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Investigating the overheating risk in refurbished social housing

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Abstract

Global average surface temperatures are predicted to rise from 1 to 5°C by 2100. Also, extreme events such as heat waves are expected to increase in intensity, frequency and duration. In most of Europe and other developed countries, existing buildings are projected to form from 70% to 80% of the built stock by 2050. Investigating the risk of overheating in the existing building stock is therefore crucial in order to adopt measures which can help to mitigate what it can be a lethal effect of global warming: prolonged exposure to high temperatures in buildings. By collecting measured data, this study investigates indoor temperatures and thermal comfort in bedrooms, kitchens and living rooms of 46 newly-retrofitted free-running social houses in Exeter, UK during the summer 2014. The overheating risk was evaluated using the CIBSE TM52 adaptive benchmark. It was seen evidence of 10 out of 86 rooms overheating in 9 dwellings. It was found that kitchens and bedrooms are the rooms with the greater overheating risk among the monitored spaces. It was also found that old and vulnerable occupants are at a higher risk of being exposed to high indoor temperatures due to fact that they spent most of their time indoor and also because of poor indoor ventilation.

Keywords: Overheating, thermal comfort, social housing, environmental monitoring

1 Introduction

Heatwaves are periods in which high outdoor temperatures persist for several consecutive days and night temperatures do not drop enough to allow buildings to cool down. Sadly famous is the heat wave of August 2003 which is estimated to have caused over 35000 deaths in Europe, including 2000 in UK, with the majority of the victims being among the elderly and long-term sick people (Stott *et al.*, 2004; Johnson *et al.*, 2005). Global average surface temperatures are predicted to rise from 1 to 5°C by 2100 (IPCC, 2013) and heat waves are expected to increase in intensity, frequency and duration (Meehl and Tebaldi, 2004; Jones *et al.*, 2008). In dense urban environments their consequences will be exacerbated by the urban heat island effect. The unusual warm summer of 2003 is expected to become usual by the 2050s and will be considered unusually cool by the 2080s (Coley *et al.*, 2012).

At the same time, climate change concerns and related mitigation strategies are driving the need of a more energy efficient built environment. As a result, super-insulated and airtight houses are currently being built or refurbished in order to reduce winter heating demand and associated greenhouse gas emissions. An attempt to reduce energy consumption for space heating has been seen in both

newly-built and refurbished UK social dwellings, which are supposed to be driving the change in the British built environment.

There is already evidence of overheating happening in UK and Northern European homes which have been refurbished or newly built in order to comply with the new energy efficiency and zero carbon standards such as, for example, passive social housing flats in Coventry, UK (Tabatabaei Sameni *et al.*, 2015) and passive houses in Linköping, Sweden (Rohdin *et al.*, 2014). The evidence is so clear that a UK national report has been written, describing interventions to improve energy efficiency that can prevent overheating in the future (Dengel and Swainson, 2012).

A plethora of studies have used dynamic thermal simulation in order to see how different energy refurbishments would affect building overheating in current and future weather scenarios (Mavrogianni *et al.*, 2012; Tillson *et al.*, 2013; Porritt *et al.*, 2011; Porritt *et al.*, 2012; McLeod *et al.*, 2013; Oikonomou *et al.*, 2012; Ji *et al.*, 2014). However, little is still known about the current situation of retrofitted “energy-efficient” buildings (Vardoulakis *et al.*, 2015) and the literature only offers a limited range of monitoring studies, the most relevant found for this work were: (Tabatabaei Sameni *et al.*, 2015; Lomas and Kane, 2013; White-Newsome *et al.*, 2012; Beizaee *et al.*, 2013; Sakka *et al.*, 2012).

This implies that there is little empirical evidence in order to inform retrofit decision-making and there is still little knowledge on the way energy efficient homes reacts to high outdoor temperatures (Dengel and Swainson, 2012). Monitoring and investigating the risk of overheating in the existing building stock is therefore important in order to adopt measures which can help to mitigate the worst effects of global warming. This is especially important for households with elderly people who spend most of their time indoor and that are particularly vulnerable to high temperatures.

Furthermore, the majority of the monitoring studies have measured indoor temperature conditions in living rooms, see for example (Sakka *et al.*, 2012), while there are only few studies which have monitored environmental parameters in other rooms such as kitchens and bedrooms.

Another problem is that existing standards used for quantifying the severity and frequency of overheating have not been derived from direct assessment in homes. The BS EN15251 adaptive thermal comfort model (Nicol and Humphreys, 2010), upon which the overheating recommendation of the UK Chartered Institution of Building Services Engineers (CIBSE) is based, has been deduced from data predominately obtained during field studies in office buildings where people have less opportunity to adapt than in their homes. This fact suggests that the BS EN15251 comfort standards might be applicable for the residential stocks but it also reveals that its applicability and validity needs to be tested with thermal comfort field-studies in homes.

In order to address the gaps seen above, our study uses data from more than 60 newly-retrofitted (i.e. reasonably well-insulated) social housing dwellings in Exeter in South West England (Figure 2). Temperature and humidity of living rooms, kitchens and bedrooms (Figure 3) were measured every 5 minutes during the summers of 2014 and 2015. Occupancy was inferred from multiple motion sensors. Additionally,

during the summer 2015, CO₂ levels were monitored in living rooms. Occupant thermal comfort was surveyed through a paper-based questionnaire distributed at the end of the summer 2014 and through telephone interviews carried out throughout the summer 2015. This paper reports the results for summer 2014, as the authors are still performing the analysis for the summer of 2015.

Different housing design characteristics (roof exposure and façade orientation) and occupant variables (vulnerability, occupant ventilation patterns) are used to conduct the meta-analysis of the 86 monitored rooms. The adaptive overheating criteria of CIBSE TM52 (based on the European Standard EN15251 adaptive model of thermal comfort) are used to assess overheating in the different monitored rooms.

2 Factors affecting overheating

Occupants' behavioural thermal adaptation refers to all the conscious or unconscious actions that a person can take in order to modify the building indoor environment, their personal situation or both of these. In reducing temperatures and hours of overheating, Coley et al. have found that occupants' behavioural adaptation (night cooling done by opening of windows, closing window when the external temperature is greater than the internal, reduced electrical gains by better housekeeping) is equally important in order of magnitude to common structural adaptations (increased thermal mass, night cooling done by additional vents, external shading above windows, solar-control glass, reduced electrical gains by using more efficient items) (Coley *et al.*, 2012). Behavioural adaptation is related to the specific characteristics of the occupants; for example, elderly and people with compromised health might have a limited control of ventilation due to restricted possibility of movement.

Since overheating depends on both occupants and dwelling characteristics, social and behavioural factors interweave with structural aspects making it particularly difficult to assess its causes.

The following has been seen about factors that can affect the severity of overheating:

- Urbanization and the associated urban heat island effect increases ambient temperatures and prevent the cooling of the buildings at night. It also influences occupant ventilation patterns especially night cooling due to outdoor pollutions, noise and security reasons (Mavrogianni *et al.*, 2012).
- Floor level, orientation of the dwelling (Porritt *et al.*, 2012) and glazing to wall ratios affect the severity of solar gains (McLeod *et al.*, 2013).
- The absence of window shading (fixed external shading devices or external shutters) also affects solar gains (McLeod *et al.*, 2013; Porritt *et al.*, 2012).
- The dwelling rate of overcrowding affects internal heat gains while their insulation and air-tightness prevents the release of the accumulated heat (Beizaee *et al.*, 2013).
- The building thermal mass influences heat amortization by absorbing heat gains during the day and releasing them during the night. This strategy is efficient if there is a drop in night temperatures and a sufficient night ventilation of the building.



Figure 1 Location of the city of Exeter in South West England (Source: Google Maps ©)

The evidence shows that properties with a particularly high risk of overheating are:

- flats (Lomas and Kane, 2013; Beizaee *et al.*, 2013) and, especially, top floor flats (Beizaee *et al.*, 2013),
- dwelling built after 1990 (Beizaee *et al.*, 2013),
- any dwelling when occupied by vulnerable tenants (e.g. old people) (Tabatabaei Sameni *et al.*, 2015),
- bedrooms of any property when compared to living room (Firth and Wright, 2008).

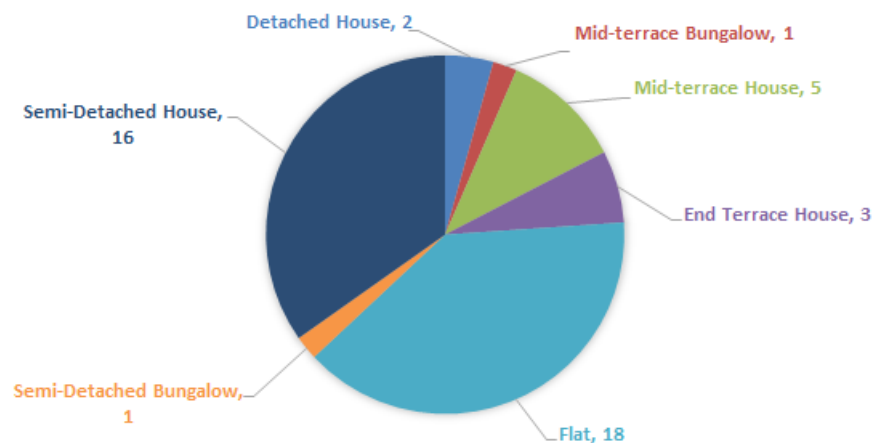


Figure 2 Distribution by built type of the 46 monitored dwellings.

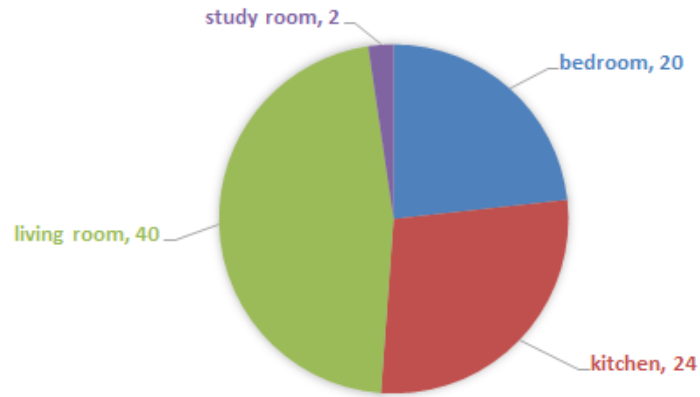


Figure 3 Overview of the 86 monitored rooms.

3 The social housing context

Social housing provides houses for those who cannot afford to buy one in the UK. Social homes represent 17% of the total number of houses in UK (DCLG, 2015a). There are some peculiar characteristics about social houses which make them particularly vulnerable to overheating:

- They have the highest rate of overcrowding in the country (DCLG, 2015a).
- Their tenants have the highest unemployment rate and the lowest average income (DCLG, 2015b).
- Their tenants belong to the highest age bands.
- Windows of new build social housing are forced to only open to an angle of no more than 10 degrees for security reasons (RoSPA, 2008); this limits the possibility of ventilation through the windows.

4 CIBSE TM52 adaptive thermal comfort benchmark

The adaptive overheating criteria of CIBSE TM52 are based on the European Standard EN15251 adaptive model of thermal comfort. According to it, the maximum allowable temperature T_{max} for free running buildings is not a fixed threshold but it depends on the outdoor temperature (Nicol and Humphreys, 2010). There are two maximum temperature limits which depend on the degree of vulnerability of the occupants:

$$T_{max} = 0.33 * T_{rm} + 20.8 \text{ for Category I}$$

$$T_{max} = 0.33 * T_{rm} + 21.8 \text{ for Category II}$$

where T_{rm} is the exponentially weighted running mean of the daily mean outdoor air temperature (Figure 7). Category I includes particularly fragile and vulnerable occupants while Category II is for normal expectation occupants (Figure 7).

According to the adaptive overheating criteria of CIBSE TM52, a room is overheated if two of the three following criteria fail:

- *Frequency of overheating: Hours of Exceedance Criterion.* The number of hours during which DeltaT (i.e. the difference between Operative and Maximum Temperature, $T_0 - T_{max}$) is above 1°C (Hours of Exceedance, H_e) should not exceed 3% of the occupied hours during the summer season (May to September). $H_e < 3\%$.

- *Severity of overheating within any day: Daily Weighted Exceedance Criterion.* The Daily Weighted Exceedance (W_e) shall be less than or equal to 6 in any day during the summer season (May to September). $\sum(W_e > 6) < 0\%$:

$$W_e = (h_{e_0} * 0) + (h_{e_1} * 1) + (h_{e_2} * 2) + (h_{e_3} * 3) \text{ where } h_{e_y} \text{ is the time in hours when } T_0 \text{ is above } T_{max} \text{ by } \gamma^\circ\text{C.}$$

- *Upper limit temperature criterion.* δT (i.e. $T_0 - T_{max}$) should never exceed 4°C . $\sum(\delta T > 4) < 0\%$.

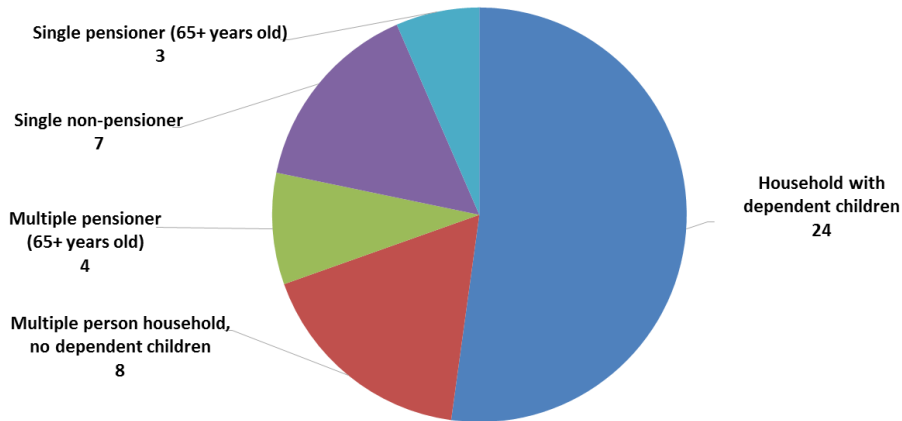


Figure 4 Overview of the demographic of the households

5 Study methodology

A monitoring campaign was conducted in living rooms, kitchens and bedrooms of more than 60 social housing dwellings in Exeter for over 2 years. Environmental and motion wireless sensors were installed in every monitored room and reported data every 5 minutes to a university-hosted database. Additionally, during the summer of 2015, CO₂ levels were monitored in living rooms. The accuracy of the used sensors is reported in Table 2. This paper reports the results of the indoor temperatures monitored during the first summer (from 1st of May to 31st of September 2014). Results from only 46 houses are reported since the rest of the houses had too many data missing or the quality of the data was not sufficient to perform the analysis. Only those sensors reporting more than 75% of the time during the hottest months of June, July and August were selected for the analysis. Occupancy patterns were derived for each monitored room using the data from the infrared motion sensor, humidity and temperature sensors.

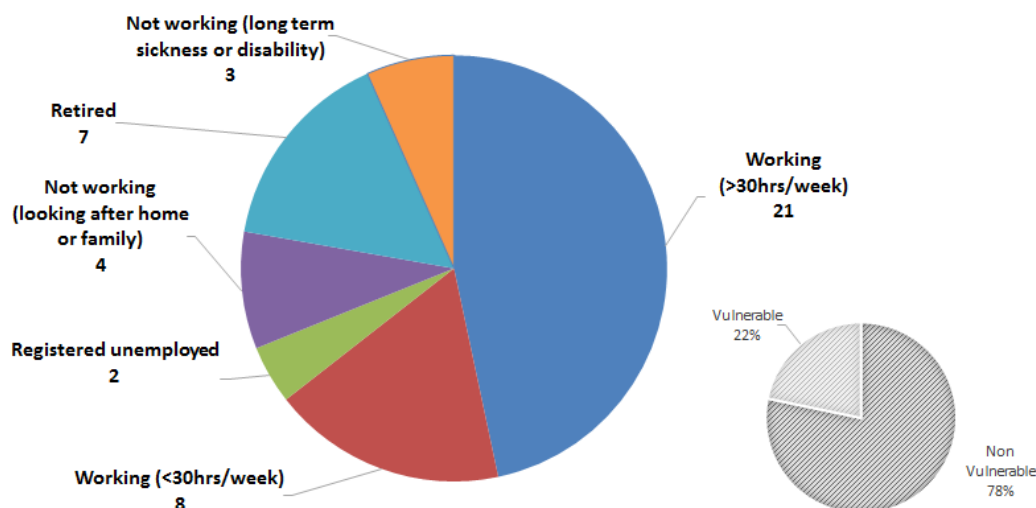


Figure 5 Economic status of households

The questionnaire administered at the end of summer 2014 included one question about the perceived subjective temperature in summer (This summer, when the weather was warm, how did you find the temperature in your home?) with 7 possible levels of comfort to choose from (1 = Much too cool, 2 = Too cool, 3 = Comfortably cool, 4 = Neither warm nor cool, 5 = Comfortably warm, 6 = Too warm, 7 = Much too warm). The questionnaire also included two questions assessing ventilation and cross ventilation habits. The first question was about window opening behaviours and can be seen in Table 1. The second question concerned cross-ventilation habits (At the moment, how often do you (or someone else in your household) open windows on opposite sides of the building to get a draught flowing through your home?) with five different level of frequency to choose from (1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Often, 5 = Every day).

Table 1 Question about window opening habits

When you open the windows in your home, how often is it for the following reasons?

To cool your home down	1, 2, 3, 4, 5
To get rid of smells or smoke	1, 2, 3, 4, 5
To get rid of moisture	1, 2, 3, 4, 5
When a room is too stuffy	1, 2, 3, 4, 5
Because you are drying clothes	1, 2, 3, 4, 5

1 = Never, 2 = Rarely, 3 = Sometimes, 4 = Often, 5 = Always

The dwellings monitored during the summer of 2014 consisted on 18 flats, 17 between semi-detached houses and bungalows, 2 detached houses, 6 between mid-terrace houses and bungalows and 3 end-terrace houses (Figure 2). A total of 17 dwelling were built in the period between 1930-1939, 9 between 1940 and 1959 and 20 between 1960 and 1989. Out of 46 dwellings 44 were built with cavity walls. All the residences were newly refurbished with double-glazed windows and, when possible, with loft and cavity wall insulation. None of the houses were air-conditioned and in none of them window shadings were present (neither fixed external shading devices nor external shutters). All the residences were meant to be

naturally-ventilated and all the rooms in which data was gathered for the study were equipped with openable windows. Out of 86 monitored rooms 35 were ground floor rooms, 17 were mid floor rooms and 34 were roof-exposed rooms. The floor area of the dwellings ranged between 35 and 110 m² with an average value of 82 m². Cross ventilation was theoretically possible in all the dwellings.

For the analysis, we have divided the households into 2 categories according to their vulnerability. The group of vulnerable households include retired occupants older than 65 years old and disable or long term sick occupants. They represent 22% of the households (Figure 5).

6 Climatic characteristics of summer 2014

The outdoor temperature (T_{out}) was obtained performing a mean of the hourly temperatures monitored at different local weather stations. Daily mean, maximum and minimum outdoor temperatures recorded during the period May to September 2014 are shown in Figure 6. It is worth noticing that minimum outdoor temperatures fall always below 18°C. This suggests that night ventilation has a great potential for preventing overheating during the monitored summer and that, if any overheating is occurring, it should primarily be related to poor indoor ventilation.

The exponentially weighted running mean of T_{out} (T_{rm}) and the maximum allowable temperature (T_{max}) for Category I and II are shown in Figure 7.

Table 2 Instrumentation details

Parameter	Range	Accuracy
DS18B20 temperature sensor (used for both air and radiator surface temperature measurements)	-10 – +85°C	±0.5°C
RHT03 humidity sensor	0 – 100%	±2%
K30 Senseair CO ₂ sensor	0 – 5000 ppm	±30ppm
HC-SR501 PIR Infrared Motion Sensor	120°, 0 - 7m	n.a.

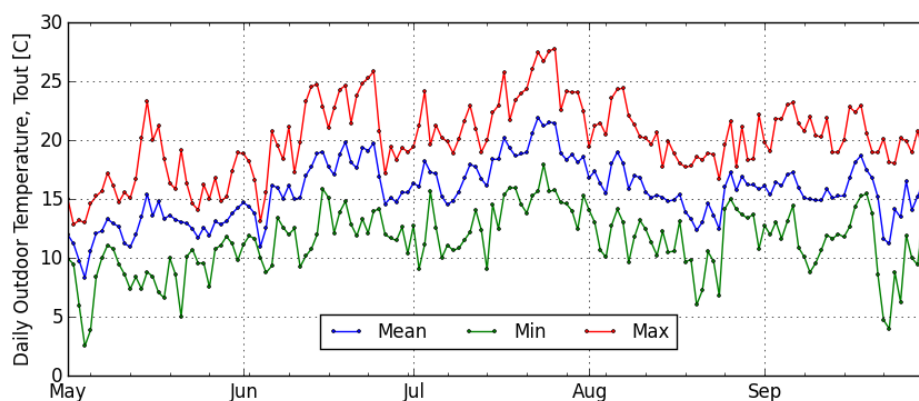


Figure 6 Daily mean, maximum and minimum outdoor temperature (T_{out}) during the period May-September 2014.

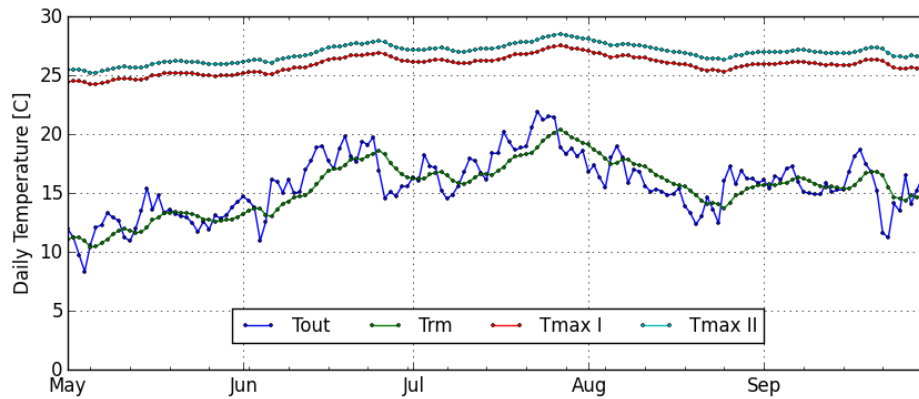


Figure 7 Daily mean outdoor temperature (T_{out}), exponentially weighted running mean of T_{out} (T_{rm}), maximum allowable temperature (T_{max}) for Category I and II during the period May-September 2014.

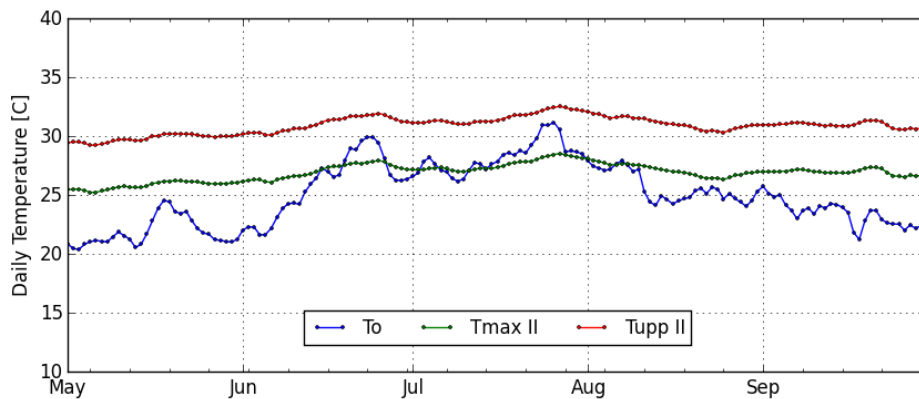


Figure 8 Daily mean indoor temperature (T_0) for the living room of home no. 33, maximum allowable temperature (T_{max}) and upper temperature (T_{upp}) for Category II during the period May-September 2014.

7 Results

Descriptive statistics of the meta-analysis of the mean indoor temperatures monitored during the months of June, July and August and filtered based on occupancy are reported in Table 3. The higher mean temperature is recorded in south-facing roof-exposed kitchens ($25.1 \pm 1.4^\circ\text{C}$), while the lowest in north-facing lower-floor living rooms ($22.6 \pm 1.2^\circ\text{C}$). Random Unbalanced Design Four-Way ANOVA was performed across the mean temperatures monitored in the different rooms and it took into account four factors: roof exposure, window façade orientation, occupants' vulnerability and type of room. Roof-exposed (RE) rooms were found to have statistically significant higher mean daily temperatures than lower-floor (LF) rooms (p -value < 0.05). South-facing rooms (i.e. rooms with at least 1 window façade facing south, between 90 and 270°C) were not found to have statistically significant different mean daily temperatures than north-facing rooms.

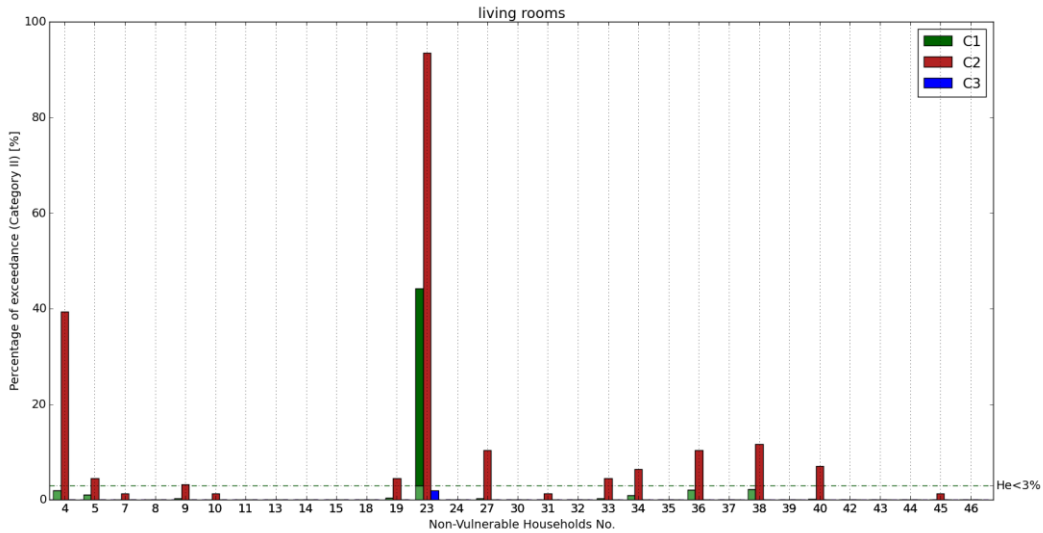


Figure 9 Percentage of exceedance for the 3 criteria (C1, C2 and C3) based on the number of occupied hours for Category II (Non-Vulnerable Households) in the monitored living rooms.

From the overheating assessment using the CIBSE TM52 adaptive benchmark, we found that 12% of the kitchens (3 kitchens, homes no. 2, 12 and 30 in Figure 10), 27% of the bedrooms (6 bedrooms, houses no. 1, 3, 9, 25, 27 and 30 in Figure 11) and 2% of the living rooms (1 living room, house no. 23 in Figure 9) suffered overheating during summer 2014. Kitchens and bedrooms were more exposed to the risk of overheating than living rooms. The higher temperatures in kitchens could be due to the high internal heat gains associated with the cooking activities, while the higher temperatures of bedrooms can be explained with the fact that they are mostly located under the roof (68% of the monitored bedrooms are roof-exposed), being kitchens and living rooms usually downstairs in majority of the English houses. High temperatures in bedrooms are particularly dangerous since there is no way of avoiding spending time in those spaces and since they cause poor sleep quality.

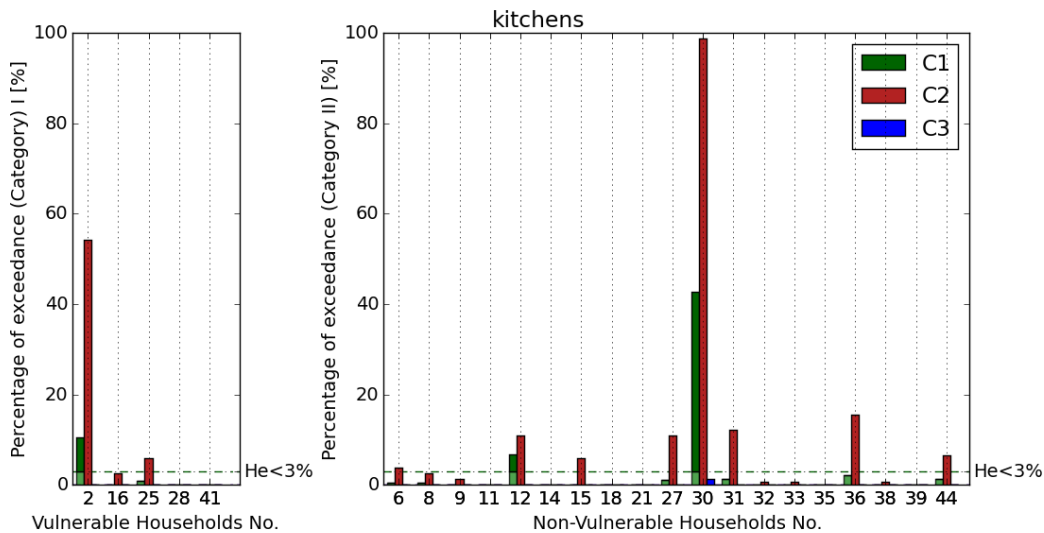


Figure 10 Percentage of exceedance for the 3 criteria (C1, C2 and C3) based on the number of occupied hours for both Category I (Vulnerable Households) and Category II (Non-Vulnerable Households) in the monitored kitchens.

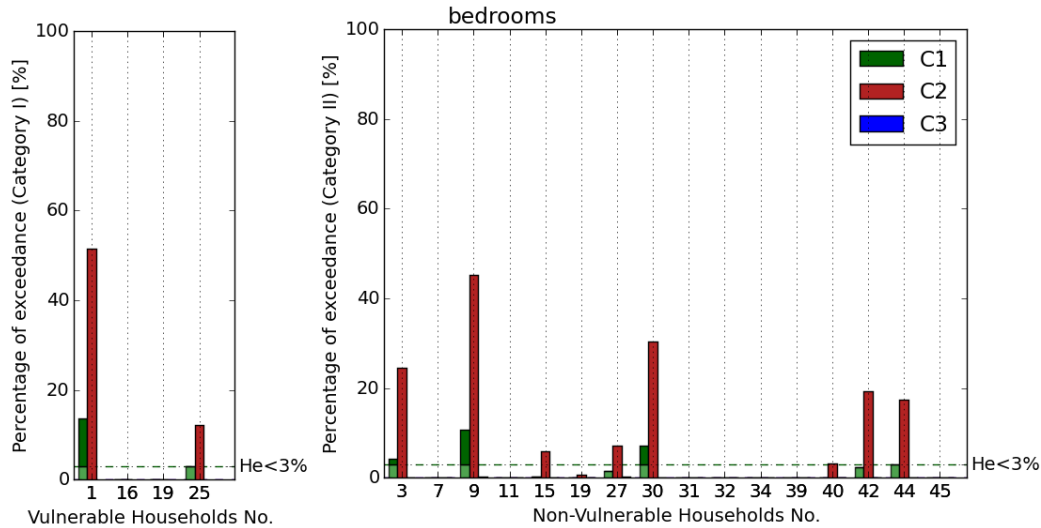


Figure 11 Percentage of exceedance for the 3 criteria (C1, C2 and C3) based on the number of occupied hours for both Category I (Vulnerable Households) and Category II (Non-Vulnerable Households) in the monitored bedrooms.

Vulnerable households were also found to have mean living rooms temperatures higher (about 0.7°C) than non-vulnerable homes but the difference is not statistically different due to the reduced sample of vulnerable living rooms compared to non-vulnerable ones. The higher temperatures recorded in vulnerable living rooms are probably due to high internal gains (high occupancy profiles) linked with poor ventilation which prevents the internal heat to be released outside.

In fact, from the statistical analysis of the survey about ventilation we have found a statistically significant difference between the average vote of vulnerable and non-vulnerable households (Figure 12 and Table 4). This indicates that old, sick and disable people have a tendency to open less the windows. This poor ventilation habit can be attributed to different reasons (e.g. reduced physical mobility and security concerns) which need to be further investigated as mechanical ventilation could be the solution to both these concerns, what implies a big argument for future design of resilient buildings.

Table 3 Descriptive statistics for mean daily indoor temperatures

Group1 vs. Group2	Room	No. Rooms Group1	No. Rooms Group2	Mean±Std Group1 (°C)	Mean±Std Group2 (°C)
S vs. N	Lr	28	12	23.4±1.9	22.7±1.2
S vs. N	Br	7	15	22.8±0.7	24±1.9
S vs. N	K	12	12	24.2±2.1	24±1.3
S-RE vs. S-LF	Lr	10	18	23.9±1.3	23.1±2.2
S-RE vs. S-LF	Br	4	3	22.9±0.8	22.7±0.7
S-RE vs. S-LF	K	2	10	25.1±1.4	24±2.2
N-RE vs. N-LF	Lr	0	12	-	22.6±1.2
N-RE vs. N-LF	Br	11	4	24.5±1.7	22.8±2.2
N-RE vs. N-LF	K	6	6	24.1±0.8	23.8±1.7

RE vs. LF	Lr	10	30	23.9±1.3	22.9±1.8
RE vs. LF	Br	15	7	24.07±1.6	22.8±1.6
RE vs. LF	K	8	16	24.4±1	24±2

S: Rooms with at least 1 window façade facing south, between 90° and 270°, N: The remaining rooms facing North. RE: Roof exposed rooms, LF: The remaining rooms in the lower floors. Lr: Living rooms, Br: Bedrooms or study rooms, K: Kitchens.

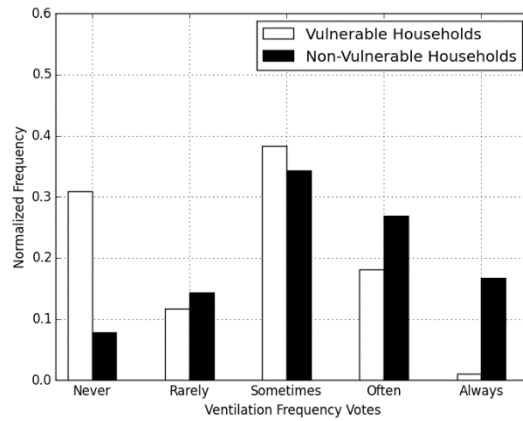


Figure 12 Ventilation frequency votes for vulnerable and non-vulnerable households.

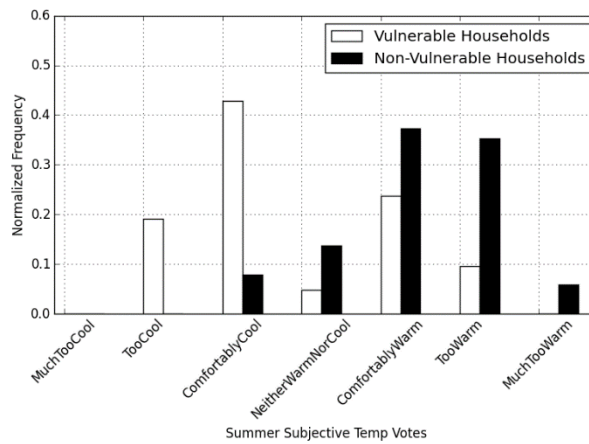


Figure 13 Summer subjective temperature votes for vulnerable and non-vulnerable households.

Table 4 Results of statistical tests for ventilation and thermal comfort votes

Groups	Items	Mean±Std Group 1 (°C)	Mean±Std Group 2 (°C)	Significance of difference	Statistical Test	P Value
V vs. nV	Ventilation votes	2.47±1.1	3.3±1.1	Strong	Mann-Whitney test	1.4E-08
V vs. nV	Cross ventilation votes	2.71±0.9	3.27±1.1	Weak	Mann-Whitney test	0.03
V vs. nV	Summer thermal comfort votes	3.62±1.3	5.18±1	Strong	Mann-Whitney test	1.2E-05

V; Vulnerable Households, nV: Non-Vulnerable Households.

Furthermore, the analysis of the thermal comfort responses indicates that vulnerable people underestimated their heat perception when compared to non-vulnerable occupants. This could potentially make them less ready to undertake

behavioural actions for heat protection. This could also indicate that it is convenient to assign lower floor dwellings to vulnerable people where they are less exposed to the risk of overheating.

8 Conclusions

This paper reports the results of the indoor temperatures monitored in 86 rooms of 46 homes during the period May to September 2014. Different housing design characteristics (roof exposure and façade orientation) and occupant variables (vulnerability and occupant ventilation patterns) were used to conduct the meta-analysis of the monitored rooms.

Firstly, it was found that roof exposed rooms are in general the ones recording the highest temperatures. Concerning room use, kitchens and bedrooms are in general warmer than living rooms. We also found that living rooms occupied by vulnerable occupants fall at higher risk of overheating due to behaviour of those. In fact, elderly and people with compromised health have restricted possibility of movement and could be socially isolated; this affects the time they spend indoor and their ability to behaviourally adapt to prolonged exposure to high indoor temperatures making their homes more at risk of overheating.

This suggests that occupants' characteristics play an important role in defining indoor conditions in newly insulated dwellings and that occupants' behaviour can powerfully alter indoor temperatures through the way occupants control ventilation in their homes. This is especially true when considering the fact that the minimum outdoor temperatures recorded during the summer 2014 are never higher than 18°C and that, therefore, night ventilation has a great potential for preventing overheating.

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