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A coupled summer thermal comfort and indoor air quality model of urban high-rise housing

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Abstract
The synergistic effects between summertime ventilation behaviour, indoor temperature and air pollutant concentration in relation to energy retrofit and climate change have been under-investigated to date. This paper explores such interactions in a social housing setting. The case study flat is located on a mid-floor of a high-rise council tower block in central London. Dwellings of this type are likely to be occupied by vulnerable individuals (elderly people or people suffering from ill health or mobility impairment). Monitoring and modelling of the thermal and airflow performance of the case study suggests that its occupants may be already exposed to some degree of overheating. Whilst improved natural ventilation strategies may reduce such risks to a certain extent, their potential may be limited in the future due to high external temperatures and the undesired ingress of outdoor pollutants, thus highlighting the need for further adaptation measures.

Keywords: comfort, overheating, indoor air quality, climate change, high-rise housing

1 Introduction
1.1 Comfort and health impacts of urban warming trends
Anthropogenic climate change is predicted to increase the frequency and severity of heatwave events (Beniston et al, 2007). Whilst developing countries are likely to be harder hit by global warming effects (The World Bank 2008), the low income groups of inner cities in temperate climates are also vulnerable to extreme weather events (IPCC 2007). As population exposure to unprecedentedly high temperatures is becoming more frequent, heat related morbidity and mortality is an increasing concern in previously heating dominated climates, as highlighted, for example, by the NHS Heatwave Plan for England (NHS England and PHE 2013). In terms of mortality, the 2003 heatwave resulted in an estimated 70,000 excess deaths across Europe (Robine et al, 2007), of which approximately 2,000 occurred in the UK (Johnson et al, 2005) and around 600 in London alone (MOL 2007). Summer temperatures are projected to increase by up to 4 ºC 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 ºC, 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; for example, the DEFRA National Adaptation Programme which outlined the UK Government’s plans for becoming more climate ready (DEFRA 2013).

It has been indicated by a number of studies that heat-related mortality risk increases in urban environments due to the exacerbation of hot spells by the urban heat island phenomenon (Kovats and Kristie 2006, Hajat et al, 2007), i.e. the inadvertent local urban climate modification caused by urbanisation 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, for example the installation of air conditioning and associated waste heat to urban canyons, could potentially lead to a further intensification of warming trends (Gupta and Gregg 2012, Peacock et al, 2010). Whilst the use of active cooling systems could be beneficial for human health in the short term (Keatinge and Donaldson 2004), these will lead to negative environmental and financial consequences for households. Active cooling equipment in residential environments is currently rare in the UK, however, it is expected that a large percentage of household spaces in England will be equipped with mechanical cooling systems by 2030 based on future climate change projections (Collins et al, 2010). It is hence essential to reverse this trend through the adoption of alternative passive adaptation solutions across the UK housing stock.

Furthermore, although there is a plethora 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, these issues are usually examined in isolation and synergistic effects between summertime ventilation behaviour, indoor temperature and air pollutant concentration have been under-investigated to date.

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

1.2 Factors influencing indoor environmental quality in dwellings

People in the UK tend to spend 95% 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 is reviewed in detail elsewhere (DCLG 2011). 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 purpose-built flats that are located in core urban areas and lack sufficient solar protection and/or ventilation are more prone to overheating (Orme and Palmer 2003, CIBSE 2005, Hacker et al, 2005, Salagnac 2007, Vandertorren 2007, Oikonomou et al, 2012, Mavrogianni et al, 2012). In particular, the relative risk of overheating in top floor 1960s flats is 6 times that of ground floor flats in the same block (depending on orientation) and around 9 times that of Victorian terraces (DCLG 2011).

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 and Wright 2008), corroborating the results of the modelling studies.

Taking into account that a large proportion of high-rise housing developments in the UK belong to the social housing sector, it is suggested that adaptation studies should give particular emphasis to this dwelling type. 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 means to adapt their homes to a changing climate by themselves, and negative impacts of climate change on social housing are likely to have repercussions to entire communities.

It has been suggested that occupant behaviour can have a measurable impact on indoor overheating (Coley et al, 2012, 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, (2013), actual data on the way people operate their homes during the summer period is 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 et al, 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. In urban centres, levels of outdoor pollutants such as $PM_{2.5}$, NO_2, and SO_2 can be high due to high volumes of traffic, dense road networks, and industry. Pollutants may also be generated from indoor activities, for example cooking, smoking, and cleaning (Shrubsole 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 2002), and is estimated to cause a 7.17% 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 may influence the degree of exposure, particularly to pollution from outdoor sources.

1.3 Study aims

Due to the increased overheating risk in certain dwelling types, the urban heat island, and the vulnerability of the occupant population in social housing, there is an urgent need to study the summertime thermal performance of high-rise council flats in central London. This paper presents preliminary results obtained from a pilot 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 South Islington 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 et al, 2013).

The geographical focus of CRISP was the South Islington area, comprising of Bunhill, Clerkenwell and Pentonville, in central London. As mentioned previously, the borough of Islington has been identified as a 'triple jeopardy hotspot' (MoL 2012) on the basis of its heatwave vulnerability for the following reasons:

- Islington is located in an area characterised 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 characterised by high inequality levels.
- It has the lowest male life expectancy in London, and its population is characterised 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.
- A large proportion of residents live in council-owned flats in tower blocks or other types of high-rise social housing.

This paper focuses on the results obtained from a case study flat located on a mid-floor of a high-rise purpose-built council tower block in the borough. Its aims are two-fold:

- to assess the current summertime thermal performance of the case study flat, using monitoring; and
- to explore 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.

2 Methods

2.1 Case study building

As mentioned earlier, 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.

The case study block of flats is representative of high-rise developments constructed under the Social Housing Schemes in the 1960s and 70s, the structural characteristics of which are widely documented (Chown 1970, Glendinning and Muthesius, 1994, Capon and Hacker, 2009). 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 building were constructed to last until the mid-21st century (Glendinning and Muthesius 1994).

The tower block under examination was built in 1963. It is a 17-storeys high 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), therefore a vulnerable group in terms of overheating risk (Kolm-Murray 2013). The tower block has a symmetrical U-shaped layout, with the long side facing broadly north-south. The building is largely unshaded, although a recent 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 elevator towers. On the ground floor, other uses are accommodated along with the caretaker's flat, linked with office and workshop spaces. The community centre and a nursery which includes an extension to the west have separate entrances. A typical floor plan is shown in Figure 1. The drawings were reproduced from drawings available by Homes for Islington and were based on interpretation of photos and onsite visits including detailed measurements inside the case study mid-floor flat facing southwest (CW). Most floors contains 6 two-bedroom flats with an area of 55 to 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 (frame-infilling and frame-cladding structures), but with some small areas of insulated cavity wall. There are a few sections of uninsulated cavity wall at ground level. Double-glazed windows with trickle vents were installed in 2004/05.

Figure 1. Standard floorplan of the case study building

2.2 Monitoring of indoor thermal conditions

Onset HOBO U12-012 data loggers (Onset Computer Corporation 2013), were used for the monitoring of indoor thermal conditions in the case study flat (mid-floor, flat CW in Figure 1). The loggers recorded dry bulb air temperature (accuracy ± 0.35 °C from 0 to 50° C) at 15-minute intervals for 2 months during the summer (early July to early September 2013). The sensors were placed in convenient locations at approximately eye level 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 will monitor indoor air pollutants alongside hygrothermal conditions.

2.3 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 (Oikonomou et al, 2013, Mavrogianni et al, 2012, Mavrogianni et al, 2013, Taylor et al, 2014, Mavrogianni et al, 2014). Simulations were then run for the following combinations:

- two levels of building fabric efficiency levels (as built and retrofitted); and
- two types of window and shading operation (daytime 'rapid' ventilation vs. night time 'purge' cooling combined with daytime shading).

The existing building fabric was modelled according to information from the site visit and architectural drawings. U-values for the walls, ground floor, roof, and windows were inferred based on the construction age of the case study building using the RdSAP methodology (BRE 2009). The building structure is a typical reinforced concrete frame grid; external walls are mainly precast concrete parts with no insulation (U-value = 2.00 W/m^2K). The floors consist 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^2K). Air infiltration was modelled through the permeability of the building envelope, taken to be 11.5 m^3/m^2h @ 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^2K), the replacement of windows with triple glazing (U-value = 1.80 W/m^2K) and the improvement of building fabric permeability to 5 m^3/m^2h @ 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 2006). In addition, windows were assumed to close when the external temperature exceeds the internal operative temperature. 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 daytime '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 6:00; this strategy was combined with internal blinds which remained closed during the day between 7:00 and 19:00. The second scenario represents three of the recommendations of the Heatwave Plan for England (NHS England and PHE 2013), as summarised 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 which are based on the UK Climate Projections (UKCP09, UKCIP 2009) such as the PROMETHEUS project (Eames et al, 2011). These weather files are appropriate 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 period. The DSY has some recognised 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 standardised weather files used for overheating analysis. Ideally, a full climate change impact assessment study would compare different time slices, e.g. 2030s vs. 2050s and 2080s. However, the PROMETHEUS weather files are created using the UKCP09 weather generator and, therefore, each file is characterised by different weather patterns. As pointed out by the creators of the files, one of the limitations of the probabilistic climate information and the weather patterns variation is that this could result in unexpected outcomes, such as reduced hours of overheating in 2080 compared to 2050, hence their direct comparison is not advised. 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 (50^{th} percentile) was used to model the potential overheating risk in the case study building due to future climate change.

2.4 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 μg/m^3, the average $PM_{2.5}$ concentration for London according to existing literature (Shrubsole et al, 2012), with a deposition rate of 0.00010833 m/s. 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.

2.5 Overheating assessment criteria

There has been significant debate in recent years regarding defining indoor overheating criteria, especially for free-running dwellings (CIBSE 2006, BSI 2007, Roberts 2008, Nicol et al, 2009, Peacock et al, 2010, Gupta and Gregg 2012, Porritt et al, 2012, Lomas and Kane 2012, CIBSE TM52 2013, Lee and Steemers 2013). Whilst the static, single temperature exceedance criteria are simpler to use, they have been widely criticised for not factoring in acclimatisation effects and other factors of adaptive capacity (Nicol 2009). Following a review by the CIBSE Overheating Taskforce, new overheating criteria were produced which 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, to a large extent, relevant to overheating assessment in domestic buildings. For instance, a recent study by Lomas and Kane (2012) compared the static CIBSE criteria (CIBSE 2006) to the newly introduced adaptive criteria (CIBSE 2013) and 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 to 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 ^{o}C. Furthermore, taking into consideration that vulnerable individuals, such as bed-ridden and elderly occupants are less able to modify their immediate environment or acclimatise 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 study and the modelled dwelling variants:

- 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 2006), 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 1), a series of metrics clearly influenced by occupancy patterns (Lee and Steemers 2013).

Table 1. CIBSE Guide A General summer indoor comfort temperatures, benchmark summer peak temperatures and overheating criteria for free-running dwellings

Room type	**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

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 ^{o}C for more than 3% of occupied hours during the summer period, where T_{max} is given by equation (1) of Category III (existing buildings where there are moderate expectations as regards to the thermal environment):

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

where T_{rm}: the exponentially weighted running mean of the daily-mean outdoor air temperature

The analysis of indoor air quality did not apply similar criteria for indoor pollution levels as there is no ‘safe’ threshold for $PM_{2.5}$.

3 Results and discussion

3.1 Current summer thermal performance

The period of monitoring occurred during late summer, and included a hot spell from July 12th to July 23rd during which outdoor temperatures achieved a maximum of 33.2 °C at London Heathrow[1], and averaged 23.4 °C during the daytime and 22.8 °C at night. The overheating assessment results are summarised in Table 2.

Table 1 Hours above overheating thresholds for bedrooms and living rooms during the monitoring period in the case study flat. Brackets () indicate the percentage of monitored hours that overheating occurred, highlighted cells indicate overheating occurring for above 1% of the monitored hours.

	Living room			Bedroom			
Criterion	**> 25 °C**	**> 28 °C**	**> T_{max} + 1 ^{o}C**	**> 23 °C**	**> 24 °C**	**> 26 °C**	**> T_{max} + 1 ^{o}C**
Hours (% occupied)	328 (43.9%)	29 (3.9%)	0 (0.0%)	286 (64.7%)	187 (42.3%)	50 (11.3%)	0 (0.0%)

The internal temperatures measured in the living rooms of the case study flat are demonstrated in Figure 2, and the bedroom temperatures in Figure 3, alongside the external temperature during the monitoring period and the static and adaptive thresholds for summer overheating and excess cold. 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. Interestingly, the internal temperature

[1] Although it would have been preferable to plot internal temperatures against local external temperature in Islington, the measurements at the London Heathrow station were deemed more reliable. It needs to be noted, however, that they do not fully capture local heat island effects.

lies well 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 acclimatisation 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.

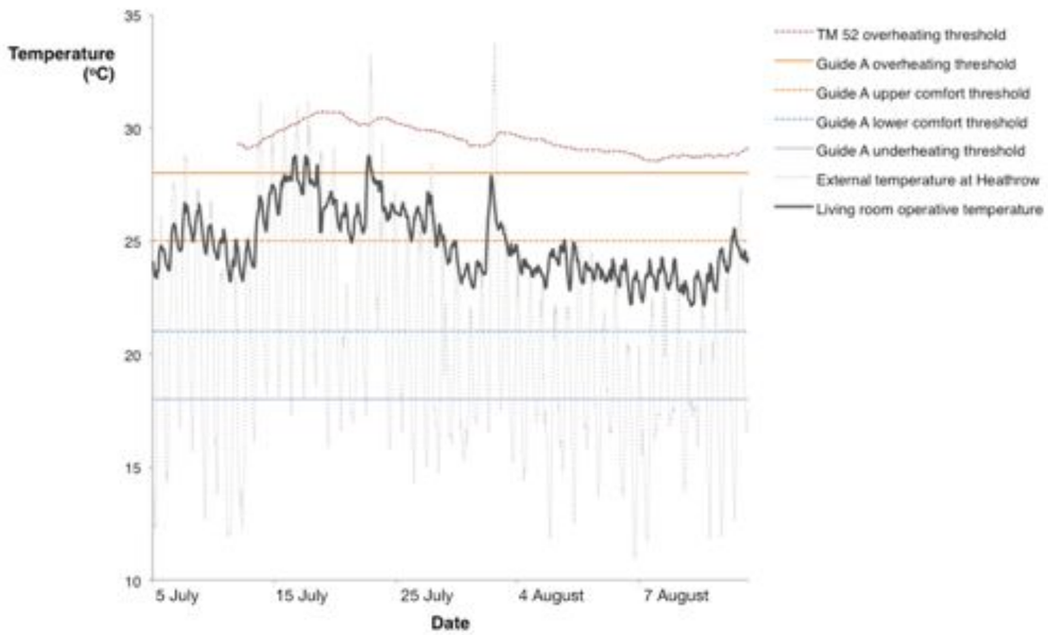

Figure 2. Living room temperature during the monitoring period

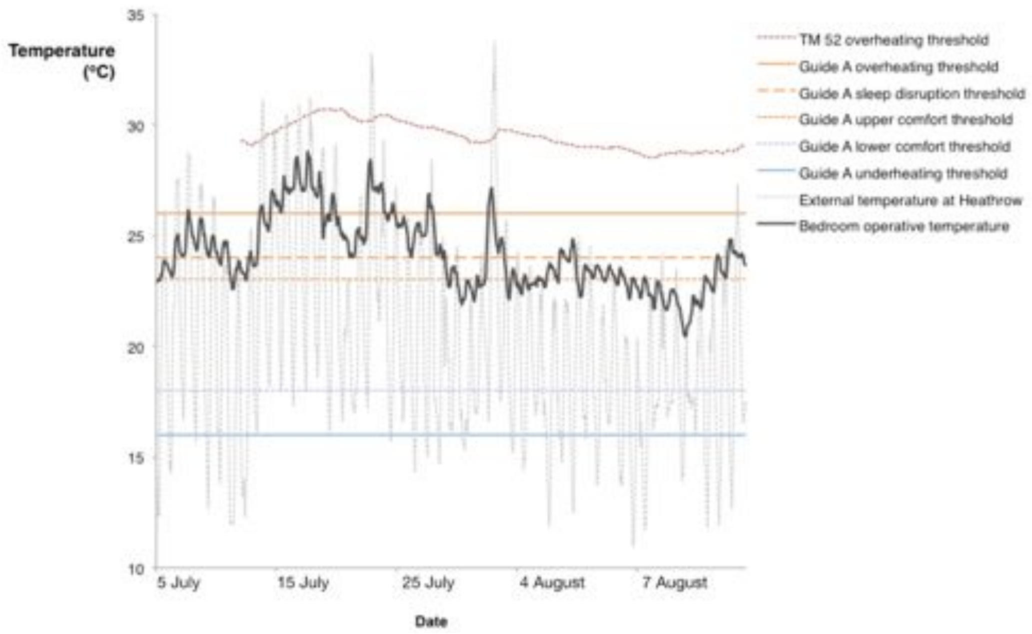

Figure 3. Bedroom temperature during the monitoring period

3.2 Future summer thermal performance and indoor air quality

The EnergyPlus simulation results are explored to further assess the overheating risk in the case study in the future. As illustrated in Figure 4, 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 ^{o}C under all variations, approaching 100% of the time for the retrofitted scenario with night only cooling and shading. Hours above 28 ^{o}C occur for between 24% to 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 daytime 'rapid' ventilation strategy appears to be more effective than the night cooling scenario combined with daytime shading (around 17% less hours above 28 ^{o}C for the retrofitted variant). This suggests that the solar protection offered by the internal curtains and the night cooling effect do not adequately cool down the south-oriented, constantly occupied during the daytime, living room. 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.

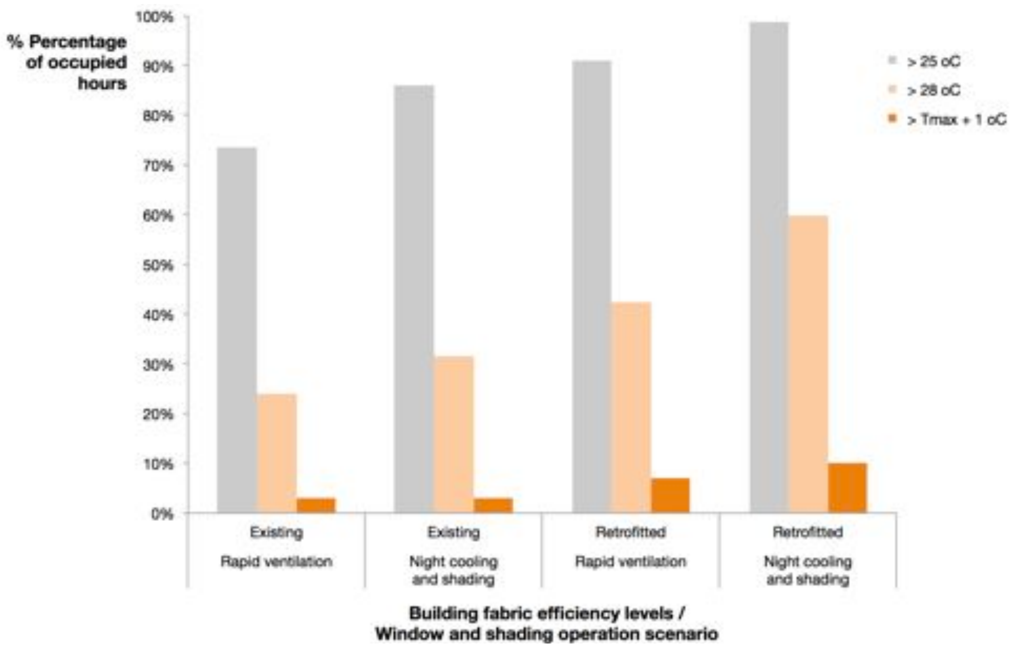

Figure 4. Living room exceedance of overheating thresholds during the summer period under the 2050s Medium emissions 50th percentile UKCP09 scenario

Similar levels of overheating are observed in the bedroom, however, night 'purge' cooling seems to be more successful in reducing temperatures (around 10% less hours above 26 ^{o}C for the retrofitted variant).

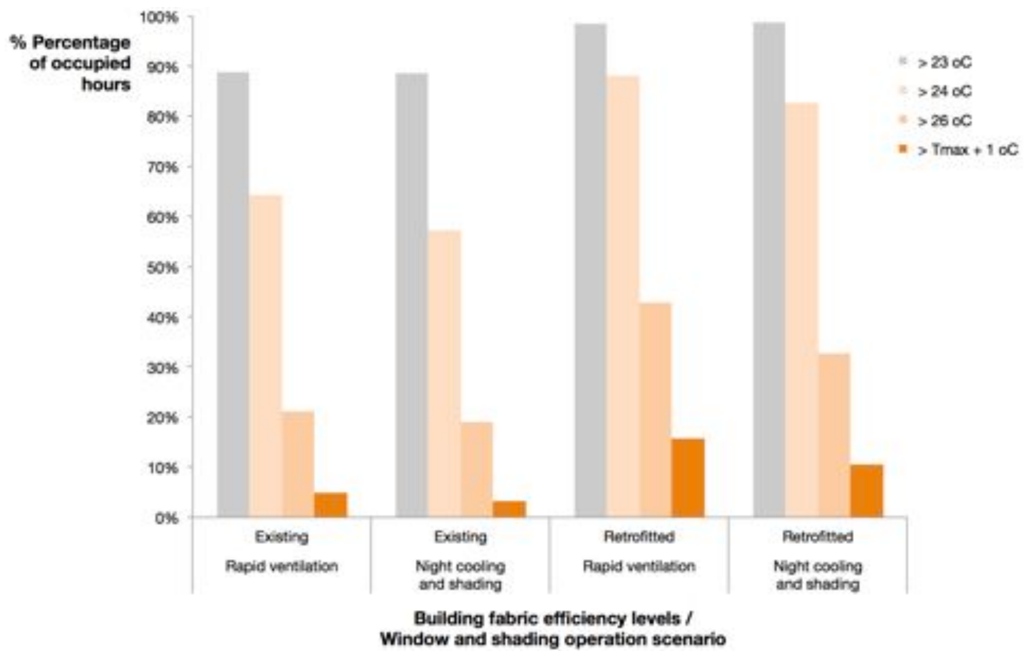

Figure 5. Bedroom exceedance of overheating thresholds during the summer period under the 2050s Medium emissions 50th percentile UKCP09 scenario

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 6 attempts to explore such interaction effects during the 3 hottest consecutive days of the selected weather file (14th-17th August). As can be observed from the graph, in the evening, bedroom internal temperatures rise above the window opening threshold of 23 ^{o}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. 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 case study flat located in core urban areas due to outdoor pollution concerns. A significant limitation of the present study is, however, the omission of indoor $PM_{2.5}$ sources or other internally generated pollutants.

The present study belongs to a series of pilot evaluations of coupled thermal comfort and indoor environmental quality models (Mavrogianni et al, 2013). Ongoing work as part of the EPSRC project 'Air Pollution and WEather-related Health Impacts: Methodological Study based On spatio-temporally disaggregated Multi-pollutant models for present day and futurE' (AWESOME 2014) aims to further develop such combined temperature and multi-pollutant models for a wide range of representative building typologies of the UK housing stock.

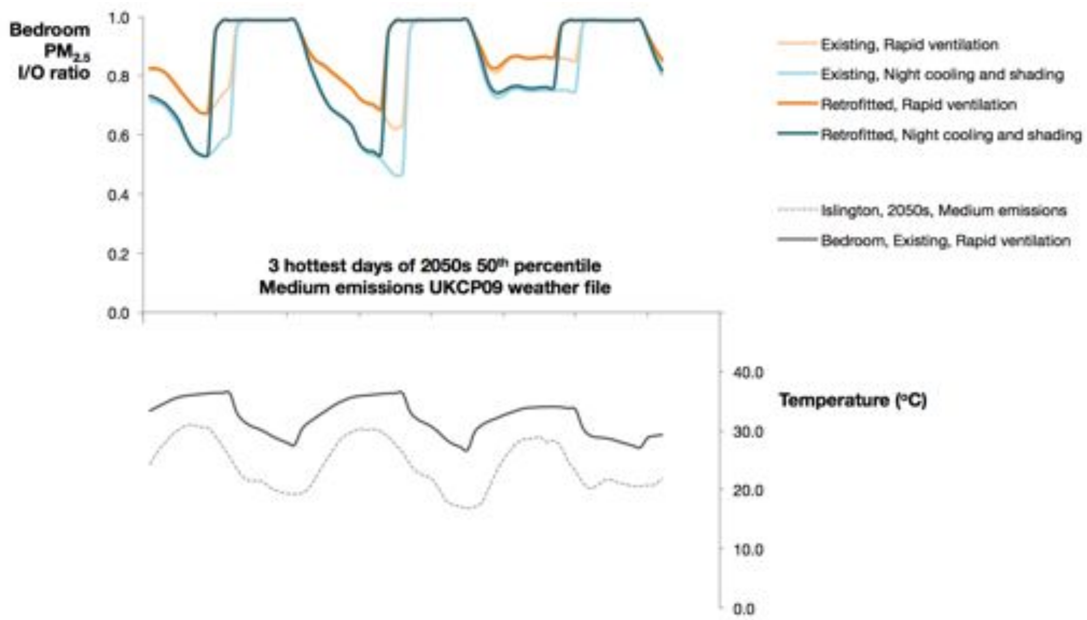

Figure 5. Bedroom temperature and $PM_{2.5}$ I/O ratios during the 3 hottest consecutive days of the 2050s Medium emissions 50th percentile UKCP09 scenario

4 Conclusions

This study set out to determine the current levels of overheating risk in a mid-floor south-facing flat of a social housing tower block in central London, occupied by vulnerable individuals, and evaluate the levels of future risk due to background regional warming and potential interaction effects with indoor air quality. The analysis of the monitored data suggested that the case study flat already experiences hours with temperatures above the recommended thresholds, even during a relatively mild summer like the one of 2013. It was shown, however, that 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 may not suffice 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 our understanding of the complex interrelationships between the indoor thermal environment and airborne contaminant transport in heat vulnerable urban homes. It is recommended that a holistic modelling approach is adopted prior to the design of retrofit interventions in heat-vulnerable properties.

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