geographical focus of CRISP was the South Islington area of London, comprising the Bunhill, Clerkenwell and Pentonville neighbourhoods. The Borough of Islington has been identified as a 'triple jeopardy' hotspot according to the MoL (2011) definition on the basis of its heatwave vulnerability. According to multifactor heat vulnerability mapping of the Greater London Area (Wolf & McGregor, 2013), Islington belongs to a ring of Central London areas north of the Thames that are characterized by a high sensitivity to heat. The various factors contributing to the heat vulnerability of the borough are discussed by Kolm-Murray et al. (2013):

- Islington is located in an area characterized by high urban heat island intensities
- It is the most densely populated borough in the UK with 206 100 people inhabiting just 5.7 square miles
- It has the second lowest proportion of green surface areas in the UK (after the City of London)
- It is the 14th most deprived borough in England and is characterized by high inequality levels
- It has one of the lowest male life expectancies in London, and its population is characterized by a high prevalence in cardiovascular and respiratory conditions, which are significant heat sensitivity proxies
- It is experiencing unprecedented levels of gentrification, which could further compound problems of social isolation among the elderly, long-term social housing tenants
- According to the latest census (ONS, 2011a), a large proportion of Islington residents (42%) live in council-owned flats in tower blocks or other types of high-rise social housing. It is worth noting that around 62% of households with a Household Reference Person aged 65 and over, one of the key proxies of heat vulnerability, live in a social rented home (ONS, 2011b).

Three different building typologies were examined in the present study: a 1900s' low-rise block, a 1950s' mid-rise block and a 1960s' high-rise tower. Monitoring of the thermal environment was performed during summer 2013 in eight flats, which were occupied by heat-vulnerable individuals (aged 65 and above). In addition, an estimation of future excess indoor heat and pollution risk levels under climate change was performed for a mid-floor flat of the 1960s' high-rise estate using dynamic thermal simulation.

The aims of the present study are:

- to assess the current summertime thermal performance of the case study flats using thermal monitoring
- to explore in more detail the complex interactions of summertime ventilation behaviour, indoor temperature and air pollutant concentration under different occupancy, operation, retrofit and climate scenarios using a coupled dynamic thermal and air contaminant transport model in one of the high-risk flats (1960s' high-rise)
- to explore the feasibility and test the logistics of a larger scale, future monitoring study in this setting.

Methods

Case study: monitored buildings

As part of CRISP (Kolm-Murray et al., 2013), a large-scale questionnaire survey was performed between November 2012 and February 2013 and its participants were asked if they would be interested in taking part in a follow-up monitoring survey during the summer. As a result, a total of eight different council flats were visited and surveyed during the period July–September 2013. These flats were located in four different buildings in Bunhill, South Islington, representing a range of different British social housing typologies:

- building A (1900s' low-rise, one monitored flat)
- building B (1950s' mid-rise, two monitored flats)
- building C (1960s' high-rise, two monitored flats)
- building D (1960s' high-rise, three monitored flats)

Case study building A is a five-storey block of flats built in 1906 by the London County Council. The properties have been recently refurbished with double-glazing, including trickle vents. As part of a complex of buildings, the flat of interest was sheltered from wind and experienced some overshadowing.

Case study building B is a 13-floor residential building containing 52 flats, built in the 1950s with cavity walls (system build construction). It has been retrofitted with double-glazing and trickle vents, while the flats are large and allow for cross-ventilation. The tower is inhabited by a mix of occupants, ranging from young families to elderly occupants.

The Borough of Islington housing production peaked before the 1970s with the Housing Development Area Programme, when a number of residential tower blocks similar to the case study buildings C and D were built to last until the mid-21st century (Glendinning & Muthesius, 1994). Case study buildings C and D are representative of high-rise developments constructed under the Social Housing Schemes in the 1960s and 1970s. Both towers are 17 storeys high. The structural characteristics of the 1960s' tower blocks are widely documented (Chown, 1970; Glendinning & Muthesius, 1994).

The key characteristics of the monitored flats are summarized in Table 1.

Monitoring of indoor thermal conditions

Onset HOBO U12-012 data loggers (Onset Computer Corporation, 2014) were used for the monitoring of indoor thermal conditions in the case study flats. The loggers recorded dry bulb air temperature (accuracy: $\pm 0.35°C$, range: 0–50°C) and relative humidity (accuracy: $\pm 2.5\%$ range: 5–95%) at 15-min intervals for 2 months during the summer (early July–early September 2013). The whole set of loggers were first calibrated by being exposed to constant thermal environmental conditions for 24 h in a thermal chamber at the Bartlett (Faculty of the Built Environment), University College London, using an eight-point calibration method. Results from the calibration test showed that all loggers had an accuracy within the range specified by the manufacturer. Unfortunately, due to participant availability restrictions, it was not possible to install all loggers on the same date so the temporal coverage varies for each flat. However, monitoring data during the hot spell period (12–23 July) is available for two flats (A1 and C3). The sensors were placed in convenient locations at approximately the eye level of a seated person (around 1.10–1.30 m) and away from sources of direct light and heat, such as radiators, light bulbs, televisions or other large electronic appliances. One sensor was installed in the main living area and one in the main sleeping space. During the survey visit of the property, information about construction materials (including wall types, insulation levels and double-glazing) and dimensions were collected. Indoor air quality was not monitored due to its increased cost but it is envisaged that future work

Table 1 Key characteristics of the monitored flats

Building	Flat	Storey	Exposed roof surface	Solar orientation of the main facade[a]	Number of bedrooms	External wall type, assumed *U*-value[b]	Window type	Shading	Cross-ventilation
A (1900s' low-rise)	A1	1	No	North	1	Solid brick (no insulation), U-value = 2.10 W/m^{2}K	Double-glazed	Yes (internal blinds or curtains)	Fair
B (1950s' mid-rise)	B1	1	No	South-east	2	Concrete system build (external insulation), U-value = 0.60 W/m^{2}K	Double-glazed	Yes (internal blinds or curtains, balcony overhang)	Good
	B2	3	No	South-east	2		Double-glazed	No (only balcony overhang)	Good
C (1960s' high-rise)	C1	3	No	North-west	1	Concrete system build (no insulation), U-value = 2.00 W/m^{2}K	Double-glazed	Yes (internal blinds or curtains)	Good
	C2	4	No	South-east	1		Double-glazed	No	Good
	C3	12	No	South-west	2		Double	No	Poor
D (1960s' high-rise)	D1	1	No	North-west	1	Concrete system build, U-value = 2.00 W/m^{2}K	Double-glazed	Yes (internal blinds or curtains)	Poor
	D2	8	No	South-east	1		Double-glazed	Yes (internal blinds or curtains)	Poor

Notes: [a]The solar orientation of the main facade is defined as the orientation of the largest proportion of exposed opaque and glazed surface areas.
[b]The *U*-values for the walls were inferred based on the construction age of the building using the Reduced Standard Assessment Procedure (RdSAP) methodology (BRE, 2009).

will monitor indoor air pollutants alongside thermal conditions.

Case study: modelled building

As mentioned above, dwellings in high-rise 1960s' social housing developments are considered to be at risk of overheating, and have often been subjects of modelling studies in the past that examined the risks associated with climate change and potential adaptation measures. It is also known that a large proportion of the occupants of the high-rise council estates are aged 65 or above and are, therefore, a vulnerable group in terms of overheating risk (Kolm-Murray et al., 2013). It was, thus, decided to focus on case study flat C3 for further modelling work as part of the present study.

Building C is a 17-storey tower block of 97 units, 21 of which are occupied by people aged over 65 (around 2.5 times the proportion of those 65+ at borough level). It has a symmetrical 'U'-shaped layout, with the long side facing broadly north–south. Built in 1963, the building is largely unshaded, although a recent adjacent development directly to the south offers some shading to the lower floors. The main entrance hall is accessible via the south and the north side of the building and leads to two central staircases and lift towers.[1] A typical floor plan is shown in Figure 1. The drawings were reproduced from those available by Homes for Islington and were based on interpretation of photographs and onsite visits including detailed measurements inside the case study 13th-floor flat facing south-west ('CW' on the plan). Most floors contain six two-bedroom flats with an area of 55–60 m^2 each, accessible via an external corridor on the north side. Four out of six of the properties in each floor are single aspect to the south. Above the roof level, water tanks, two lift motor rooms and a ventilation chamber are located. The roof slab is covered by concrete tiles. The walls are predominantly concrete system-build though some parts are likely to consist of *in situ* reinforced concrete. There are a few sections of uninsulated cavity wall at ground level. Double-glazed windows with trickle vents were installed in 2004–05.

Modelling of indoor thermal conditions

A simplified geometric model of the case study building was constructed using the widely tested and validated building performance modelling software EnergyPlus, version 8.0.0.007 (US DoE, 2014). To assess the heat and pollutant exposure risk levels of vulnerable occupants, it was assumed that the flat was occupied by a couple of elderly individuals who remained constantly indoors. The occupancy patterns of the residents, and the resulting appliances use and internal heat gains were specified in line with previous studies (Mavrogianni et al., 2012, 2013, 2014; Oikonomou et al., 2011; Taylor et al., 2014a). Simulations were then run for the following combinations:

- two levels of building fabric efficiency levels (existing and retrofitted)
- two types of window and shading operation (all-day 'rapid' ventilation versus night time 'purge' cooling combined with daytime shading).

The input modelling data for the two levels of building fabric efficiency levels (existing and retrofitted) are summarized in Table 2. The existing building fabric was modelled according to information from the site visit and architectural drawings. *U*-values for the walls,

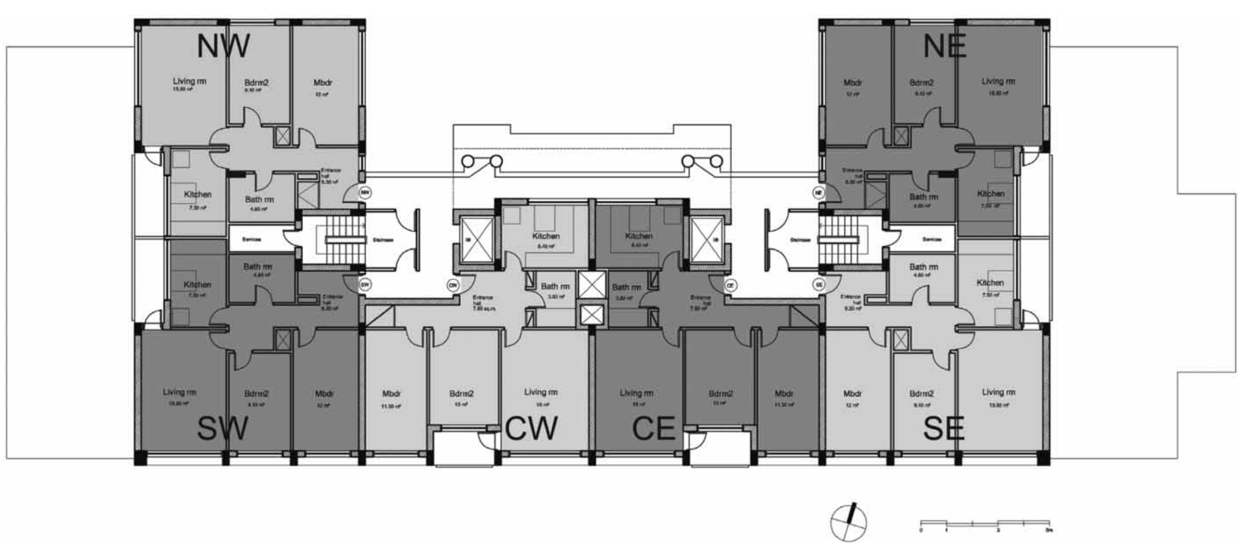

Figure 1 Standard floorplan of the case study modelled building

Table 2 Building fabric modelling input data for case study building C (1960s' high-rise)

	Existing	Retrofitted
External walls	Precast concrete parts with no insulation, U-value = 2.00 W/m^{2}K	Precast concrete parts with internal insulation, U-value = 0.60 W/m^{2}K
Ground floor	Solid concrete slab, U-value = 1.60 W/m^{2}K	Solid concrete slab, U-value = 1.60 W/m^{2}K
Roof	Solid concrete slab, U-value = 2.30 W/m^{2}K	Solid concrete slab, U-value = 2.30 W/m^{2}K
Windows	Post-2002 double-glazed with a uPVC frame, U-value = 2.00 W/m^{2}K	Triple-glazed with a uPVC frame, U-value = 1.80 W/m^{2}K
Air infiltration	11.5 m^3/m^{2}h at 50 Pa	5.0 m^3/m^{2}h at 50 Pa

ground floor, roof, and windows were inferred based on the construction age of the case study building using the Reduced Standard Assessment Procedure (RdSAP) method (BRE, 2009). The building structure was modelled as a typical reinforced concrete frame grid; external walls were assumed to be mainly precast concrete parts with no insulation (U-value = 2.00 W/m^{2}K). The floors consisted of 20 cm-thick hollow pot concrete slabs. Windows were modelled as being post-2002 double-glazed with a uPVC frame (U-value = 2.00 W/m^{2}K). Air infiltration was modelled through the permeability of the building envelope, taken to be 11.5 m^3/m^{2}h at 50 Pa for unretrofitted walls. The retrofit scenario consists of the addition of wall insulation applied internally (retrofitted wall U-value = 0.60 W/m^{2}K), the replacement of windows with triple-glazing (U-value = 1.80 W/m^{2}K) and the improvement of building fabric permeability to 5 m^3/m^{2}h at 50 Pa according to values provided for 'best-practice' retrofitted dwellings. Due to the limited overshadowing levels of mid-floor flats by surrounding buildings, the case study was simulated as a stand-alone tower and no adjacent volumes were included in the model.

A simple window opening pattern depending on internal temperatures was specified in the model. Windows were assumed to open when temperature exceeds the CIBSE Guide A upper thermal comfort temperature, which is 23°C for bedrooms and 25°C for living rooms and other spaces, and to have 100% aperture when internal operative temperature reaches the overheating limit, which is 26°C for bedrooms and 28°C for living rooms and other spaces (CIBSE, 2007). In addition, windows were assumed to close when the external temperature exceeds the internal operative temperature. This scenario chiefly aims to simulate thermal comfort-driven ventilation patterns.[2] Taking into account that the windows are fitted with trickle vents, it was assumed that occupants would not tend to open windows frequently at lower temperatures with the aim to solely improve indoor air quality. The internal doors of the living room and kitchen were considered to be always open, while bedroom doors were considered to be closed during the night. The door of the bathroom was considered to be open when unoccupied. Two natural ventilation and cooling strategies were tested: The all-day 'rapid' ventilation scenario assumed that all windows open if the internal temperature goes above CIBSE overheating thresholds (as explained above) and close if the external rises above the internal, during the entire day if the room is occupied. The night cooling scenario assumed that all windows would open if the internal temperature goes above CIBSE overheating thresholds (as explained above) and close if the external rises above the internal only during the night time between 22:00 and 06:00; windows were modelled as closed outside this period. This strategy was combined with internal blinds, which remained closed during the day between 07:00 and 19:00.

The second scenario represents three of the recommendations of the Heatwave Plan for England (NHS England & PHE, 2014), as summarized in the Key Public Health Messages, *i.e.* to keep indoor environments cool by keeping windows that are exposed to the sun closed during the day; opening windows at night when the temperature has dropped; and closing curtains that receive morning or afternoon sun.

A number of recent EPSRC-funded research projects have generated hourly weather files based on the UK Climate Projections (UKCP09, UKCIP, 2009) such as the PROMETHEUS project (Eames, Kershaw, & Coley, 2011). These weather files can be used for building simulations, and are available for several future time slices, and a number of UK locations. A PROMETHEUS Design Summer Year (DSY) weather file for Islington, London, was used in the present study to represent a hot, but not extreme, summer (defined as the period from April to September; CIBSE, 2002). The DSY has some recognized limitations that contradict its definition as a near extreme summer year, and has been found not to be always a reliable metric for overheating for certain UK locations (CIBSE, 2009). The reason for this is that a relatively cooler summer can have strong heatwaves, causing more overheating problems than a generally warmer summer (*i.e.* that of a DSY) with less intense peaks in temperatures. Nonetheless, DSYs are the standardized weather files used for overheating analysis.[3] Taking into consideration the case study building's projected lifetime, one DSY weather file, representing the projected climate for Islington in the 2050s under the a1b Medium emissions scenario (50th percentile) was used to model the potential overheating risk in the case study building due to future climate change.

Modelling of indoor air pollutant concentrations

In addition to thermal modelling, EnergyPlus was used to simulate the infiltration of $PM_{2.5}$ from the outdoor environment into the indoors. The airflow network algorithm and the recently introduced generic contaminant model of EnergyPlus v. 8.0.0.007 (US DoE, 2014) allows the simultaneous simulation of the thermal, airflow and air contaminant transport behaviour of a building. Only $PM_{2.5}$ infiltration from the outdoor environment was considered. The constant outdoor $PM_{2.5}$ concentration was set to 13 $\mu g/m^3$, the average $PM_{2.5}$ concentration for a number of London monitoring sites according to existing literature (Shrubsole et al., 2012), with a deposition rate of 0.39 h^{-1} (Ozkaynak et al., 1996). No internal sources were included in the model as the objective of the paper is to examine infiltration of outdoor pollutants into the indoor environment. The ratios of indoor/outdoor (I/O) concentrations for each room were then calculated for the modelled summer period.

Overheating assessment criteria

There has been significant debate in recent years regarding defining indoor overheating criteria, especially for free-running dwellings (BSI, 2007; CIBSE, 2007, 2013; Gupta & Gregg, 2012; Lee & Steemers, 2013; Lomas & Kane, 2013; Nicol, Hacker, Spires, & Davies, 2009; Peacock et al., 2010; Porritt et al., 2012; Roberts, 2008a, 2008b). Whilst the static, single temperature exceedence criteria are simpler to use, they have been widely criticized for not factoring in acclimatization effects and other factors of adaptive capacity (Nicol et al., 2009). Following a review by the CIBSE Overheating Taskforce, new overheating criteria were produced that adopt the adaptive approach to thermal comfort (CIBSE TM52, CIBSE, 2013), which are based on BS EN 15251 (BSI, 2007). It is pointed out that although the guidance is primarily intended for application to non-domestic buildings, the approach is likely to be, to some extent at least, relevant to overheating assessment in domestic buildings. For instance, a recent study by Lomas and Kane (2013) compared the static CIBSE criteria (CIBSE, 2007) to the newly introduced adaptive criteria (CIBSE, 2013). The study suggested that although the static criteria are simpler to use, the adaptive approach is more appropriate for free-running buildings where occupants have high adaptive capacity, such as opening windows, using blinds and curtains, consuming cold beverages, having cold showers and adjusting clothing and metabolic activity levels. However, there are some issues regarding the applicability of adaptive criteria in residential spaces occupied by vulnerable individuals during heatwave periods that require further investigation. First, the adaptive thresholds were initially developed for office buildings; further research is needed to see how these could be adapted for residential environments. A wider range of adaptive opportunities are usually available to people at home compared with office buildings, and, thus, the use of the current BS EN 15251 temperature ranges may overestimate heat-related discomfort; they could, however, still be used to indicate upper thresholds of comfort. Second, Porritt et al. (2012) notes that the BS EN 15251 adaptive thresholds are not adequately tested for running mean outdoor temperatures above 25°C. Furthermore, taking into consideration that vulnerable individuals, such as bedridden and elderly occupants are less able to modify their immediate environment or acclimatize to the external weather, a more static criterion may still be suitable for the assessment of overheating in such properties.

Taking the above into account, indoor overheating was assessed using both sets of criteria for the monitored case studies and the modelled dwelling variant:

- the static single temperature exceedance approach (CIBSE Guide A, CIBSE, 2007)
- the adaptive external climate dependent approach (CIBSE TM52, CIBSE, 2013).

According to the static thresholds of CIBSE Guide A (CIBSE, 2007), overheating in naturally ventilated residential spaces is deemed to occur when indoor temperature exceeds the specified thresholds for at least 1% of the occupied hours during the summer period (Table 3), a series of metrics clearly influenced by occupancy patterns (Lee & Steemers, 2013).

The adaptive equation for comfort used in BS EN 15251 relates the indoor comfort temperature to the outdoor air temperature. A full multi-criteria adaptive thermal comfort analysis exceeds the scope of the present paper. Indicatively, only Criterion I of the adaptive approach was applied to estimate the frequency of overheating occurrences in the monitored dwelling and modelled variants, according to which the difference between the internal operative temperature and $T_{\max}$ should be not greater than or equal to 1°C for more than 3% of occupied hours during the summer period, where $T_{\max}$ is given by equation (1)

Table 3 CIBSE Guide A acceptable summer indoor comfort temperatures, benchmark summer peak temperatures and overheating criteria for free-running dwellings

Room type	Acceptable operative temperature for indoor comfort in summer	Benchmark summer peak temperature	Overheating criterion
Living rooms	25°C	28°C	1% annual occupied hours over 28°C
Bedrooms	23°C (sleep may be impaired above 24°C)	26°C	1% annual occupied hours over 26°C

of Category III (existing buildings where there are moderate expectations as regards to the thermal environment):

$$T_{\max} = 0.33T_{\mathrm{rm}} + 22.8^{\circ}\mathrm{C} \qquad (1)$$

where T_{rm} is the exponentially weighted running mean of the daily mean outdoor air temperature.

A common characteristic of the indoor overheating assessment criteria presented above is that they are based on the measurement of *operative* temperature. A limitation of indoor temperature monitoring studies is that *dry bulb air* temperature rather than operative temperature is normally collected due to the increased cost and complexity associated with the measurement of mean radiant temperature. A commonly made assumption is, therefore, that dry bulb temperature is equal to mean radiant temperature and, as a result, to operative temperature (CIBSE, 2007). This, however, may not be the case in indoor spaces with high levels of exposed thermal mass or high indoor air velocity.

The analysis of indoor air quality did not apply similar criteria for indoor pollution levels as there is no 'safe' threshold or level of exposure to $PM_{2.5}$ below which no adverse health effects occur (WHO, 2013). Although guidelines exist for outdoor $PM_{2.5}$ concentrations (10 μg/m^3 for the annual mean and 25 μg/m^3 for the daily mean not to be exceeded for more than 3 days/year), these are deemed to only represent an achievable objective and further reductions are encouraged where possible as health effects have been observed even at low concentrations. Furthermore, the contribution of indoor $PM_{2.5}$ exposure on adverse health impacts is less well understood.

Results, analysis and discussion

Current summer thermal performance

The period of monitoring included a hot spell period between 12 and 23 July during which outdoor temperatures reached a maximum of 33.2°C at London's Heathrow Airport, and averaged 23.4°C during the daytime and 22.8°C at night. The outdoor temperatures for the monitoring period can be seen in Figure 2, with the hot spell period highlighted. As mentioned above, data loggers were only placed in two of the case study flats during this period (A1 and C3).

The internal temperatures measured in all flats are summarized for living rooms in Figure 3 and bedrooms in Figure 4, alongside the static CIBSE thresholds for summer overheating. Indoor temperatures in living rooms were found to exceed the 28°C overheating threshold only during the hot spell period, while the 25°C upper thermal comfort threshold was exceeded regularly during the monitoring period. Bedrooms exceeded the 23°C and 24°C upper thermal comfort and sleep disruption thresholds regularly, and exceeded the 26°C overheating threshold during the hot spell event, and later in the observation period when heating systems are likely to have been switched on. Temperatures were observed to go below the minimum thresholds for the living rooms and bedrooms in late summer before the communal central heating systems were turned on.

The results for the overlapping monitored period 15–22 August, when all dwellings had monitors installed, were analysed to determine the differences in thermal performance under common weather conditions. Descriptive statistics for all dwellings can be seen in Tables 4 and 5. The flats with the highest percentage of hours spent above temperature thresholds were those of the 1960s' high-rise blocks. The results indicate that flats C2 and C3 performed the worst during the daytime (Table 4), and flats B1, C1, C2 and C3 had the greatest overheating problems during the night (Table 5).

To explore further the relationship between external and internal temperatures, the daily mean living room and bedroom air temperatures were regressed against the corresponding daily outdoor ambient values during the monitoring period for each flat (Figures 5 and 6). As can be observed in Table 6, relatively strong correlation coefficients were obtained for all flats except for flat C2 (not displayed in the scatter plots). This provides evidence of close coupling between the external and internal environment in the case study social housing settings that could potentially be attributed to poor building fabric insulation levels

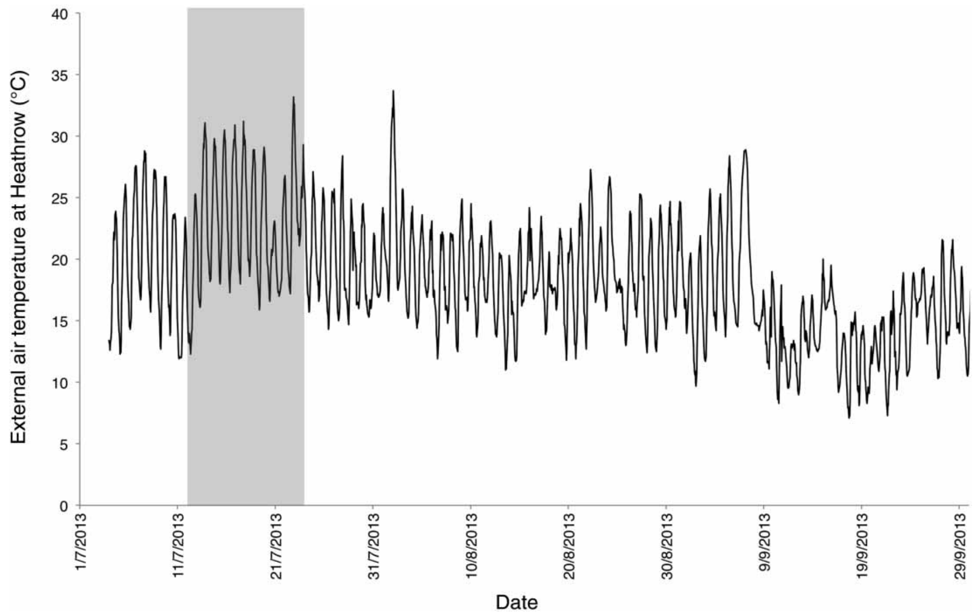

Figure 2 External air temperature at London's Heathrow airport

or frequent window opening, or a combination thereof.

The highest indoor-outdoor temperature correlation coefficients were obtained for flat C3, which is located in one of the 1960s' tower blocks and was monitored during the hot spell. Its thermal performance is, therefore, examined in greater detail in Figures 7 (living room) and 8 (bedroom), alongside the external temperature during the monitoring period and the static and adaptive thresholds for summer overheating and excess cold. Indoor

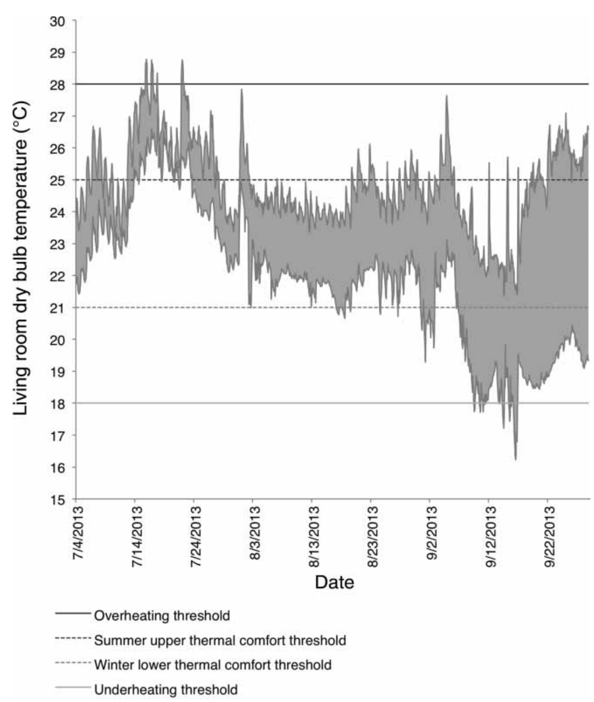

Figure 3 Living room temperatures and thresholds for monitored properties

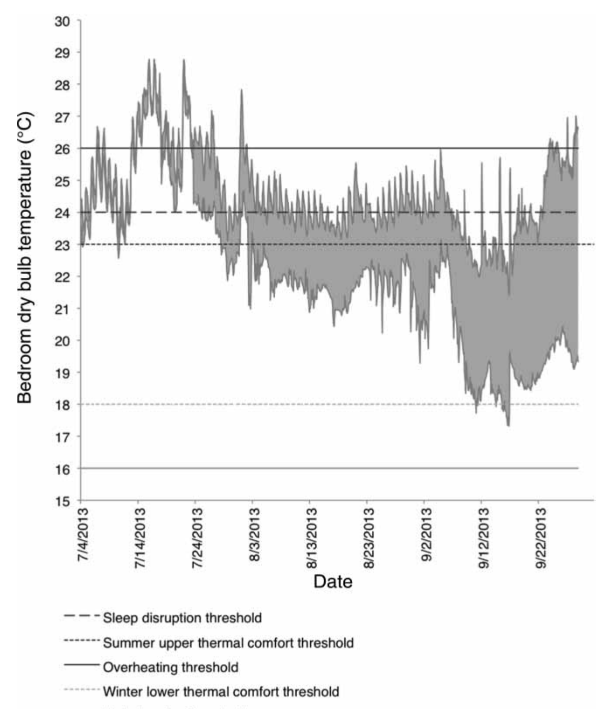

Figure 4 Bedroom temperatures and thresholds for monitored properties

Table 4 Overheating metrics during the common monitoring period (15–22 August)

Flat	Living room: > 25°C (acceptable comfort temperature threshold)	Living room: > 28°C (overheating threshold)	Bedroom: > 23°C (acceptable comfort temperature threshold)	Bedroom: > 24°C (sleep impairment threshold)	Bedroom: > 26°C (overheating threshold)
A1	0 (0%)	0 (0%)	11 (17.5%)	0 (0%)	0 (0%)
B1	0 (0%)	0 (0%)	25 (39.7%)	0 (0%)	0 (0%)
B2	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
C1	0 (0%)	0 (0%)	19 (30.2%)	0 (0%)	0 (0%)
C2	18 (17.6%)	0 (0%)	21 (33.3%)	4 (6.3%)	0 (0%)
C3	9 (8.8%)	0 (0%)	18 (28.6%)	9 (14.3%)	0 (0%)
D1	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
D2	0 (0%)	0 (0%)	42 (66.7%)	5 (7.9%)	0 (0%)

Note: Parentheses indicate the percentage of monitored hours that overheating occurred; text in bold indicates the number of hours overheating occurred beyond the 1% of monitored hours threshold.

temperatures in both rooms were found to exceed the static overheating threshold only during the hot spell period, while the upper thermal comfort thresholds were exceeded regularly. Interestingly, the internal temperatures lay below the TM 52 Criterion I overheating threshold for the entire monitoring period.

The results presented above indicate that the case study flat is prone to overheating during a period of hot weather under the current climate, if the static threshold approach is adopted, which does not factor in acclimatization and other adaptation actions the residents may take. Considering the fact that the adaptive capacity of most vulnerable individuals residing in social housing units is likely to be fairly limited, this is an indication that attention needs to be paid to such properties. However, when the adaptive approach is used, the risk of overheating appears to be significantly lower under the current climate.

Table 5 Mean maximum daytime operative temperature in the living room and mean minimum night time operative temperature in the bedroom during the common monitoring period (15–22 August)

Flat	Mean maximum living room operative temperature (°C)	Mean minimum bedroom operative temperature (°C)
A1	23.9	22.1
B1	24.1	22.9
B2	22.1	22.1
C1	23.6	22.6
C2	24.6	22.8
C3	24.2	22.2
D1	21.8	21.3
D2	23.6	23.0

Future summer thermal performance and indoor air quality

The EnergyPlus simulation results are explored to further assess the overheating risk in case study flat C3 in the future. As illustrated in Figure 9, the living room of the flat is projected to face a significant risk of overheating in the 2050s under the Medium (a1b) emissions scenario. As is evident from the graph, an unintended consequence of the thermal upgrade of the building envelope with the specific measures described earlier appears to be the increase of summer indoor temperatures, with more than 70% of occupied hours above 25°C under all variations, approaching 100% of the time for the retrofitted scenario with night only cooling and shading. Hours above 28°C occur for between 24% and 60% of occupied time, which is well above the 1% CIBSE Guide A threshold, whereas when the adaptive thermal comfort criterion is applied, living room temperatures are found to be equal or higher than the specified overheating limit for 3% of the time or higher. An important finding to emerge from this analysis is that, for this dwelling geometry and the specific set of assumptions made, the all-day ‘rapid’ ventilation strategy appears to be more effective than the night cooling scenario combined with daytime shading (around 17% less hours above 28°C for the retrofitted variant). This suggests that the solar protection offered by the internal curtains and the night cooling effect do not adequately protect the living rooms in south-oriented flats when constantly

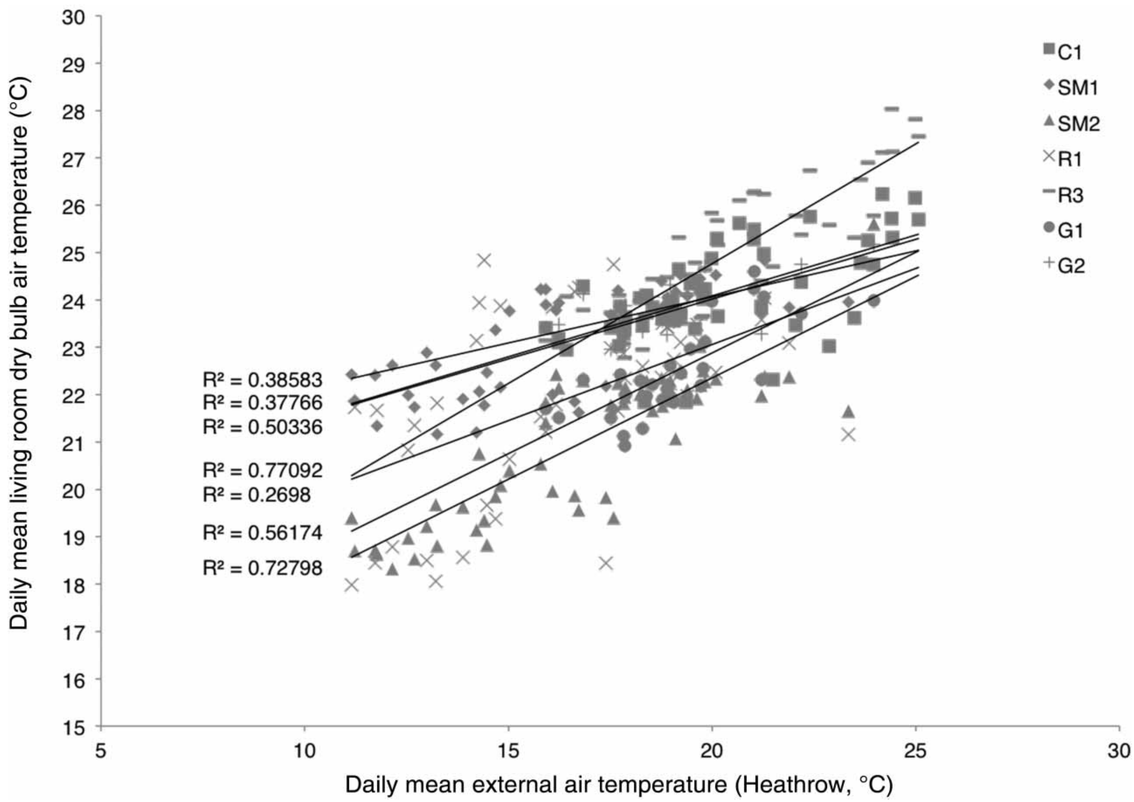

Figure 5 Scatter plot of daily mean living room operative temperature in each flat during the monitoring period against daily mean external air temperature in Heathrow

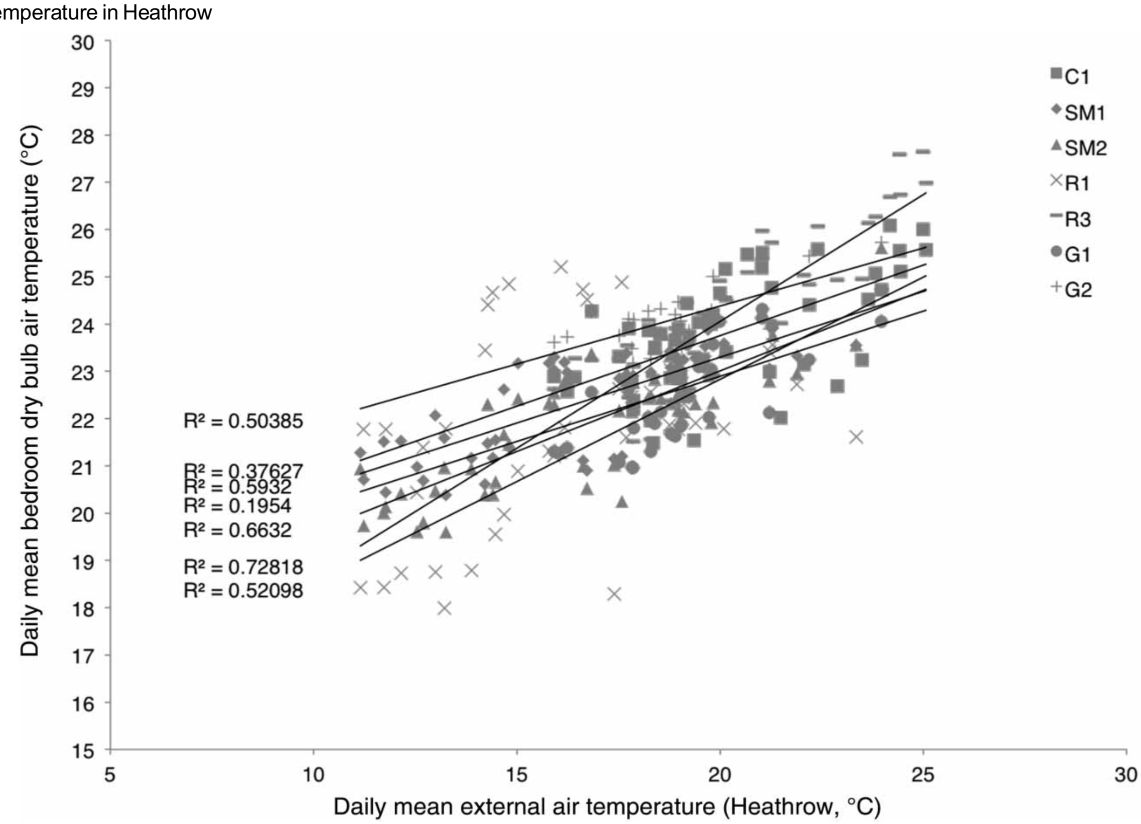

Figure 6 Scatter plot of daily bedroom operative temperature in each flat during the monitoring period against daily mean external air temperature in Heathrow

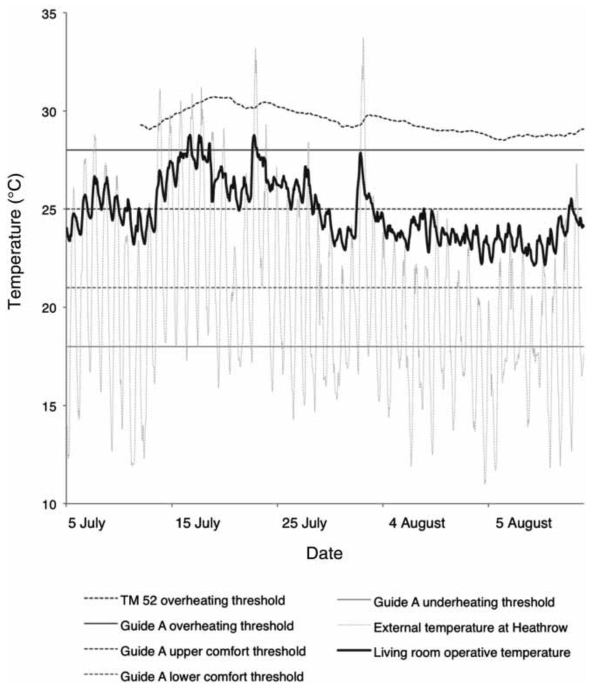

Figure 7 Living room temperature during the monitoring period

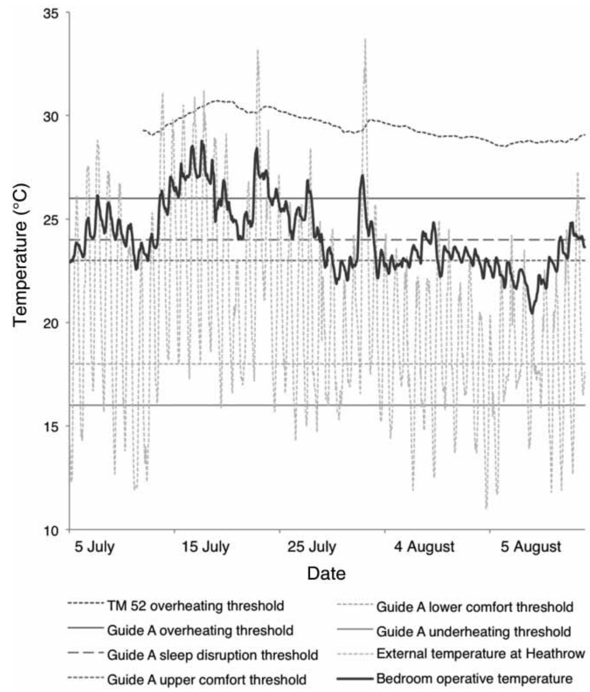

Figure 8 Bedroom temperature during the monitoring period

occupied during the daytime. It is, thus, recommended that properties of this type, which are heavily occupied by vulnerable individuals during the daytime, are either ventilated throughout the day or are protected by more efficient solar protection measures, such as external louvres or other shading devices. Similar levels of overheating are observed in the bedroom (Figure 10), however, night 'purge' cooling seems to be more successful in reducing temperatures (around 10% less hours above 26°C for the retrofitted variant).

Whilst night ventilation may offer some relief from elevated night time temperatures in the bedroom, potential trade-offs between thermal comfort and indoor air quality need to be investigated. Figure 11 attempts to explore such interaction effects during the three hottest consecutive days of the selected weather file (14–17 August). As can be observed from the graph, in the evening, bedroom internal temperatures rise above the window opening threshold of 23°C, which causes windows to remain open for most of the night and $PM_{2.5}$ I/O ratios to approach 1.0 due to the ingress of outdoor air, an effect that is common for both ventilation strategies. During the day, when the bedroom is unoccupied I/O ratios fall markedly but still lie above 0.5 for most of the time, with the absolute indoor concentration lying between 6.0 and 12.9 $\mu g/m^3$. The lowest mean indoor concentration value was observed for the existing, night cooling and shading scenario (10.4 $\mu g/m^3$), whereas the highest one for the retrofitted, all-day rapid ventilation scenario (11.7 $\mu g/m^3$).

Table 6. Pearson correlation of determination (R^2) of daily mean operative temperature in each flat during the monitoring period and daily mean external air temperature at Heathrow

Flat	Bedroom	Living room
A1	0.376	0.378
B1	0.593	0.503
B2	0.663	0.728
C1	0.195	0.270
C2	0.033	0.122
C3	0.728	0.771
D1	0.521	0.562
D2	0.504	0.386

As mentioned above, there are no 'safe' $PM_{2.5}$ concentration thresholds, as there could be health risks associated with exposure even at low concentration levels (WHO, 2013). However, according to a study on the long-term health effects of exposure in European cities (Boldo et al., 2006), even small reductions in annual average $PM_{2.5}$ concentration levels (by around 3.5 $\mu g/m^3$) could potentially lead to significant reductions in all-cause mortality. An implication of this finding is that the applicability of night ventilation strategies as, for example, suggested by the NHS Heatwave Plan, may be hindered in dwellings similar to the

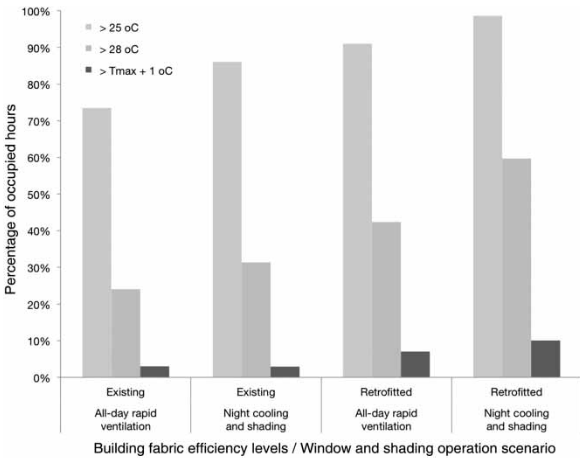

Figure 9 Living room exceedance of overheating thresholds during the summer period under the 2050s Medium emissions 50th percentile UKCP09 scenario

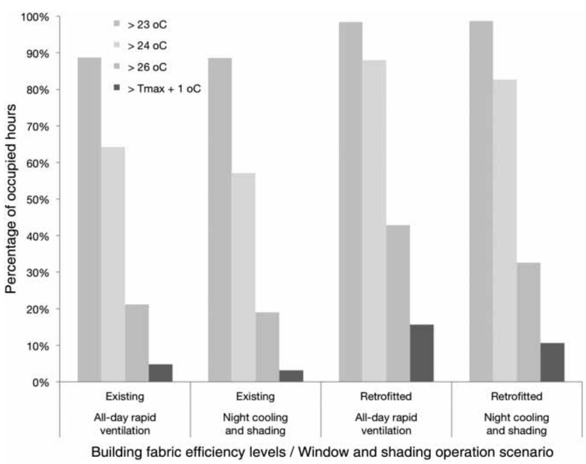

Figure 10 Bedroom exceedance of overheating thresholds during the summer period under the 2050s Medium emissions 50th percentile UKCP09 scenario

case study flat located in core urban areas due to outdoor pollution concerns.

Study limitations

The main sources of uncertainty in the monitoring described in this study are outlined below:

- For the purposes of internal overheating assessment, it was assumed that dry bulb air temperature is equal to operative temperature.
- The study results need to be interpreted with caution due to its small sample size. Some of the differences in monitored data between dwelling types, for example, could potentially be explained by differences in individual occupant behaviour rather than building characteristics. Despite the small number of monitored dwellings, however, this pilot study offers valuable insights into the relationship between external and internal temperatures in social housing in South Islington and has raised a number of questions that could be addressed by a future large-scale monitoring study in these estates.
- Both the static and adaptive overheating criteria were applied in this study. An arguable limitation of the adaptive thermal comfort criteria is the fact that they have been derived from studies carried out in non-domestic environments.

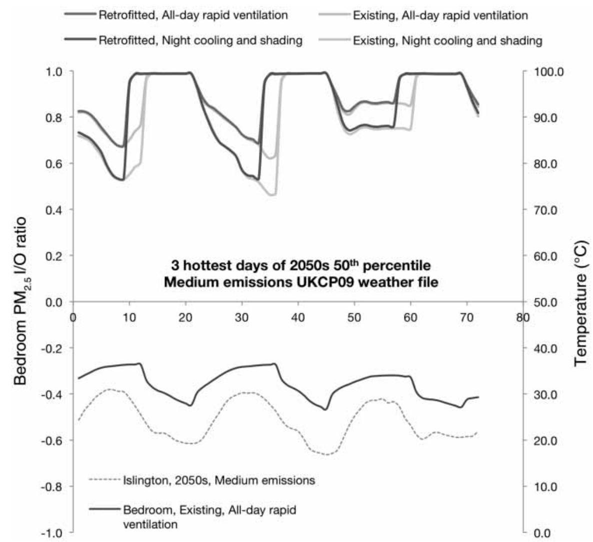

Figure 11 Bedroom temperature and PM2.5 I/O ratios during the 3 hottest consecutive days of the 2050s Medium emissions 50th percentile UKCP09 scenario

The findings of the modelling study are also subject to a number of limitations:

- One of the case study flats was studied in detail using dynamic thermal simulation. Unfortunately, it was not possible to calibrate the model using the monitored data from this flat due to the lack of detailed information on the behaviour of the occupants.
- The use of EnergyPlus has allowed the investigation of interactions between indoor thermal conditions and air quality but the monitoring part of the study only involved temperature measurements.
- The case study building model also only examined the ingress of external $PM_{2.5}$ and omitted indoor $PM_{2.5}$ sources or other internally generated pollutants.

Suggestions for future research

As mentioned in the Introduction, the work presented in this paper was a pilot study aiming to investigate the feasibility of a larger scale monitoring study across a statistically representative sample of social housing in Central London. It was indicated that a range of different participant engagement strategies needs to be explored for the particular socioeconomic group (elderly social housing residents), in order to elicit engagement and achieve a larger sample size in future studies. In order to address the limitations of the present monitoring study that were outlined in the previous section, a number of suggestions for future work are provided below:

- Future monitoring work should include the measurement of mean radiant temperature to increase the accuracy of the assessment.

- To minimize the level of uncertainty associated with occupant behaviour, it is recommended that in future studies occupants could keep logs to record specific behaviour variables, such as clothing levels, activity, hours of sleep, use of blinds, etc. In addition to this, CO_2 monitors, occupancy sensors and electricity sub-meters could be installed in a subsample of dwellings in order to collect data about door and window opening behaviour, occupancy patterns, use of appliances and resulting internal heat gains.

- With regard to thermal comfort assessment, adjustment factors for domestic environments that take into account a broader range of adaptive capacity parameters could be developed.

The present study belongs to a series of pilot evaluations of coupled thermal comfort and indoor environmental quality models (Mavrogianni et al., 2013). In addition, ongoing work[4] aims to develop further such combined temperature and multi-pollutant models for a wide range of representative building typologies of the UK housing stock:

- the collection of occupant behaviour data described above could aid in the development of realistic scenarios of occupancy scenarios and building systems use, which could increase the accuracy of the modelling inputs

- simultaneous monitoring of indoor temperature and airborne contaminant concentrations would greatly help the understanding of interrelationships between the two and allow the validation of the air contaminant transport component of the model

- the addition of other internally generated pollutants, such as volatile organic compounds (VOCs), nitrogen dioxide (NO_2), ozone (O_3) and carbon monoxide (CO), forms part of ongoing work.

Implications for building design practice and seasonal health policy

This study extends the knowledge on the summer thermal performance of council-owned residential blocks. A number of implications arise for both building designers and energy retrofit providers, as well as local authority health policy-makers:

- *Retrofit and design*. Monitoring work demonstrates that some of the flats experience a significant number of overheating hours even during a warm, but not extremely hot, period. The modelling work indicates that currently applied passive cooling strategies, such as internal blinds and window opening would not adequately reduce excess indoor temperatures. It is, thus, suggested that future retrofit plans of the estates should incorporate more efficient cooling design options, such as external shutters (Gupta & Gregg, 2012) while, at the same time, ensure that the whole-year performance of air tightness and insulation measures is studied to avoid any unintended consequences on the summer thermal behaviour of the building (Shrubsole et al., 2014). A combined matrix of the year-round performance of energy efficient retrofit measures and passive cooling strategies for different social housing typologies could assist with the selection of the most appropriate set of interventions by local authorities and housing associations.

- *Public health*. This study adds to a growing body of evidence on the importance of housing characteristics on occupant exposure to excess indoor heat and pollutants. This is particularly important as it is often suggested that public health professionals often do not fully recognize the importance of the built environment for population health. Studies similar to the one presented in this paper can contribute to raising awareness as regards to the importance of building fabric and indoor environment on occupant health and encourage the adoption of a proactive rather than reactive approach to indoor overheating and pollution prevention. This study adds to an emerging body of literature indicating the need to identify current and future climate vulnerability in a more systematic way. Using existing heatwave vulnerability mapping tools (Mavrogianni et al., 2009; MoL, 2011; Wolf & McGregor, 2013), early seasonal health prevention strategies could, for example, focus on targeting heat vulnerability 'triple jeopardy' hotspot areas and prioritize retrofit work in flats designated as unsuitable for vulnerable residents. Where such interventions are not feasible within a given time frame, such an approach could also aid in the identification of certain dwelling types that may pose a significant risk to vulnerable residents for certain periods of time, *e.g.* during a prolonged heatwave. It would, therefore, help seasonal health professionals identify the vulnerable residents and develop targeted responses in an efficient and timely manner, *e.g.* by offering other means of heat protection to high-risk groups, according to the recommendations of the Heat Wave Plan for England (NHS England & PHE, 2014). This could involve the close monitoring of vulnerable individuals, access to cooler spaces, provision of health and social care, communication of messages on how to keep cool and mobilization of community networks in the targeted areas.

Conclusions

The primary aim of this pilot study was to assess the current summer thermal performance of a small number of council-owned flats in Central London occupied by individuals who are likely to be susceptible to hot weather. Further modelling work set out to evaluate the levels of future overheating risk due to background regional warming and potential interaction effects with indoor air quality. The analysis of the monitored data suggests that the case study flat already experiences hours with temperatures above the recommended thresholds, even during a relatively mild summer (*e.g.* the summer of 2013). However, estimates of the magnitude of current summer thermal discomfort risk largely depend on the criterion used; static or adaptive. In the future, such risks are likely to be exacerbated by a rise in ambient temperatures and certain retrofit measures (increased airtightness, internal wall insulation). Natural ventilation alone is likely to be insufficient to keep indoor thermal conditions within acceptable limits and its cooling potential may be further limited due to outdoor air pollution concerns. This preliminary study enhances the understanding of the complex interrelationships between the indoor thermal environment and airborne contaminant transport in heat vulnerable urban homes. It is recommended that a comprehensive modelling approach is adopted prior to the design of retrofit interventions in heat-vulnerable properties.

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Endnotes

[1]On the ground floor, other uses are accommodated along with the caretaker's flat, linked with the office and workshop spaces. The community centre and a nursery, which includes an extension to the west, have separate entrances.

[2]It does not aim to capture intermittent, indoor air quality-driven window use, *e.g.* to remove odours etc., which is likely to occur at lower temperatures but for shorter periods of time.

[3]Ideally, a full climate change impact assessment study would compare different time slices, *e.g.* 2030s versus 2050s and 2080s. However, the PROMETHEUS weather files are created using the UKCP09 weather generator and, therefore, each file is characterized by different weather patterns. As pointed out by the creators of the files, one of the limitations of the probabilistic climate information and the variation in weather patterns is that this could result in unexpected outcomes, such as reduced hours of overheating in 2080 compared with 2050, hence their direct comparison is not advised.

[4]Ongoing work includes an EPSRC-funded project 'Air Pollution and Weather-Related Health Impacts: Methodological Study based on Spatio-temporally Disaggregated Multi-Pollutant Models for Present Day and Future' (http://www.bartlett.ucl.ac.uk/iede/research/project-directory/projects/awesome) and the NIHR Health Protection Research Unit (HPRU) in Environmental Change and Health (http://www.bartlett.ucl.ac.uk/iede/research/project-directory/projects/health-protection-research-unit).