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Performance of medium-rise, thermally lightweight apartment buildings during a heat wave

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Abstract: There is growing evidence that medium rise, thermally lightweight, well-insulated, naturally ventilated, single apartment blocks are at risk of overheating especially when sited in the SE of England.

This paper reports the thermal comfort and heat stress conditions recorded in 15 apartments located in North London on the outer fringes of the urban heat island. The apartments were built using off site, light gauge steel prefabrication methods. Bedrooms on floors one and two and on floors seven to eleven were monitored for 22 days during July and August 2013, a period that included a heat wave, which precipitated a level 3 heat wave alert. The risk of overheating was assessed using the static criteria in CIBSE Guide A and the three CIBSE TM52 adaptive thermal comfort criteria. Heat stress levels in one room were assessed using the Humidex and Heat Index metrics.

The bedrooms on floors one and two did not overheat whereas all the apartments on the upper floors failed both the static and the adaptive criteria producing conditions that would lead to heat stress.

The results strongly suggest that the design, ventilation and servicing strategy, combined with the inherent fragility of thermally lightweight and well insulated construction, is inappropriate in some areas of the UK and may even be dangerous in hot summers. The findings have significance for construction companies, landlords and social housing providers and those concerned with construction guidelines and the building regulations.

Keywords: Apartment buildings, modern methods of construction, overheating, heatwave, measurement

1. Introduction

Homes from the south of England to the north of Scotland are at risk of overheating during the summertime (Bezaiee et al, 2013; Lomas and Porritt, 2017). Excess heat affects the health and well-being of occupants, especially if sleep is degraded. In extremis, heat stress can lead to premature mortality, especially amongst more vulnerable members of society (PHE, 2015). As the climate warms, and heat waves become more frequent and severe, the problem will become ever more pressing, heat-related deaths could treble by 2050 if action is not taken (ZCH, 2015). The UK Committee on Climate Change, Adaptation Sub-Committee (CCC) advises the UK government that '*more action is needed*' to reduce the risks to health and well-being (CCC, 2014; CCC, 2017).

New dwellings are particularly vulnerable and apartment buildings can suffer from chronic overheating (McLeod and Swainson, 2017). A number of factors combine to create the problem. The potential to ventilate adequately is restricted due to limited operable window area, external noise and pollution, and geometries that preclude cross ventilation. Expanding urban areas create heat islands, which generate elevated temperatures curtailing night time ventilation cooling. The need to prevent winter heat loss, reduce heating energy demands and so reduce greenhouse gas emissions levels of insulation are increasing. There is also greater use of thermally lightweight construction techniques, which speed construction and may improve buildings' thermal integrity. A desire to reduce costs leads to simplified designs and militates against potentially important details, for example external shading to control solar gain. So-called modern methods of construction, in which elements of the building, or whole rooms, are constructed off site, exemplify this approach. Finally, apartments are becoming smaller, with lower ceilings, which results in higher heat gain, from occupants, electrical appliances and hot water distribution pipework, per unit floor area (Lomas and Porritt, 2017).

The risk of overheating in UK apartments is a well-known industry problem (ZCH, 2015; GHA, 2014) and has been a concern for the UK government for some time (DCLG, 2012). However, the problem remains largely unreported in open literature. This paper reports a monitoring study (Quigley, 2016) that provides evidence of the extent and severity of overheating in a medium rise apartment block in north London, UK.

2. Description of the apartment building

The apartment building designed as student accommodation is located in north London. It comprises two blocks, Block A has seven storeys and Block B has 12 storeys, but steps down in height to the west end, such that the 12th floor is approximately two thirds the area of the ground floor (Fig.1.).

Figure 1: Plan of the buildings (left) and images showing Block A and Block B from within the courtyard (centre) and Block B from the north-west (right) (Images from Google Maps, 2014)

Table 1: Description of building, Block B

Feature	Description
Location	North London
Year constructed	2011-2012
Building use	Student hall of residence
Building occupancy	355 days per year
Number of storeys	Up to 12
Number of apartments	55
Number of occupants	529
Apartment size	Mix of 3, 5, 7, 9 and 10 bedroom apartments (mainly larger apartments)
Construction system	Light-gauge steel, modular system – bedrooms and some kitchens. Reinforced precast concrete - ground floor, stair cores and most kitchens.
External facade	Rendered and clad rigid insulation
Fenestration	Double glazed, aluminium frames
Space heating	Hydronic radiators supplied from a community CHP plant
Ventilation	Centralised extract systems in apartments with outlets in en-suite shower rooms, kitchen and hall. Window opening restricted to 150mm from frame.
Solar shading	Internal blinds, slightly recessed windows in places

The monitored bedrooms were in Block B, one faced south and the others faced either east or west, none faced north. The east facing apartments on the lower floors are shaded from the morning sun by Block A.

The two blocks are predominantly formed of room modules made off-site using light gauge steel as the primary structural component. Timber board and plasterboard assisted with lateral racking rigidity, with insulation placed between the steel elements to control heat loss. Parts of the building were constructed from precast concrete beams, columns and panels including: the ground floors, stair cores, the majority of kitchens and six bedrooms in Block B (Table 1). Non-modular components were used for the external cladding and other structural purposes.

Each apartment comprises a corridor, kitchen and from three to ten bedrooms with en-suite bathrooms (average of 9.6 bedrooms per apartment). The blind, i.e. windowless, corridors run down the centre of the blocks with stair cores at one end and kitchens at the other They are double banked with bedrooms which have a single aspect, kitchens have either one or two aspects. A number of the bedrooms provide easier access for less-mobile people (Fig. 2).

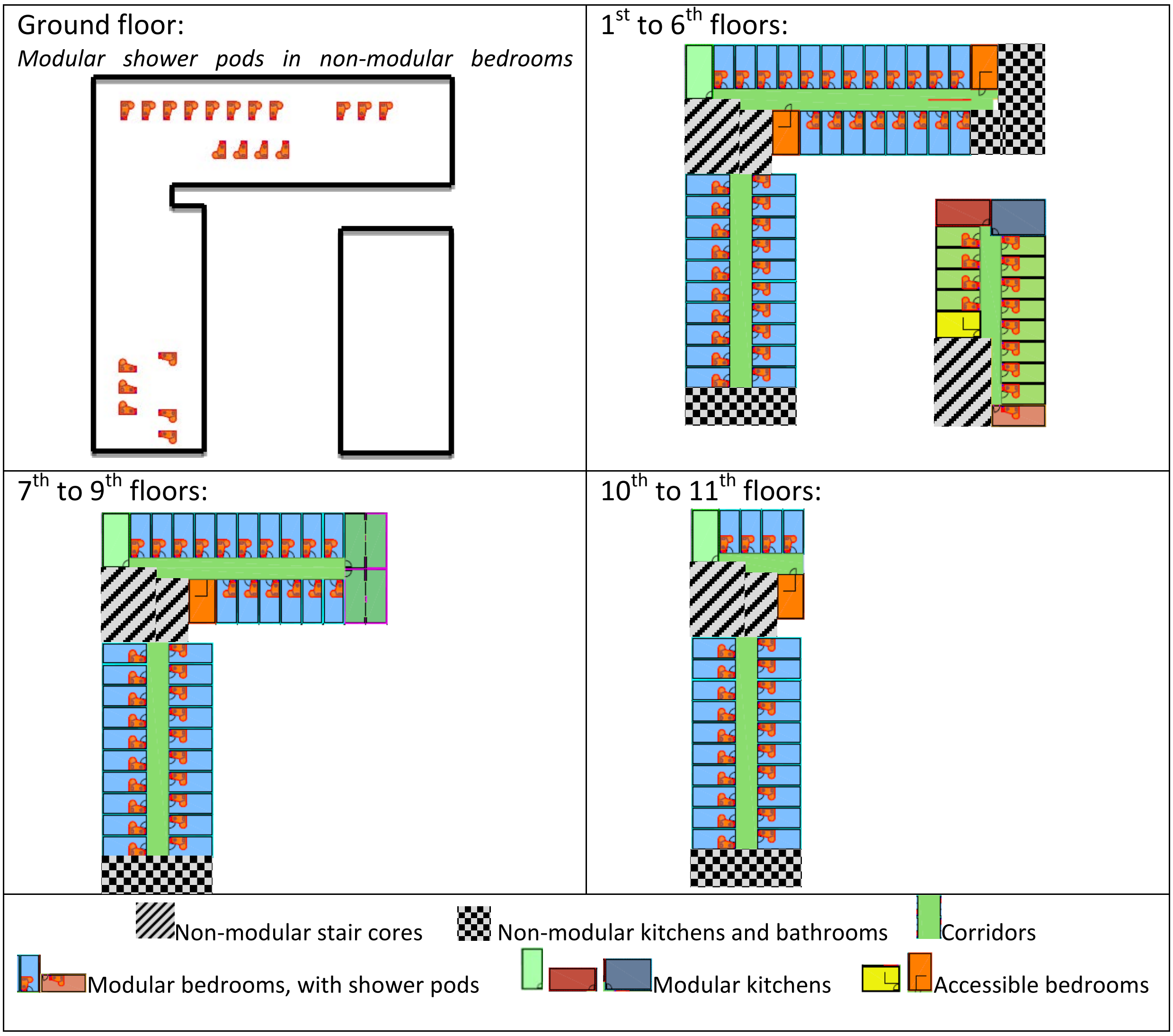


Figure 2: Floor layouts highlighting modular and non-modular components

The external facade was fitted on site and comprised of rigid insulation fixed to the modules, with finishes of white or grey render and cladding (Fig. 3). Various types of rain screen cladding are used across the entire ground floor and on all facades that face away from the courtyard. Some individual modular rooms have three or four different types of facade material, but the majority have just one or two.

Four thicknesses of rigid insulation were used, resulting in a variable wall thickness, the thickness of rigid insulation is linked to the facade materials used (Fig. 3). Nothing was known about the thermal properties of the facade materials, or the impacts that using differing facade materials and insulation thicknesses had on the U-value of different sections of wall.

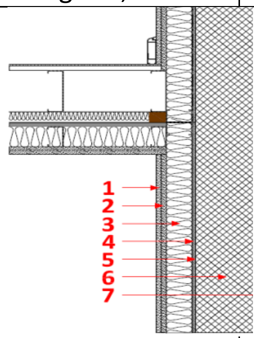
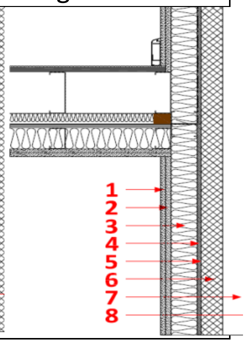
Components	Designs 1, 2 & 3	Design 4
1. 15mm Plasterboard		
2. 15mm Plasterboard with a low-e, foil vapour control layer (VCL)		
3. 75mm steel stud wall with 60mm Rockwool		
4. 10mm racking board		
5. 2mm breather membrane		
6. Designs 1, 2 and 3: 100, 150 or 200mm rigid insulation with a low-e VCL facing		
7. Designs 1, 2 and 3: External render. Design 4: 90mm air cavity.		
8. Design 4: Cladding		

Figure 3: Different external facade designs for the London case study building

The buildings contains 21 different styles of window plus curtain walling on the ground floor, the style of glazing varies depending on the type of room and location in the building. The windows in bedrooms and kitchens are double-glazed with top hung openings that were fitted in the factory to the external face of the modules (Fig. 4A). Due to the variable thickness of the external walls, some windows are recessed within the facade (Fig. 4B) and some are not. Opening is restricted to 150mm horizontally from the window frame, so windows in walls with 200mm of rigid insulation barely open past the facade (Fig. 4C).

The stair cores have fixed opaque windows on the external facade; however, they do not penetrate into the stair cores (Fig. 4D). Their only function seems to be to provide the external appearance of windows. The original architect's drawings showed louvered panels which would have enabled ventilation of the stairwells; but the constructed building features the fake windows in their place.

A B C D

Figure 4: Window in bedroom module, not recessed in facade (A), Bedroom window recessed in facade showing the extent of window opening (B), Bedroom window in planar facade showing the extent of window opening (C), Stair core showing fixed, opaque windows with large bedroom windows left & right (D)

Space heating and hot water are provided by a CHP plant that supplies the whole site; it is believed to use biomass fuel. Hot water from the CHP plant is transferred to the building via a heat exchanger in Block B and the hot water then pumped around the building. All the buildings' services are routed from the plant and switch rooms on the ground floors, via the stair cores. There are back up boilers and communications rooms located throughout the stair cores. Services are then routed along the corridors to each of the apartments.

Each bedroom and kitchen has a radiator, rated at 807 watts and 1417 watts respectively. Thermostatic radiator valves (TRVs) on each radiator are the only means of occupant control. Space heating is available whenever the external temperature is below 15°C, which is measured by an external temperature sensor connected to the BMS system.

Each apartment has its own ventilation system, which is centrally powered from the kitchen. Air is extracted via the cooker hood in kitchens, the vents in the en-suite bathrooms and the apartment corridors. It is not clear if there is any inlet ducting.

3. Monitoring

Fifteen rooms were monitored, three east-facing rooms on the first floor and an east-facing room of the second floor (1Ea, 1Eb, 1Ec and 2E). To test whether there was a difference in room temperature with height, eleven rooms across floors 7 to 11 were also monitored, all faced east or west except for one room on floor 8, which faced south (7Wa, 7Wb, 7Wc, 8S, 9Ea, 9Eb, 9W, 10Wa, 10Wb, 10Wc and 11W).

An EnOcean-enabled wireless sensor network (WSNs) was set up to monitor internal air temperature, relative humidity and window opening. The network comprised a network controller and repeaters to capture data from temperature and relative humidity sensors fixed to bedroom walls away from direct solar radiation and heat sources. In addition, standalone MadgeTech temperature sensors were fixed to the radiators in each room. The intention was to identify the use of heat emitters, but during the monitoring period no heat was available and the radiators were definitely not used (Table 2).

Problems with the reception of data from the WSN, thought to be caused by signal shielding, meant that the only reliable wireless data was temperature and humidity data from room 10Wa. It was discover however that the temperature sensors fixed to the radiators provided reliable measures of the room temperature, providing very similar values to those recorded by the wall- mounted sensor (Fig 5); temperature recorded by these sensors are reported throughout this work.

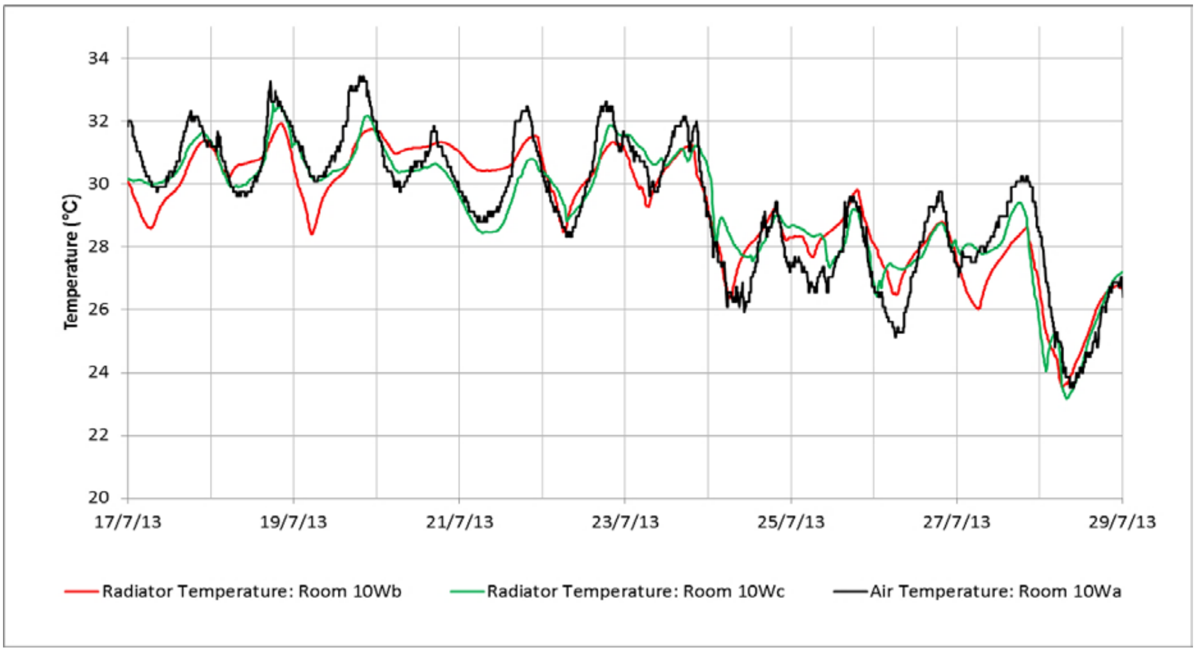


Figure 5: Comparison of temperatures recorded by wall-mounted and radiator sensors

Table 2: Monitoring equipment used in case study building (EnOcean Alliance, 2014; MadgeTech, 2014)

Equipment	**Specifications**
Smart Building Ltd: temperature and relative humidity sensor 	Solar powered Temperature measurement: 0°C – 40°C Relative humidity measurement range: 0% – 100% Temperature measurement accuracy: ±0.5°C Relative humidity measurement accuracy: ±5%
MadgeTech 101A: standalone temperature sensors 	Battery powered Temperature measurement range: -40°C to 80°C Temperature measurement accuracy: ±0.5°C Logging capacity: 1 million readings

4. Overheating and heat stress metrics

To determine the occurrence and severity of overheating, the temperature data were analysed using static (CIBSE, 2006) and adaptive (CIBSE, 2013, BSI, 2007) overheating metrics. The heat stress due to the combined effects of temperatures and humidity in room 10Wa was analysed using heat stress metrics, Humidex (Humidex, 2015) and the Heat Index (Heat Index, 2015).

Both the static and adaptive criteria are applicable to occupied hours with the former applying to the whole year and the latter to the summer period (May to September inclusive). Of course, in monitoring studies, it is not always possible to monitor for these lengths of time and it is not always possible to be confident about when rooms are, or are not occupied. In this work, the criteria are applied only to the data from the monitoring period assuming that the apartments, which are student accommodation, could be occupied at any time. Many previous monitoring studies have adopted the same approach.

The static overheating criteria were taken from CIBSE Guide A (CIBSE, 2006), where overheating is deemed to occur if the measure operative temperatures:

in bedrooms exceeds 26°C for more than 1% of occupied hours per year; and

in living areas exceeds 28°C for more than 1% of occupied hours per year.

In this research, the percentage of hours during the monitoring period for which the measured temperatures exceeded these criteria is reported along with an estimate of the percentage of hours that would exceed the limiting values if there were no more hours of overheating during the whole of the rest of the summer.

Static criteria have been criticised in recent times because they do not take into account the extremity or duration of overheating, or people's ability to adapt to a changing climate (CIBSE, 2013). The recently published CIBSE Technical Memorandum 59 (CIBSE, 2017) retains the static criterion for bedrooms, but neither TM59 nor the most recent CIBSE Guide A (CIBSE, 2015) use the static living room criterion. However, by retaining the use of this criterion here, it is possible to compare our results with those from earlier monitoring studies.

The adaptive overheating criteria were taken from CIBSE Technical Memorandum TM52 (CIBSE, 2013), which takes the upper operative temperature threshold (T_{max}) and the lower threshold (T_{min}) to be those defined in BSEN15251 (BSI, 2007) for normal healthy people (BSEN15251, Cat II), which is appropriate for the occupants of the monitored apartments. The thermal comfort thresholds increase with the running mean of the ambient temperature to account for peoples' adaptation to gradually changing ambient temperatures. Three criteria are used in TM52 to determine the extent and severity of overheating and a building is deemed to overheat if it fails two or more criteria.

Criterion 1: The operative temperature should not exceed T_{max} by more than 1K for more than 1% of occupied hours.

Criterion 2: The daily weighted operative temperature, W_e, should not exceed 6^{o}C.h.

Criterion 3: The upper threshold T_{max} should never be exceeded by more than 4K (labelled T_{upp} herein).

In this research, for Criterion 1, the percentage of hours that exceed T_{max}+1K is calculated. For Criterion 2, a value of 1^{o}C.h was recorded if T_{max} was exceeded by 1K for one hour, 3.2 °C.h if it was exceeded by 3.2K for one hour, etc. The totals of these exceedances (W_e °C.h) for each day in the monitoring period, were then compared with the limiting value of 6°C.h. The maximum daily exceedance is reported, along with the number of days for which the limiting value was exceeded. For Criterion 3, the number of days that exceeded T_{upp} is also reported.

Heat stress was calculated for room 10Wa using two metrics, which combined the effects of humidity and temperature. The Canadian Humidex index is used by meteorologists and reported in weather forecasts, and can be used to indicate when workplace conditions are uncomfortable or dangerous. The Humidex value is calculated using:

$$H = T_{air} + 0.5555 * (6.11 * \exp(5417.753 * (1/273.16 - 1/(T_{dp} + 273.16))) - 10)$$

Where H = Humidex index (^{o}C);

T_{air} = measured air temperature (°C); and

T_{dp} = dew point temperature (°C).

The degree of discomfort or heat stress is then described by the terms given in Table 3.

Table 3: Humidex heat stress scale

Humidex index, H/ °C	**Degree of discomfort**
H<30	No discomfort
30≤H<40	Some discomfort
40≤H<45	Great discomfort: avoid exertion
45≤H<54	Dangerous
H>54	Heat stroke imminent

In this research, the dew point temperature was calculated from the measured hourly relative humidity and temperature values, and the variation of the Humidex value over the monitoring period calculated.

The Heat Index (HI), which is used in the USA in weather forecasts, but can also be used for workplace assessment, is given in Fahrenheit by:

$$HI_1 = 0.5 * \left(T_{air} + 61 + \left(\left(T_{air} - 68\right) * 1.2\right) + (RH * 0.094)\right) \quad \text{If} \quad \frac{(HI_1 + T_{air})}{2} < 80°\text{F}$$

Otherwise:

$$HI_2 = -42.379 + 2.04901523 * T_{air} + 10.14333127 * RH - 0.22475541 * T_{air} * RH - 0.00683783 * T^2 - 0.05481717 * RH^2 + 0.01228774 * T^2 * RH + 0.00085282 * T * RH^2 - 0.0000199 * T^2 * RH^2$$

Where: T_{air} = air temperature (^{o}F); and

RH= measured relative humidity (%).

Adjustments have to be made to these equations for very high and very low relative humidity, but they were not needed for this research. The degree of discomfort or heat stress is then described by the terms shown in Table 4.

Table 4: Heat Index heat stress scale

Heat Index / °F	**Heat Index / °C**	**Category**
80≤HI<90	26.7≤HI<32.2	Caution
90≤HI<105	32.2≤HI<40.6	Extreme caution
105≤HI<130	40.6≤HI<54.4	Danger
HI>130	HI>54.4	Extreme danger

5. Prevailing weather conditions

During the summer of 2013, the months of May and June were cooler in the south east of England than the 30-year average. However, in July and August, when the monitoring took place, the temperatures were higher than the 30-year average. In fact, July 2013 was the third warmest July in the region since records began in 1910 (UK Met Office 2014). The heatwave lasted but was not particularly extreme. Over the 19 days, from 6th to 24th July, a daily maximum temperature of 28°C or more was measured somewhere in the UK, with maximum temperatures of 33.5°C recorded at Heathrow and Northolt on 22nd July.

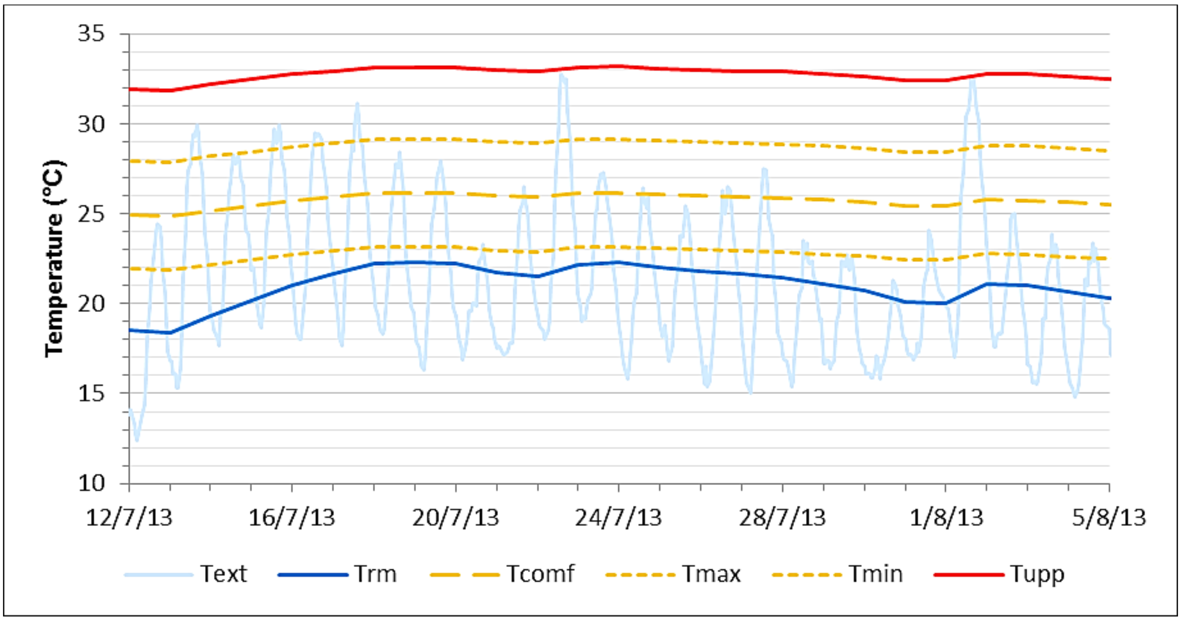


Figure 6: Ambient temperature recorded at St James' Park in London between 12th July and 4th August 2013, showing the running mean of the ambient temperature (T_{rm}), the Cat II adaptive thermal comfort thresholds (T_{max} and T_{min}) and the CIBSE TM52 Criterion 3 upper temperature limit (T_{upp}).

The temperature measured at St James' Park in London (UK Met Office, 2014b), which is the source of the temperature data for the work reported here, reached above 28°C for five consecutive days from 13th to 19th July inclusive, reaching a maximum of nearly 33°C on 22nd July and 1st August (Fig. 6). Based on the World Health Organisation's definition, a heat wave occurred was from 13th to 18th July inclusive (WHO, 2015). On 17th July 2013, Public Health England issued a level 3 heat wave alert for London and the south east (PHE, 2013), means there was a *'90% chance of heat wave conditions where temperatures are high enough over threshold levels to significant effect on health'* (PHE, 2015).

6. Measured internal temperatures

During the monitoring period, the internal temperatures in the four east-facing rooms on the first and second floor were warm but not excessively so (Fig. 7). All four rooms maintained peak indoor temperatures below the peak outdoor temperature, and on individual hot days of 18th and 22nd July, and 1st August, the room temperatures were up to 5K below ambient. Of these four rooms, both the minimum and maximum temperature (of 29.7°C on 1st August), were recorded in room 1Ea. Throughout the monitoring period all four rooms' temperatures were virtually always between the upper and lower Cat II, adaptive thermal comfort thresholds. This suggests that the combination of construction, shading and ventilation provision enabled occupants to regulate their thermal environment effectively.

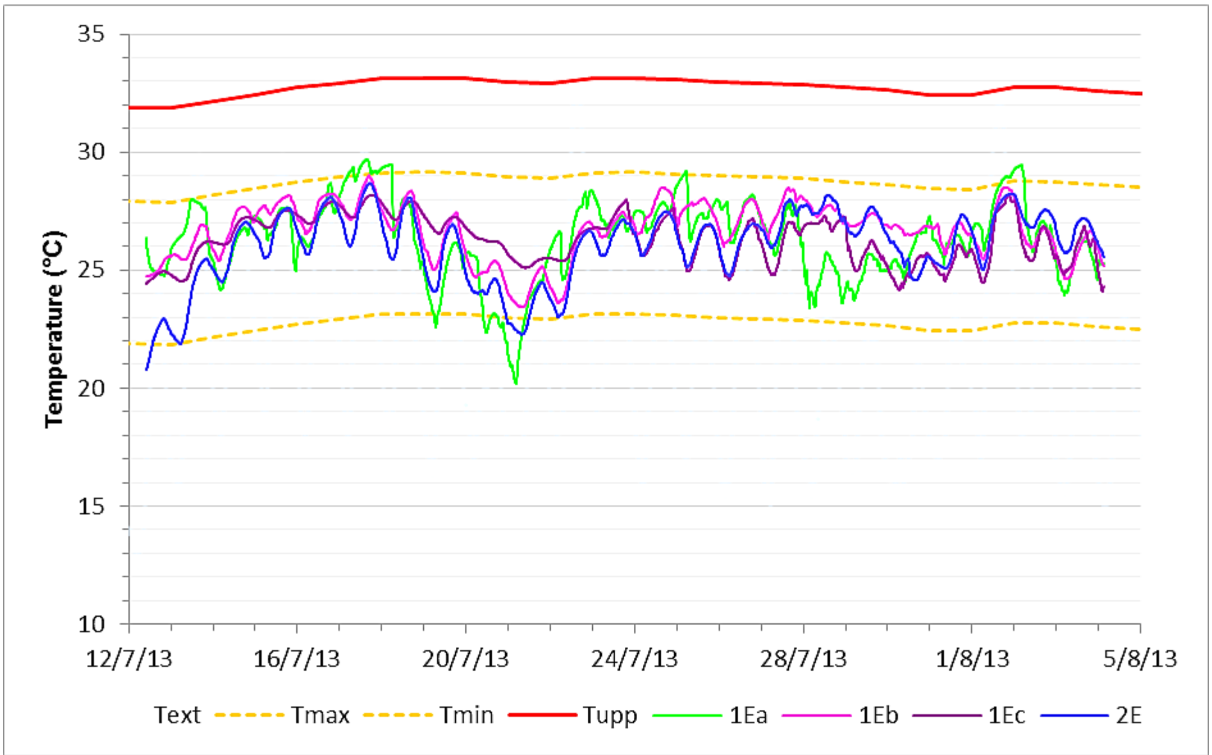


Figure 7: Internal temperatures in rooms on first and second floor between 12th July and 4th August, showing the Cat II adaptive thermal comfort thresholds (T_{max} and T_{min}) and the CIBSE TM52 Criterion 3 upper limit temperature (T_{upp})

The eleven rooms on the upper floors behaved quite differently (Fig. 8). The indoor temperatures were similar to those on the lower floor during the sustained cooler periods, e.g. 28th to 31st July, however, they reacted much more strongly to warmer ambient conditions. For example, between 12th July and 27th July, the indoor temperatures were high, and they stayed high, exceeding the ambient temperature at all times. Even on slightly cooler days, e.g. 18th to 21st July, the indoor temperatures floated well above the ambient temperatures at all times. Consequently, the indoor temperatures were above the upper limit of thermal comfort (T_{max}) for prolonged periods, during the day and night, and during the day, they frequently exceeded the CIBSE TM52, allowable upper-bound temperature (T_{upp}). The west-facing rooms tended to be warmer than those facing east, which is a commonly observed phenomenon in unshaded, naturally ventilated, thermally light-weight spaces (e.g. Iddon et al, 2015)

The data suggests that, on the upper floors, the building lacked resilience and that occupants may not have had the adaptive opportunities required to prevent overheating. Nor, it seems could they take retrospective action to bring the temperatures back down even when cooler night time ambient air was available for cooling, e.g. in the early morning of 20th July, the ambient temperature was 15K or more less than the indoor temperature!

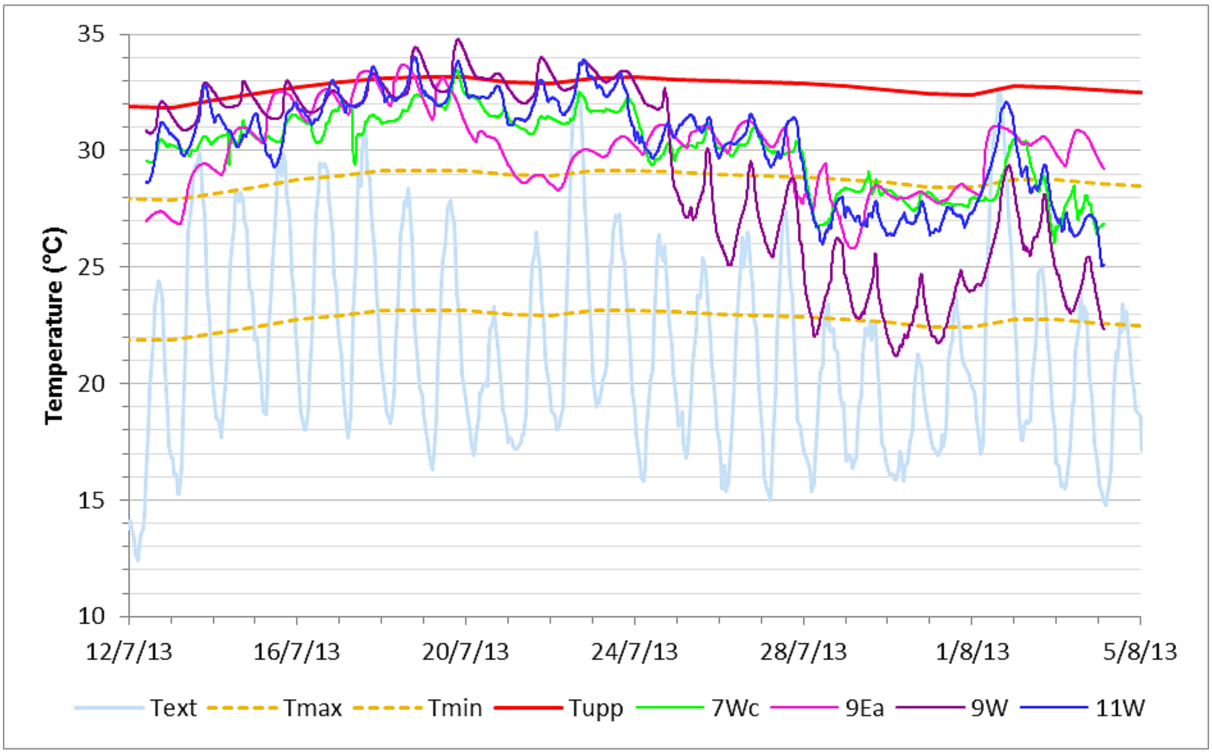


Figure 8: Internal temperatures in rooms on the upper floors between 12th July and 4th August, showing the Cat II adaptive thermal comfort thresholds (T_{max} and T_{min}) and the CIBSE TM52 Criterion 3 upper limit temperature (T_{upp})

7. Overheating analysis

To quantify the extent, or otherwise, of overheating, both the CIBSE static and adaptive criteria were used. No data were collected about the occupancy of the monitored rooms but as student accommodation could theoretically be occupied at any time of the day or night, being both a bedroom and a living area, it was concluded that overheating should be avoided at all times. Although the CIBSE use different static criteria for the day and night, any reasonable division made no difference to the conclusions from the overheating analysis. The temperature threshold of 26°C was assumed to apply from 22:00 to 08:00 and with 28°C applying during the daytime hours, between 08:00 and 22:00. The measured temperatures, which are not true operative temperatures, were used in the analysis.

7.1 Static criteria

The temperatures recorded in all the rooms were above the 26°C threshold for a significant proportion of the night (Fig. 9 and Table 5). Although room 2E performed the best, with 44.3% of night time hours above 26°C, this is still well in excess of the 1% limit. All other rooms were above 26°C for at least 50% of the time, with rooms 7Wc, 9Ea and 11W above for 98.8%, 96.5% and 98.2% of night time hours, respectively.

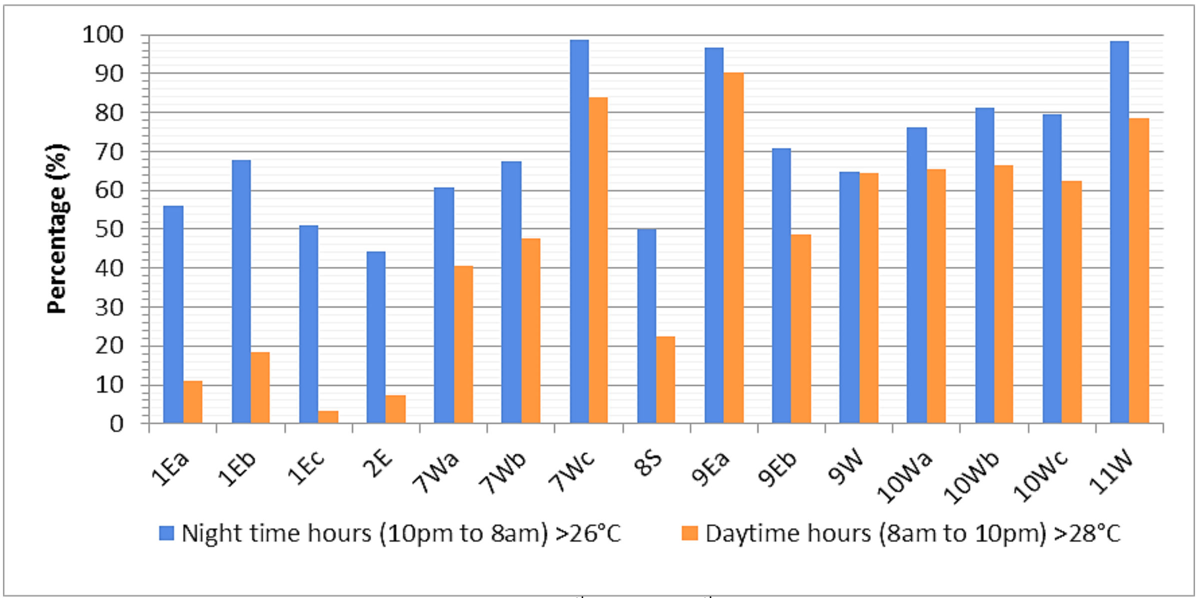


Figure 9: Percentage of the monitored period, 12th July to 4th August for which the day and night time temperatures exceeded the CIBSE threshold temperatures of 26°C and 28°C respectively.

Table 5: Summary of the recorded room temperatures between 12th July to 4th August and the percentage of day and night time hours above the day and night time static temperature thresholds.

	Temperatures recorded during monitoring period			Hour exceedance during the monitoring period		Equivalent annual hours exceedance[1]	
Room	Maximum (°C)	Minimum (°C)	Average (°C)	Night time 22:00-08:00 >26°C %	Daytime 08:00-22:00 >28°C %	Night time 22:00-08:00 >26°C %	Daytime 08:00-22:00 >28°C %
1Ea	29.7	20.2	26.3	56.2	11.0	3.5	0.7
1Eb	29.0	23.4	26.7	67.9	18.5	4.2	1.1
1Ec	28.2	24.2	26.3	51.1	3.2	3.2	0.2
2E	28.7	20.8	26.0	44.3	7.3	2.7	0.5
7Wa	31.1	21.8	26.8	60.7	40.5	3.8	2.5
7Wb	31.4	21.3	27.1	67.5	47.6	4.2	3.0
7Wc	33.5	26.0	30.1	98.8	83.9	6.1	5.2
8S	30.2	21.1	26.2	50.1	22.4	3.1	1.4
9Ea	33.7	25.8	30.1	96.5	90.2	6.0	5.6
9Eb	30.5	23.8	27.5	71.0	48.6	4.4	3.0
9W	34.8	21.2	29.2	64.6	64.6	4.0	4.0
10Wa	33.4	23.2	28.6	76.2	65.4	4.7	4.1
10Wb	31.9	23.3	28.4	81.3	66.3	5.1	4.1
10Wc	32.6	23.2	28.4	79.6	62.3	4.9	3.9
11W	34.0	25.1	30.3	98.2	78.4	6.1	4.9

[1] The monitored period of 543 days was just 6.2% of the hours in a whole year.

Shaded indicates failing the criterion.

The rooms exceeded the daytime threshold of 28°C far less often than the night time threshold. However, ten of the rooms exceeded the threshold at least 40% of the time, with rooms 7Wc, 9Ea and 11W again performing worst. The four rooms on the lower floors, 1Ea, 1Eb, 1Ec and 2E, along with room 8S performed less poorly, but were still well in excess of the 1% criterion.

The monitoring period spanned 22.7 days, which is only 6.2% of the year. It is salutary to note that even if there were no further hours of overheating in the rest of the year, and the 1% day and night time criteria were deemed to apply to annual hours over 26 and 28°C, all the rooms would still be considered as overheated at night, and all but three overheated during the day.

7.2 Adaptive criteria

The Cat II upper thermal comfort threshold, T_{max}, which provides the basis for all three of the CIBSE TM52 criteria, varied from 27.9°C to 29.2°C, average of 28.7°C, during the monitoring period (Figs. 6, 7 and 8), which is higher than both static overheating thresholds.

Considering Criterion 1, the four rooms on the first and second floors never exceeded T_{max} by more than 1K and so all passed this Criterion. All the remaining rooms exceeded T_{max} by more than 1K and all for more than 3% of the hours during the monitoring period. As with the static overheating analysis, rooms 7Wc, 9Ea and 11W performed worst, exceeding the threshold 64.7%, 60.8% and 66.2% of the time, respectively (Table 6).

With regard to Criterion 2, because the rooms on floors 1 and 2 never exceeded T_{max}, all four passed Criterion 2 (Fig. 7). All the other rooms had weighted exceedances, W_e, far greater than 6°C.h on at least four days, with three rooms so overheated that they failed on eighteen days, i.e. c80% of the time. Criterion 2 is designed to indicate the severity of overheating, and with such high weighted exceedances on so many days, it is clear that the rooms on the upper floors were severely and chronically overheating.

Table 6: Performance of rooms against the CIBSE TM56 criteria during the period 12 July to 4th August 2013 and overall overheating assessment

	Criterion 1	Criterion 2		Criterion3		Overall
Room	**Percentage of hours above upper threshold T_{max} %**	**Maximum weighted exceedance W_e °C.h**	**Number of days with W_e>6°C.h Days**	**Maximum exceedance of upper threshold T_{max} K**	**Number of days where temperature exceeds T_{upp} =T_{max}+4K Days**	**Failed two or more criteria?**
1Ea	0	5	0	0	0	Pass
1Eb	0	0	0	0	0	Pass
1Ec	0	0	0	0	0	Pass
2E	0	0	0	0	0	Pass
7Wa	5.6	14.7	5	0	0	Fail
7Wb	12.0	30.8	8	0	0	Fail
7Wc	64.7	77.8	18	4.4	1	Fail
8S	3.6	13.0	4	0	0	Fail
9Ea	60.8	90.3	18	4.6	3	Fail
9Eb	6.1	23.2	4	0	0	Fail
9W	54.8	104.0	13	5.6	11	Fail
10Wa	41.8	62.0	14	4.3	2	Fail
10Wb	32.8	49.2	12	0	0	Fail
10Wc	25.6	46.3	10	0	0	Fail
11W	66.2	87.0	18	5.0	8	Fail

Shaded indicates failing the criterion.

Regarding criterion 3, five of the fifteen rooms failed, exceeding T_{upp} on one or more occasions between 12th and 23rd of July, (Fig. 8). Room 9W displayed the most severe and most frequent overheating, failing on eleven days; 11W also overheated badly, failing on eight. When these rooms exceeded T_{upp} they did so for between two to twelve hours.

Overall, the rooms on the first and second floors passed all three criteria and so would be deemed free of overheating risk. In contrast, the eleven rooms on floors 7 and above failed two or more criteria. Five rooms, 7Wc, 9Ea, 9W, 10Wa and 11W, were severely and chronically overheated and failed all three criteria.

7.3 Heat stress

The conditions were so severe in room 10Wa that, on the Humidex scale, they would have caused '*some discomfort*' (30°C≤H<40°C) for most of the monitoring period with short periods of '*great discomfort*' (40°C≤H<45°C) (Fig. 10).

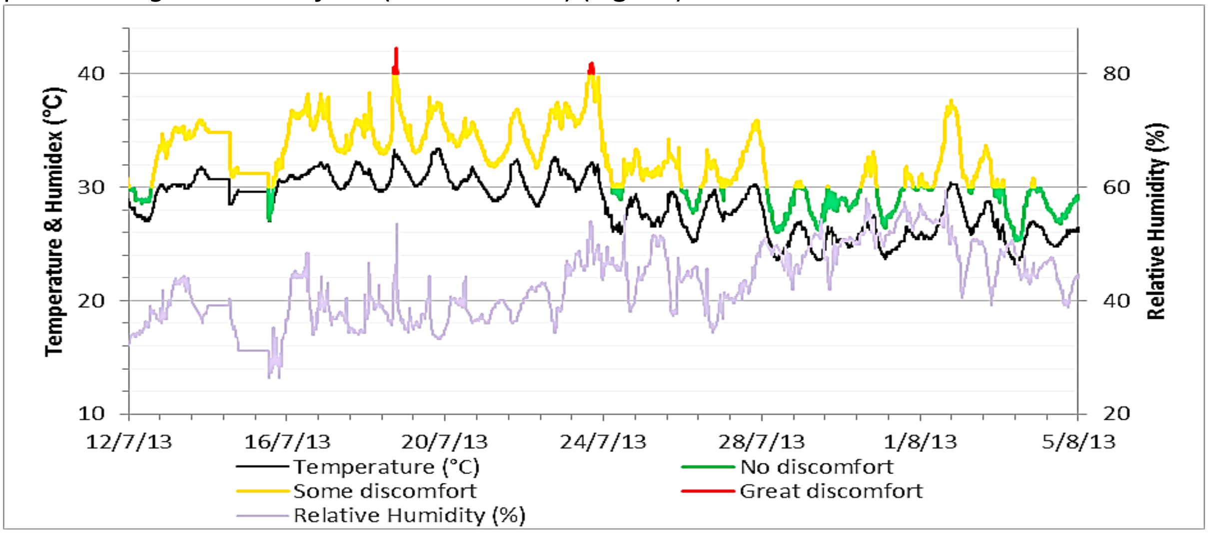


Figure 10: Humidex rating, measured temperatures and relative humidity for room 10Wa between 12th July and 4th August

On the Humidity Index scale, *caution* would be advised (26.7≤HI<32.2°C) for much of the monitoring period with short periods of '*extreme caution*' (32.2≤HI<40.6°C) (Fig. 11). Heat stress would be likely when undertaking moderate levels of activity or if exposure is prolonged; which it is in this apartment, and the others with similar temperatures.

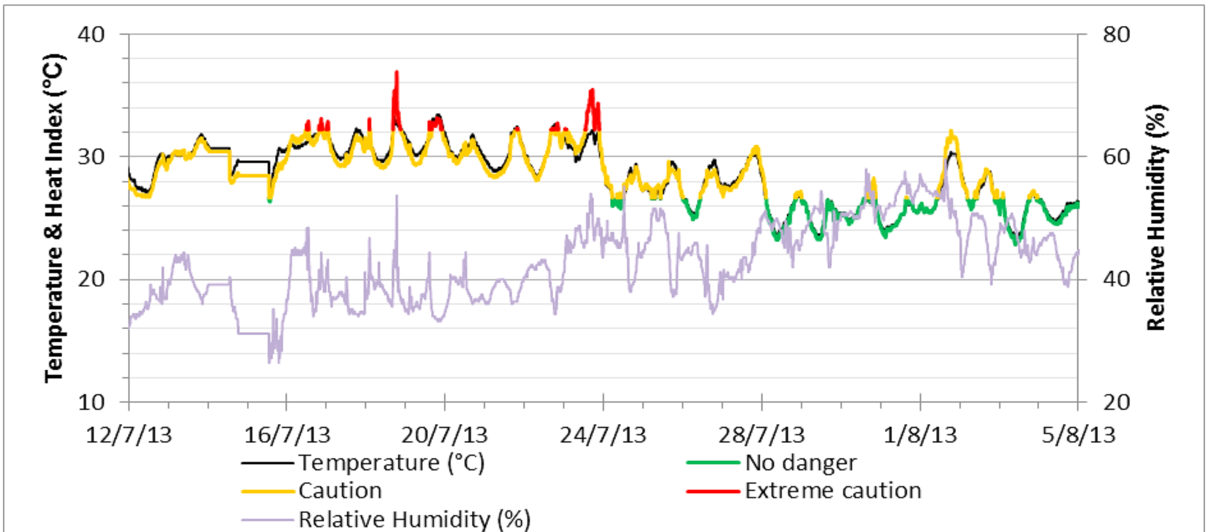


Figure 11: Heat Index rating, measured temperature and relative humidity for room 10Wa between 12th July and 4th August

8. Discussion

The building chosen for this case study is emblematic of a type that has raised concern about overheating within the building research and construction community. That is, thermally lightweight, medium rise apartment blocks, located in the south east of England. The building was in its first year of operation to there was no prior knowledge of its likely summertime performance. The monitoring period, the summer of 2013, included a heat wave so it was possible to see how the building would respond under conditions that will become typical as the UK climate warms.

The rooms on all floors significantly exceeded the CIBSE 26^{o}C/1% night time overheating criterion suggesting that all occupants of this building may suffer from disrupted sleep for many nights successively. Whilst the rooms on the lower floors did not overheat as indicated by the adaptive thermal comfort criteria in CIBSE TM52, those on floors seven and above did. Five rooms were chronically and severely overheated which could render them effectively uninhabitable. Heat stress conditions were monitored in one room, but others in which humidity was not measured, had similar temperatures; conditions in the upper parts of the building might therefore be damaging to health.

In addition to the intrinsic thermal fragility of the construction form, other factors conspired to create the severely overheated conditions. There was no external shading or any other form of purposefully designed overheating reduction features. The results indicate that temperatures in the room on east-facing and site-shaded aspects are substantially lower than in the other rooms.

Internal heat generation was also a factor. As well as the density of heat gain from occupants and their electrical equipment, heat from the hot water services leaked into the stairwells and corridors and rose up the building. Spot measurements taken off the building's energy management system during a site visit in November 2012, indicated stair well temperatures varying from 15^{o}C on the ground floor up to 27^{o}C on the top floor. The corridors had no direct connection to the outdoors and so heat could not be ventilated away. In fact, the original drawings showed windows to the stair core, but these had been omitted in the final building and replaced by fixed window-imitating panels. An example perhaps, of post design, ad-hoc cost reduction.

The mechanical extracts installed in the apartments, which might have exhausted some of the heat, were also ineffective. They were also very noisy and so tended not to be used; the facilities manager reported that some residents had requested their ventilation systems to be turned off. Others have also reported the contribution that cheap, noisy and poorly installed MVHR systems make to overheating risk (Mcleod, 20??).

The only form of adaptive action that the occupants might have taken to effect cooling was to increase the natural ventilation by opening windows. This was inherently limited by the single-aspect design of the rooms, but was also severely curtailed by the restriction of window opening to 150mm which, given the external insulation of 100 to 200mm, meant the free area for ventilation was very limited indeed. In essence, therefore, there is nothing the occupants can do to escape the heat except to leave their room and possibly the building.

Whilst there is no doubt that the building had severe overheating problems, it was difficult to understand fully all the causes and this. For example, although window opening sensors were installed, because the wireless network did not work it wasn't possible to understand what contribution to cooling, if any, the operable windows were making. Because of privacy and other ethical concerns, it was impossible to know reliably whether rooms were occupied or not. Thus, it wasn't possible to calculate overheating just for the occupied periods and neither was it possible to know if adaptive actions to combat heat could have been taken. Finally, the study did not incorporate a questionnaire survey so the measured temperatures could not be compared with the thermal perceptions of the occupants.

The monitored building is unlikely to be an isolated example. It might just be that the early C21st, has seen the construction in the UK of a stock of apartment buildings that will be uninhabitable by the mid-century. This work will, it is hoped, provide further ammunition for those who wish to take action to prevent the continued production of such toxic assets: the construction industry, land lords, social housing providers and tenant groups, and for those concerned with building guidelines and regulations. The work will also aid those concerned about the health and well-being of UK citizens.

9. Conclusions

Summertime temperatures were recorded in a medium rise, thermally lightweight, well insulated, naturally ventilated, single aspect apartment block built using off site construction methods located in north London UK. The apartments were monitored for 22 days during July and August 2013, which included a 19-day hot period, which precipitated a level 3 heat wave alert. Temperatures were monitored in fifteen apartments on the lower two floors and on floors 8 to 11 with relative humidity also recorded in one apartment on floor 10.

The risk of overheating was assessed using the static CIBSE Guide A criteria of 26°C/1% for night time hours and 28°C/1% for the daytime. Analysis was also conducted using the CIBSE TM52 adaptive thermal comfort criteria and heat stress was assessed using the Humidex and Heat Index metrics.

The night time temperatures in all the apartments had more than 44% of night time hours above 26^{o}C, thereby significantly exceeded the 26^{o}C/1% criterion, suggesting that the sleep of occupants could be seriously disrupted, and for a prolonged period. Whilst the rooms on the lower floors passed the CIBSE TM52 adaptive criteria, those on floors 7 and above did not. Four of these apartments were seriously overheated with conditions in a 10th floor room that would lead to heat stress.

It appears that the single aspect geometry of the rooms, the well-insulated and thermally lightweight construction, and the lack of external shading, combined with the blind corridors, the accumulation of internally-generated heat in the stair wells and corridors, the restrictions of window opening and the curtailment of background mechanical ventilation, created a cocktail of factors that led to chronic and severe overheating.

The results support the findings of others, and indicate that this form of construction is dangerous in hot weather and so entirely inappropriate for, possibly many, areas of the UK, especially as the climate warms further. The findings have significance for construction companies, land lords and social housing providers, those concerned with building guidelines and the regulations, and those concerned about the health and well-being of UK citizens.

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11. References

Beizaee, A., Lomas, K. J., & Firth, S. K. (2013). National survey of summertime temperatures and overheating risk in English homes. *Building and Environment*, 65, 1–17. doi:10.1016/j.buildenv.2013.03.011

British Standards Institution, 2007. BS EN 15251: 2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. London: *British Standards Institution*.

CCC, 2014. Managing Climate risks to well-being and the economy, *Committee on climate change, adaptation sub-committee*, Progress Report 2014, 202pp.

CCC, 2017. Progress in preparing for climate change, 2017 Report to Parliament, *Committee on Climate Change, Adaptation Sub-Committee*, June 2017, 234pp.

CIBSE, 2006. Guide A: Environmental Design (7th ed.). (edited by K. Butcher). London: *Chartered Institution of Building Services Engineers*

CIBSE, 2013. The limits of thermal comfort: avoiding overheating in European buildings, Technical memorandum, TM52, *Chartered Institution of Building Services Engineers,* London.

CIBSE, 2015. Guide A: Environmental Design (8th ed.). *Chartered Institution of Building Services Engineers,* London:

CIBSE, 2017. Design methodology for the assessment of overheating risk in homes. Technical memorandum TM59, *Chartered Institution of Building Services Engineers*, London.

DCLG 2012. Investigation into overheating in homes, Literature review, AECOM for the *Department for Communities and Local Government*, 124pp. ISBN: 978-1-4098-3592-9

EnOcean Alliance, 2014. EnOcean Alliance Products. [online] Available at: https://www.enocean-alliance.org/en/products/, accessed 15 November 2014.

GHA. (2014). Preventing overheating: investigating and reporting on the scale of overheating in England, including common causes and an overview of remediation techniques. London: *Good Homes Alliance.* February, 2014.

Heat Index, 2015, What is the heat index?. Available at: http://www.srh.noaa.gov/ama/?n=heatindex, accessed June 2015.

Humidex, 2015, Humidex Rating and Work. Available at: http://www.ccohs.ca/oshanswers/phys_agents/humidex.html, accessed June 2015.

Iddon CR, Mills TC, Giridharan R and Lomas KJ, 2015. The influence of hospital ward design on resilience to heat waves: an exploration using distributed lag models. *Energy and Buildings*, 86, p573-588. Doi. 10.1016/j.enbuild.2014.09.053.

Lomas KJ and Porritt SM, Overheating in buildings: lessons from research. *Building Research & Information*, 45(1-2), pp 1-18, (2017), ISSN 0961-3218. doi:10.1080/09613218.2017.1256136.

MadgeTech, 2014. MadgeTech Temp101A Data Logger. [online]. Available at: http://www.madgetech.com/data-loggers/applications/shipping-transportation/temp101a.html, accessed 16 November 2014.

McLeod, R and Swainson, M, 2017. Chronic overheating in low carbon urban developments in a temperate climate. *Renewable and Sustainable Energy Reviews*, 74, p201-220.

PHE, 2013. Level 3 'heatwave' alert issued for London and the South East, *Public Health England*, Press Release, 17 July 2013. Available at: https://www.gov.uk/government/news/level-3-heatwave-alert-issued-for-london-and-the-south-east, accessed 120118.

PHE 2015, Heat Wave Plan for England, Protecting health and reducing harm from extreme heat and heatwaves, *Public health England*, May 2015, 32 pp.

Quigley ES, 2016. The energy and thermal performance of UK modular residential buildings. *PhD thesis*, Loughborough University, 340pp.

UK Met Office, 2014a. Sunny and warm July in 2013. Available at: http://www.metoffice.gov.uk/news/releases/archive/2013/warm-july-stats, accessed 120118.

UK Met Office, 2014b. UK Meteorological Office. MIDAS Land Surface Stations data (1853-current). NCAS *British Atmospheric Data Centre*, 2014, Available at: http://badc.nerc.ac.uk/view/badc.nerc.ac.uk_ATOM_dataent_ukmo-midas, accessed 1st May 2014.

UK Met. Office, 2014. 2013 July heatwave. https://www.metoffice.gov.uk/learning/learn-about-the-weather/weather-phenomena/case-studies/heat-wave-july2013

ZCH, 2015. Overheating in homes, the big picture, *Zero-Carbon Hub*, Full report, 96pp, June 2015.