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Design to Thrive

Vulnerability and resilience in energy efficient homes: thermal response to heatwaves.

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Abstract: During heat waves, people experience both external and internal temperatures, but they are likely to spend most of their time indoors. This situation is aggravated by the fact that the majority of excess-deaths during a heat wave occur amongst the vulnerable population. In addition, energy efficient homes can worsen this scenario since internal temperatures are prone to respond quicker to heat gains, aggravating heat stress.
This paper is concerned with the vulnerability and resilience to heat waves of low carbon homes. A monitoring study of four energy efficient homes in the UK during the short heat wave experienced in 2015 is analysed. A close exploration of the variability of internal temperatures recorded with high resolution and in each room allows the areas of greatest risk to be mapped. These results are linked to occupants' responses. The analysis shows how building characteristics and ventilation can affect thermal conditions, and how design should take this into account.

Keywords: climate change, heatwaves, energy efficient homes, passive design, resilience

Introduction

Climate change is widely recognised as one of the greatest emerging humanitarian challenges of our time. Since the severe 2003 heatwave and associated excess deaths across Europe, the status of heatwaves has shifted from an interesting weather anomaly to precursors of potentially dangerous climate change; the 16% excess mortality was reported during that period, placing heat waves as a major risk and number one among the natural hazards of post-industrial societies (Poumadère et al. 2005). This situation is more alarming since climate change projections suggest that this number could rise to 5000 per year in 2080 (DCLG 2012).

There is no universal definition of heat waves. Heat wave is generally defined as a period of abnormally and uncomfortably hot and usually humid weather. In the UK, the Met Office adheres to a relativist definition "*a heatwave is an extended period of hot weather relative to the expected conditions of the area at that time of year*". On a tentative reconstruction around this theme, Perkins lists a number of definitions in which duration of exposure to high temperatures and intensity are found in different degree to characterise heatwaves making it difficult to compare changes at different regional scales (Perkins 2015).

The UK NHS heat wave plan (NHS 2015) triggers a heat wave alert when temperatures are being '*high enough on at least two consecutive days to have significant effects*'. And the Met Office National Severe Weather Warning Service (NSWWS) has defined day and night threshold temperatures by region, reflecting long term adaptation of the population to the local climate. For the homes object of this study, the relevant regions are the Midlands and Yorkshire, which both have external temperatures threshold values of 15˚C night (min) and 30˚C/29˚C day (max) respectively.

By investigating the relationship between heat and mortality for a 21 year period, Armstrong et al. concluded that a growth in heat-related deaths begins at a relatively low average external temperature of about 19˚C, and at about the same centile temperatures (the 93rd) in all regions and have provided with a list of threshold temperatures for heat effects, i.e. 22.2˚C for Yorkshire and 23.0 ˚C for the Midlands (Armstrong et al. 2011).

There is clearly a link between internal and external temperatures, but this is not well understood due to lack of data (Dengel & Swainson 2012). And during heat waves, people experience both external and internal temperatures, but they are likely to spend most of their time indoors. This situation is aggravated by the fact that the majority of excess-deaths during a heat wave occur amongst the elderly, who are known to spend an even higher proportion of time indoors than the general population (Poumadère et al. 2005).

The UK government has set up emissions reduction binding targets imposing substantial reduction of emissions from buildings with consequential substantial changes to the UK building regulations, resulting in homes with significantly improved standards of thermal insulation and much higher levels of airtightness (HM 2013). However, energy efficient homes are prone to overheat (Toledo et al. 2016) because such homes respond quickly to heat gains. As a result, internal temperatures tend to be higher, especially at evenings. The lack of thermal mass and solar protection can exacerbate internal temperatures, and there is no guarantee that effective ventilation through the windows may be achieved. On the other hand, mechanical ventilation with heat recovery (MVHR) is often installed with no summer by-pass, so removal of excess heat is made slow and night cooling would not be possible with the 1.5 air changes per hour (ACH) provided with MVHR (at least 10ACH are required to provide night ventilation) (Orme & Palmer 2003).

There is scarce evidence of internal temperatures responding to heatwaves (Dengel & Swainson 2012), especially when considering the energy efficient housing stock. On a monitoring study of 9 traditional dwellings between Manchester and London, Wright et al. found that, during August 2003 heat wave, when the daily averages of external temperatures were exceptionally high for the UK (20°C), the high thermal mass in some monitored dwellings had the effect that internal temperatures both in Manchester as in London were up to 5K higher that the (night) outdoor air temperature, suggesting that thermal capacity may restrict the effectiveness of night ventilation to provide comfort at night (Wright et al. 2005). From a 101 homes survey, Mavrogianni reported that on both typical and warm days, respondents reported opening the windows mostly due to the need of fresh air rather than high indoor temperatures; respondents stated that they do not open the windows concerned of security reasons, and due to high external noise levels (Mavrogianni et al. 2016).

From monitoring of 25 energy efficient dwellings during three summers (2011, 2012, 2013), Tabatabaei Sameni at al. found no direct relationship between such factors external environmental factors and indoor overheating, while and occupant is the most relative important factor (Tabatabaei Sameni et al. 2015). A recent report presented by Innovate UK (Jason Palmer, Daniel Godoy-Shimizu 2016) one Passivhaus dwelling was reported to have exceeded 28˚C for 9% of the summer and exceeded 25˚C for one-fifth of the summer, probably due to non-window opening. However, leaving the windows closed and letting the MVHR "do the job" is the instruction provided to the residents, even though window ventilation in summer is part of the Passivhaus design.

The present research aims to contribute to this tradition by presenting the monitored data of four energy efficient homes across the UK during the short heat wave experienced in

2015. The aims of this paper are (a) to provide a graphical description and statistics on the response of 4 energy efficient homes to the 2015 heatwave; (b) to determine the influence of building characteristics on internal temperatures; and (c) to determine the influence of user behaviour on internal temperatures (the variability of internal temperatures recorded will be linked to occupants' responses).

Methods

Longitudinal data were collected through Onset Hobo pendant sensors placed every room of the each house monitored during summer 2015 (see table 1). The sensors recorded air temperature readings at 10 min intervals. These measurements were complemented by an occupant questionnaire. Questionnaires were aimed at collecting a feedback on the effectiveness of new highly efficient designs, as well as collecting data regarding occupants' behaviour, control, and comfort sensation in order to relate to the environmental measurements in their home.

Table 1. Overview of case studies homes

House code	*House type & location*	*U-value ext. walls (W/m2.K)*	*Thermal mass*	*Orientation (solar gain)*	*Ventilation type*	*Cross ventilation*	*Solar control*
UK51	Refurbished terrace Leicester (UK)	0.12	NO	E-W	MVHR (no summer by-pass)	YES	Only internal blinds on Velux windows
UK52	New detached bungalow Sandiacre (UK)	0.09	NO	N-S	MVHR (no summer by-pass)	YES	Not provided
UK54	New terrace York (UK)	0.19	YES	N-S	MV	YES	Only internal blinds on Velux windows
UK55	New detached York (UK)	0.19	YES	E-W	MVHR (no summer by-pass)	YES	Only internal blinds on Velux windows

There was a brief but sharp heat wave peaking at above 30°C on 1 July 2015 in the East Midlands of England, coinciding with high solar gain. For the present analysis, the period chosen closely related to the generic definition of heatwave "*period of abnormally and uncomfortably hot and usually humid weather*" and satisfying two conditions: (a) when daily averages of external temperatures were above 20°C and (b) when the NSWWS threshold peak temperature was reached. The below graphical representation is able to best represent this period, which corresponds to the period 28 June- 3rd July 2015 (figure 1).

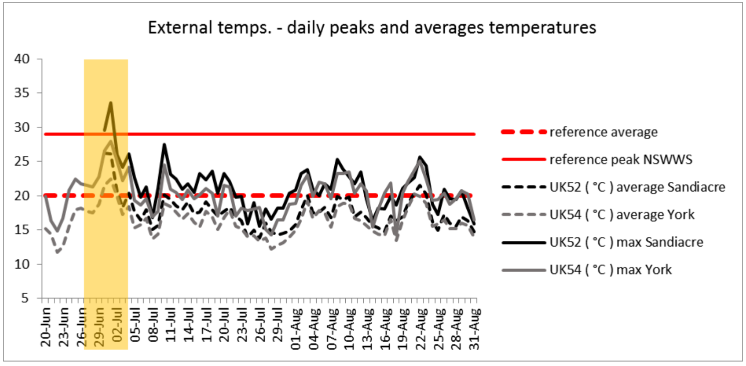


Figure 1. External temperatures recorded in case study homes, evidencing the period considered as heatwave.

Results and discussion

Descriptive statistics

Figure 2 shows the median, interquartile range (box) and max/min values over the hot period. In general the internal/external median differences lie between 4-8K, confirming reviewed monitored studies. Also, noticeable to extreme values, circled in red: (a) the room in UK52 containing the water tank for domestic hot water, and (b) the East facing sunspace in UK55 with no solar protection. Both spaces are located within the thermal envelope of the homes and would be expected to contribute to overall heat gains.

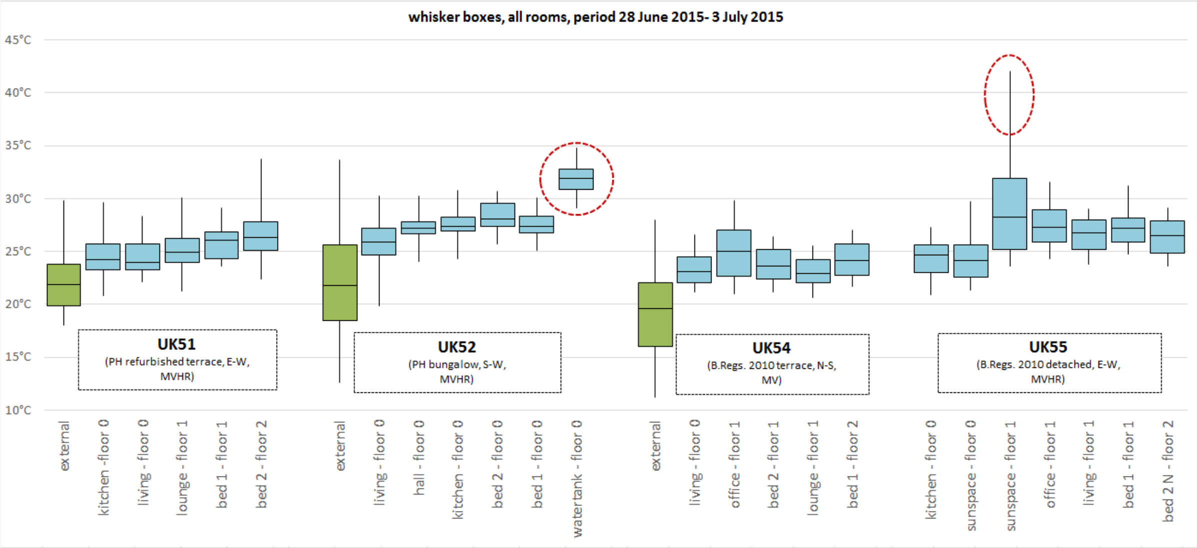


Figure 2. Box and whiskers plot, from 28 June 2015 until 3 July 2015.

For House UK51, the highest temperature ranges have been found in bedroom 2, located in the 2nd floor loft conversion and provided with two windows in the slope of the roof facing East and West. Here temperatures are shown to be too uncomfortable for sleep during the heatwave, to the point that occupants of this room slept in the living room on a lower floor during these days. Later, was found that even though this room is provided with an inlet for fresh air (tested to working properly), it suffered from a lack of air flow, due to the fact that the nearest outlet is located in the lower floor bathroom. During the 1st July 2015, in house UK51 all room temperatures varied between 25-34°C (most rooms between 25-30°C). When external temperatures were at the lowest, around 5:00-6:00 am, internal temperatures were 3-6K higher. During the morning, internal temperatures are mostly kept fairly stable and below external temperatures, ad exception of bedroom 2.

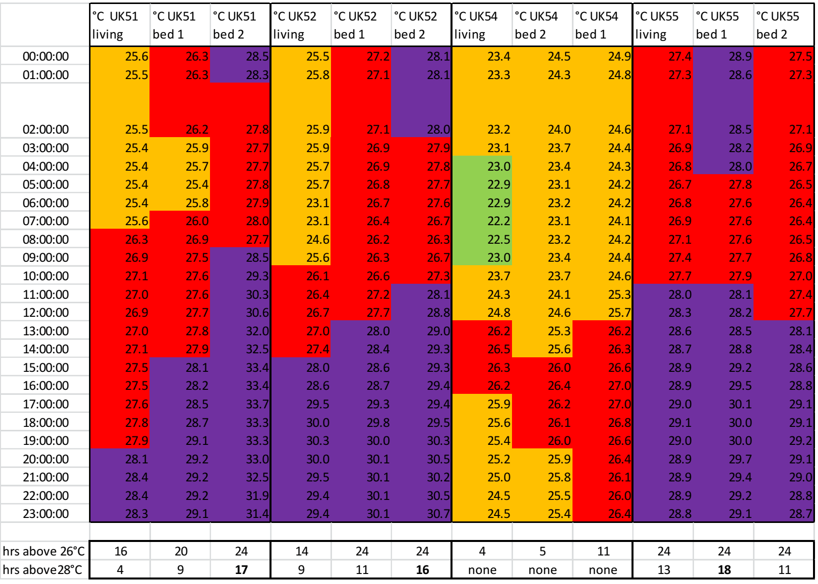
House UK52 showed less variation compared to the other homes. The living room performed to be the coolest space of this house, presumably due to the provision of cross ventilation within that room. The bedrooms temperatures on the other hand were always above 25°C. The occupant reported leaving the windows slightly open (in a lockable position) open during daytime. However, this being bungalow of lightweight construction, it will be expected for temperatures to fall quickly as the night progressed, but it is not the case. This could be due to the MVHR with no summer bypass or due to window closing during sleep hours (as reported by the occupant). Confirming that small volumes for fresh air would not provide significant night cooling, as previously reported by Orme & Palmer (2003). During the 1st July 2015, in house UK52, all room temperatures were between 23-31°C. When external temperatures were at the lowest, around 5:00 am, internal temperatures were 8-10K higher. All room temperatures increased as the day progressed.

Descriptive Statistics

	N	Range	Minimum	Maximum	°C Mean	Std. Deviation	Variance
°C UK51 living (f 0-E)	144	6.2	22.1	28.4	24.590	1.6004	2.561
°C UK51 bed 1 (f 1-E)	144	5.6	23.6	29.2	25.891	1.5741	2.478
°C UK51 bed 2 (f 2 -E&W)	144	11.3	22.4	33.7	26.728	2.5676	6.593
°C UK52 living (f 0/N&W)	82	10.4	19.9	30.3	25.894	2.3023	5.301
°C UK52 bed 2 (f 0/S)	82	5.0	25.7	30.7	28.492	1.3245	1.754
°C UK52 bed 1 (f 0/S)	82	4.9	25.1	30.1	27.615	1.1622	1.351
°C UK54 living (f 0/N&S)	144	5.4	21.2	26.5	23.260	1.3362	1.786
°C UK54 bed 2 (f 1/N&S)	144	5.2	21.2	26.4	23.749	1.5116	2.285
°C UK54 bed 1 (f 2/ N&S)	144	5.3	21.7	27.0	24.248	1.5115	2.285
°C UK55 living (f 1/S&W)	144	5.3	23.8	29.1	26.664	1.4869	2.211
°C UK55 bed 1(f 1/W)	144	6.4	24.8	31.2	27.142	1.5254	2.327
°C UK55 bed 2 N (f 2/W)	144	5.6	23.6	29.2	26.360	1.6431	2.700

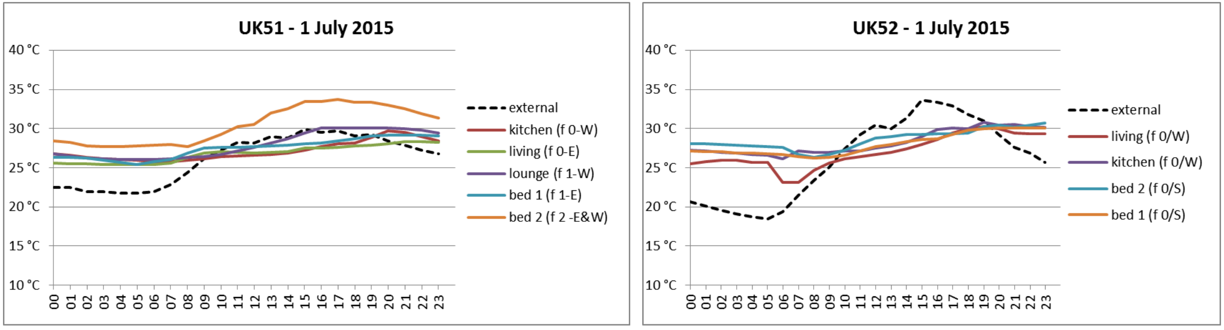
Figure 3. Descriptive statistics.

Table 2. Hourly temperature readings during 1st July 2015. In green temperatures up to 23°C, in yellow temperatures 23-26, in red temperatures above 26°C and in purple above 28°C.



	°C UK51 living	°C UK51 bed 1	°C UK51 bed 2	°C UK52 living	°C UK52 bed 1	°C UK52 bed 2	°C UK54 living	°C UK54 bed 2	°C UK54 bed 1	°C UK55 living	°C UK55 bed 1	°C UK55 bed 2
00:00:00	25.6	26.3	28.5	25.5	27.2	28.1	23.4	24.5	24.9	27.4	28.9	27.5
01:00:00	25.5	26.3	28.3	25.8	27.1	28.1	23.3	24.3	24.8	27.3	28.6	27.3
02:00:00	25.5	26.2	27.8	25.9	27.1	28.0	23.2	24.0	24.6	27.1	28.5	27.1
03:00:00	25.4	25.9	27.7	25.9	26.9	27.9	23.1	23.7	24.4	26.9	28.2	26.9
04:00:00	25.4	25.7	27.7	25.7	26.9	27.8	23.0	23.4	24.3	26.8	28.0	26.7
05:00:00	25.4	25.4	27.8	25.7	26.8	27.7	22.9	23.1	24.2	26.7	27.8	26.5
06:00:00	25.4	25.8	27.9	23.1	26.7	27.6	22.9	23.2	24.2	26.8	27.6	26.4
07:00:00	25.6	26.0	28.0	23.1	26.4	26.7	22.2	23.1	24.1	26.9	27.6	26.4
08:00:00	26.3	26.9	27.7	24.6	26.2	26.3	22.5	23.2	24.2	27.1	27.6	26.5
09:00:00	26.9	27.5	28.5	25.6	26.3	26.7	23.0	23.4	24.4	27.4	27.7	26.8
10:00:00	27.1	27.6	29.3	26.1	26.6	27.3	23.7	23.7	24.6	27.7	27.9	27.0
11:00:00	27.0	27.6	30.3	26.4	27.2	28.1	24.3	24.1	25.3	28.0	28.1	27.4
12:00:00	26.9	27.7	30.6	26.7	27.7	28.8	24.8	24.6	25.7	28.3	28.2	27.7
13:00:00	27.0	27.8	32.0	27.0	28.0	29.0	26.2	25.3	26.2	28.6	28.5	28.1
14:00:00	27.1	27.9	32.5	27.4	28.4	29.3	26.5	25.6	26.3	28.7	28.8	28.4
15:00:00	27.5	28.1	33.4	28.0	28.6	29.3	26.3	26.0	26.6	28.9	29.2	28.6
16:00:00	27.5	28.2	33.4	28.6	28.7	29.4	26.2	26.4	27.0	28.9	29.5	28.8
17:00:00	27.6	28.5	33.7	29.5	29.3	29.4	25.9	26.2	27.0	29.0	30.1	29.1
18:00:00	27.8	28.7	33.3	30.0	29.8	29.5	25.6	26.1	26.8	29.1	30.0	29.1
19:00:00	27.9	29.1	33.3	30.3	30.0	30.3	25.4	26.0	26.6	29.0	30.0	29.2
20:00:00	28.1	29.2	33.0	30.0	30.1	30.5	25.2	25.9	26.4	28.9	29.7	29.1
21:00:00	28.4	29.2	32.5	29.5	30.1	30.2	25.0	25.8	26.1	28.9	29.4	29.0
22:00:00	28.4	29.2	31.9	29.4	30.1	30.5	24.5	25.5	26.0	28.9	29.2	28.8
23:00:00	28.3	29.1	31.4	29.4	30.1	30.7	24.5	25.4	26.4	28.8	29.1	28.7
hrs above 26°C	16	20	24	14	24	24	4	5	11	24	24	24
hrs above28°C	4	9	**17**	9	11	**16**	none	none	none	13	**18**	11

House UK54 performed the best of all case studies. Different from all the other homes, this house is the only one managed with natural ventilation (extract mechanical ventilation was available, but the occupant had turned this off for the summer). During the 1st July 2015, in house UK54, all room temperatures were between 21-30°C (most rooms between 23-26°C). When external temperatures where at the lowest, between 4:00-5:00 am, internal temperatures were 5-10K higher. The office, with south facing sloping roof windows, is the only room with daytime temperatures above external temperatures. All the other rooms maintained lower temperatures during external peak times.



Figures 4 and 5. Temperatures swing of UK51 and UK52 during 1st July 2015 (all same scale)

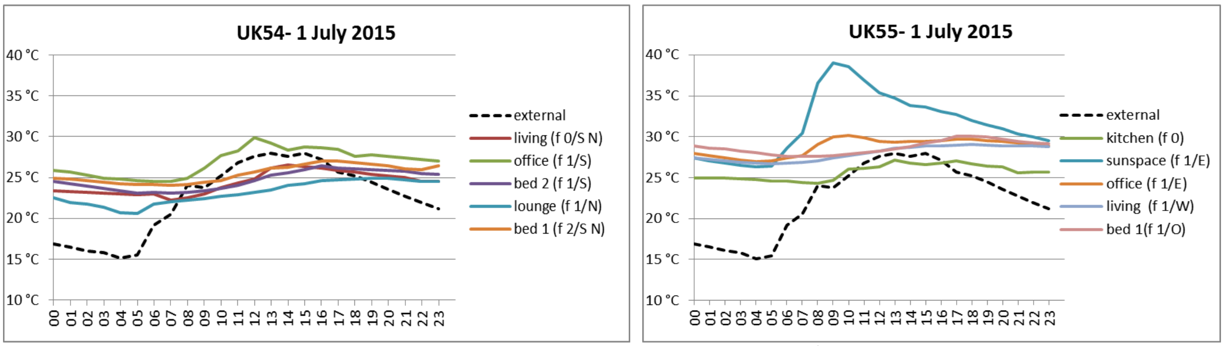


Figure 6 and 7. Temperatures swing UK54 and UK55 during the 1st July 2015 (all same scale)

In house UK55, where most windows were kept close during the heatwave, and MVHR was ‘left to do the job’, there was found the biggest internal-external median difference, suggesting that MVHR only ventilation results in unappropriated purge ventilation and the building up internal temperatures. The colder room was found to be the kitchen, which was managed via window opening by the other tenant. This appears to be the consequence of uncontrolled morning solar gains and lack of windows opening, confirmed by the occupant’s questionnaire.

During the 1st July 2015, in house UK55, apart from the sunspace, all room temperatures were between 25-30°C. When external temperatures where at the lowest, between 4:00-5:00 am, internal temperatures were 10-15K higher. The East facing sunspace with no solar gain control presented the highest peak temperatures, with a difference with external temperatures up to 18K. When external temperatures peaked in the afternoon, the west facing bedroom exceeded 30°C. The high night time temperatures in all rooms suggest that no night cooling was applied. It was reported from the occupants that, at certain times, they found thermal relief only outdoors.

Lag

From visual inspection of the plotted temperatures in days before and after the heatwave, it became evident that while external temperatures lowered from 2nd July 2015, the high internal temperatures were maintained in all the homes and with a different degree of intensity. House UK52 (lightweight construction) the main bedroom temperatures were above 25°C for over 3 days after. House UK54 (heavyweight construction/natural ventilation) the main bedroom temperatures were below the peak day external temperature but above the following day. Similar situation happened in house UK55 (heavyweight construction/MVHR), but 3-4K difference higher.

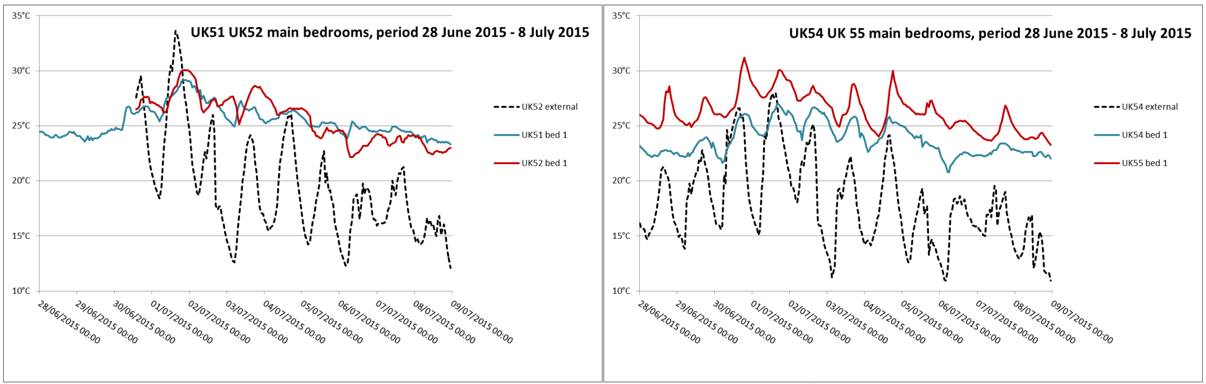


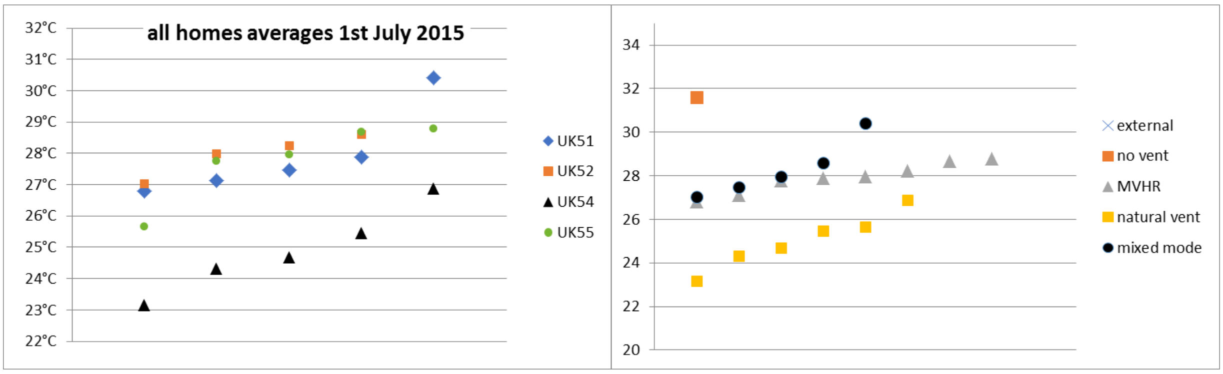
Figure 8 and 9. Temperatures swing during the 1st July 2015.

Resilience

In terms of resilience to heatwaves, all inhabitable rooms' data has been examined to look for cooler rooms within the houses (figure 10). From all these energy efficient homes, house UK54 had the lowest temperatures during the heatwave. The coolest room was the north facing lounge at the first floor where temperatures never exceeded 26°C.

House UK55 was found to perform the worst, though it provides with the second most resilient room, this room is the kitchen, located in the ground floor and with little or no solar gain, and, importantly, known to be naturally ventilated. Interestingly, UK52 (lightweight) and UK55 (heavyweight) bedrooms average temperatures were very similar. It is know that both homes relied on MVHR, but UK52 occupant incorporated additional ventilation through window opening. This brings questions into the effectiveness of lightweight buildings compared to a thermal mass exposed dwelling.

In general, bedroom temperatures tend to be higher than living areas. The reasons hypothesised being that in UK51 the ground floor was much cooler, in UK52 the availability of crossed ventilation, in UK54 both the previous reasons in addition to the generous dimensions and in UK55 probably the big dimensions.



Figures 10 and 11. Ranking of rooms temperatures (left) and by ventilation type during the 1st July (right)

At last, figure 11 depicts an interesting effect that the ventilation strategy has with the thermal performance during heatwaves: within the four case studies, homes that managed the ventilation via MVHR and MVHR&window opening (mixed mode ventilation) showed the highest temperatures (after the non-ventilated sunspace) and that natural ventilation at its worst performed like MVHR at its best.

Conclusions

The present paper has provided a graphical and statistical description of the four energy efficient homes during the 2015 heatwave. Within it, it became clear that internal temperatures across all homes were all uncomfortably high, ad exception of UK54.

Some of the rooms became unusable, and occupants have to relocate to another type of room. This opportunity is not always available (for instance in flat apartments or in overcrowded homes. Also the coolest room average temperature range varied of 4K. Therefore designers should think of the variability of thermal spaces to provide a resilient energy efficient home to heatwaves.

The persistence of high indoor temperatures after the peak day (i.e. four days in some homes) stresses the urge to consider energy efficient homes at a potential risk for health, under certain layout, typology, and orientation. Also, it has been provided evidence that, in a non-dense urban area, such as Derwenthorpe, thermal mass in highly insulated homes can handle effectively night cooling, if the proper orientation and ventilation strategy is in place (among the two heavyweight homes, the one with no MVHR and natural ventilation performed outstandingly).

It has also been found that occupants adapt to their environments (all occupants ventilated at least one room). However, as shown by house UK52 (lightweight bungalow Passivhaus), user behaviour alone is not sufficient to adapt to heatwaves: external shading and secure night ventilation are the bare minimum that their homes design should provide. This capability of environments to adapt (or to let people adapt) to extreme weather events constitutes the key to move away from vulnerable designs to resilient and thriving designs.

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