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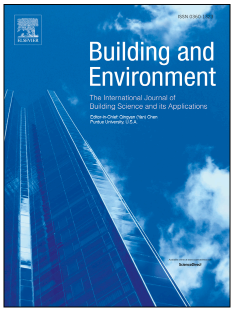

Overheating investigation in UK social housing flats built to the Passivhaus standard

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Global environmental and energy concerns have led to a rapid growth in mandating the construction of more energy efficient dwellings in the UK. This is particularly true for the social housing sector which is partly founded by the government and it is expected to lead the way in this respect.

To address this issue energy efficiency standards such as Passivhaus are increasingly adopted by both private and social housing sectors in the UK. However, data describing actual thermal performance of dwellings built to such standards, particularly in dense social housing flats, are scarce.
This study considers the overheating risk in social housing flats built to the Passivhaus standard in the UK during the cooling season. It considers 25 flats over three cooling seasons in Coventry, UK.
Overheating assessment based on Passivhaus criteria, using a fixed benchmark, suggests there is a significant risk of summer overheating with more than two-thirds of flats exceeding the benchmark. While the level of overheating in different flats varies considerably, detailed analysis indicates that this is more related to occupant behaviour than construction. An alternative approach to evaluating overheating risk is the adaptive thermal comfort model, which takes into account occupant vulnerability and actual outdoor temperature. Use of the adaptive benchmark suggests this overheating risk is lower for normal occupants; but higher for vulnerable occupants. These results not only have implications for the evaluation of overheating risk but also for the way in which social housing landlords place tenants of differing vulnerabilities.

Key words: Passivhaus, Social housing, Overheating, Adaptive thermal comfort

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1. Introduction

This paper investigates the risk of overheating in social housing flats built to the Passivhaus standard in the UK. Fixed and adaptive thermal comfort benchmarks are used to assess the overheating risks.

The UK Government's climate change mitigation strategy [1], which introduced zero carbon targets for new homes, has generated significant interest in how this can be achieved [2, 3, 4]. In response to such interest and the recast European Energy Performance in Buildings Directive (EPBD) [5], revised 'zero carbon' dwelling standards will be mandated in the UK by 2016 [3, 6]. This legislation, and the voluntary use of energy efficiency standards such as Passivhaus, BREAAM and LEEDs etc., have resulted in significant changes in the design and construction of new dwellings [7].

In response to new regulations and the UK's move towards zero carbon homes, housing developers are under an obligation to build more energy efficient homes. This situation applies in particular to social housing developers who, as a sector partly funded by housing corporations, are expected to lead the way [8].

The Passivhaus standard was developed in Germany in 1990 as a way of reducing energy consumption and providing ultra-low energy and zero carbon dwellings [7]. Central to this approach is the reduction of space heating demand through minimising thermal transmission losses and optimising passive solar gain [4, 9]. In recent years the Passivhaus approach has gained popularity in the UK but, while considerable research has been undertaken regarding its effectiveness in reducing heating loads, less attention has been paid to its annual and whole-life performance characteristics [7].

The internal temperature of houses in the summer is of increasing concern, even in the mild summers experienced in the UK. High indoor temperatures can be life threatening [10].The heat-wave of 2003 is estimated to have caused an additional 2,091 deaths amongst vulnerable groups in the UK [11] with as many as 70,000 other deaths between June and September across Europe [12].

Whilst the summer of 2003 was very unusual, climate change projections indicate that, by the 2050s, similar extreme weather events will take place every two or three years and by the 2080s such temperatures would be considered unusually cool [13]. Indeed, the Zero Carbon Hub (ZCH) [6] highlighted the risk of overheating and cautioned that "*There is some anxiety that homes we are building today may be at risk of overheating even in the current climate. Given the prospect of significant warming, well within the expected lifetime of homes this risk will increase with potentially serious consequences*".

While much attention has been focused on ways to mitigate the causes of climate change, mainly by minimising the use of fossil fuels to generate the energy used in buildings, there is wide recognition that climate change is already happening. Consequently, there is a need to examine how the built environment can adapt to change and ensure that all buildings are capable of dealing with greater climate extremes [14].

Any evaluation of the risk of overheating needs to reflect the occupants' perceptions of thermal comfort, particularly those vulnerable groups which are often tenants in social housing. There are two approaches to evaluate the risk of overheating which can be characterised as the fixed and the adaptive approaches. The fixed approach considers a benchmark for evaluating overheating, while the adaptive approach suggests that a fixed maximum temperature is not appropriate and that the benchmark should reflect the outdoor climate at the time and the likely vulnerability of different groups to changing comfort conditions [15, 16].

This paper investigates the risk of overheating for social housing constructed using Passivhaus principles during the cooling season; the implications of adopting different approaches to evaluate internal comfort conditions and the likely impact on tenants with different vulnerabilities.

2. Background study

2.1 Social housing

Social housing provides secure and decent homes for those who cannot afford open market prices in the UK.

The development of social housing in the UK started in the late 19th Century and reached its peak by the mid-20th Century. Social housing is one of the most important sectors in the UK, with 3.8 million households representing 17% of all UK homes [17]. This stock belongs to local authorities and housing associations [18]. In 2012, 53% (around 2.1 million) of social tenants rented their homes from a housing association and the rest (around 1.9 million) from local authorities [17].

Social housing also has the highest rate of overcrowding in the UK, at 7%, compared to an overall rate of 3% [17].With the increase in the UK population, social housing providers are under pressure to build more houses [8]. The UK housing sector is also under pressure to move towards zero carbon houses to comply with UK regulations. This applies in particular to the social housing sector, since it benefits from public funds [8]. For example, the government's Standard Assessment Procedure (SAP) is used in the UK to assess the energy and environmental performance of UK dwellings. The average SAP rating of UK homes increased from 45 to 57 (12 points) between 1996 and 2011, while in the same period the rating in the social housing sector rose by 14 points, from 49 to 63. In 2011-2012, the social housing sector also had the biggest proportion of dwellings earning A to C scores, the highest on the UK's Energy Efficiency Ratings (EER) scheme [17].

But in 2012, the social housing sector had the highest unemployment rate, around 10%, amongst occupants and almost two-thirds of social tenants were in receipt of Housing Benefit (HB) to help to pay their rent, approximately 40% more than private tenants [17]. The ability of social tenants to pay their rent both now and in the future is essential for the long-term business of registered social landlords (RSLs).

It has been estimated that in 2011 11% of UK households suffered from fuel poverty (when a household spends more than 10% of its total income on energy) [19]. Average energy bills have also seen a sharp rise (24%) between August 2009 and August 2013, while the average household income increased by only 3% in this period [20]. Unless energy demand reduction techniques are integrated into social housing sector to improve the energy efficiency, there is further risk of more households going into fuel poverty. This risk is particularly relevant for social housing tenants, given that their average gross annual income is noticeably lower than that of private renters and owner occupiers; £17,600 for social renters in comparison to £30,100 and £40,500 for private renters and owner occupiers respectively [21].

Since tenants in the social rented sector also have a higher age profile – 45% aged 55 or over and 29% aged 65 or over [21] – it is important to consider the relative degrees of vulnerability of different tenants.

Given the specific sensitivities of the social housing sector outlined above, it is vital for social housing providers to adopt a standard of supplying energy efficient, comfortable and affordable dwellings now and in future climatic conditions, during both cooling and heating seasons.

2.2 Passivhaus

The Passivhaus standard was developed in Germany in the late 1980s; it sets very high requirements for energy efficiency in building design and construction. The Passivhaus Institute of Darmstadt, Germany, promotes and controls the standard and defines the associated quality assurance process [22]. The main aim of Passivhaus is to minimise the requirements for space heating and cooling. It also largely focuses on avoiding and reducing thermal transmission losses and increasing and optimising the benefits from passive solar gain [9]. Furthermore Passivhaus aims to provide effective indoor air quality and increase thermal comfort. By definition, a Passivhaus home focuses on passive design features such as insulation, airtightness and solar orientation. However, it also allows certain active elements to be included – notably mechanical ventilation with heat recovery (MVHR). The fundamental principle of the Passivhaus standard is for a home to maintain its internal temperature and air quality simply by adding a small amount of heat to the air being circulated by the ventilation system, thereby eliminating the need for a traditional wet central heating system [9, 22].

Since the late 1980s, some 37,000 Passivhaus buildings have been constructed worldwide [23]. It is often referred to as a "comfort standard" as well as an energy standard, and the popularity of Passivhaus in Germany – including a 92% positivity rating by occupants – has been largely due to a combination of social, political and financial circumstances which are specific to this nation [22].

The adoption of the German Passivhaus standard in the UK as a template for providing low energy or zero carbon dwellings has increased significantly in recent years. Around 250 Passivhaus certified buildings were completed by 2013 and up to 1000 units are completed, on site, or in the planning phase [24]. According to the UK Passivhaus projects map [25], these projects are spread all over the UK and include some new social housing projects. Wimbish and Sampson Close Passivhaus schemes are two examples of new social housing developments built to this standard [26].

Touhy et al. [27] investigated and monitored three dwellings, including the first Scottish Passivhaus, a Low Energy House (without MVHR), and a 1950s dwelling located in Dunoon, Scotland. Their results show that Passivhaus is a successful example of providing thermal comfort with a small amount of energy during the heating season. Bearing in mind that low income families and also vulnerable groups are the main occupants of social housing, the Passivhaus standard is likely to be able provide an affordable and comfortable building for them during the heating season.

In addition to providing affordable comfort during the heating season it is also essential that dwellings constructed to the Passivhaus standards are able to deliver affordable comfort during the cooling season, given the particular vulnerability of many tenants.

2.3 Summer overheating risk in social housing dwellings built to Passivhaus standard

Questions regarding the performance in summer and the risk of overheating for some Passivhaus buildings located in different European climatic zones have been raised in a number of studies [28, 29, 30, 31, 32]. In the UK, research studies focusing on summer temperatures and thermal comfort during the cooling season are fewer and more limited than those concerned with performance in the heating season [10].

Athough in recent years there has been an increase in the construction of Passivhaus in the UK, the first Passivhaus certified buildings were completed only in 2010 [33]. Consequently, post occupancy data for these dwellings are limited and minimal [7].

A comprehensive review by Dengel and Swainson [22] of the evidence of overheating in new UK homes indicates that there is a growing body of evidence that new energy efficient homes (i.e. well insulated, airtight dwellings) do suffer from overheating, and can in some cases result in adverse health effects for the occupants.

The important provisions which can help to avoid or reduce overheating [34] are a proper layout which can minimise unnecessary solar gain, an adequate thermal mass, a good level of ventilation and reduced internal gains. In order to identify the risk of overheating in dwellings built to the Passivhaus standard, the potential impact of such factors should be considered.

Roaf et al. [35] argued that limited attention is paid to traditional means of reducing overheating, such as the inclusion of thermal mass and openable windows for natural ventilation in buildings constructed with the Passivhaus standard.

Urban areas and dense social housing, flats in particular, limit the opportunities for ventilating through windows [7]. In addition, in response to the arguments of the Royal Society for the Prevention of Accidents (RoSPA) [36], the windows of new build social housing in the UK can open to an angle of only 10 degrees. This can limit opportunities for natural ventilation, notably in highly airtight dwellings.

The social housing sector not only has a higher proportion of dense, purpose-built flats, with more than two thirds of social renters having less than 70 m^2 usable floor space [17] it also experiences high rates of overcrowding [21]. Therefore, the impact of internal gains is likely to be higher than in other kinds of housing [7].

These risks are exacerbated when the implications of uncertain future climate conditions are considered [36].

2.4 Thermal comfort and overheating benchmarks

According to Nicol and Fionn [14], various factors should be considered in relation to comfort, however, thermal comfort and climate adaptation studies currently coincide in one key area: overheating.

The Chartered Institution of Building Services Engineers (CIBSE) [38] also states that it is vital to know the limits beyond which a building will overheat.

To evaluate the risk of overheating in a building, the Passivhaus standard uses a fixed threshold temperature which remains the same irrespective of the external conditions and occupants' vulnerabilities. The standard states that that it is not acceptable for living areas to exceed an operative temperature of 25^0C for more than 10% of the total occupied hours.

According to CIBSE TM52 [38], the current advice on overheating in CIBSE Guide A is very limited. Therefore, the CIBSE Overheating Task Force have taken the adaptive approach and decided that it is no longer suitable to have a fixed indoor temperature regardless of the outdoor conditions and a new approach should be considered for evaluating overheating, in particular for free running buildings.

The adaptive approach implies that as a benchmark, a fixed maximum temperature is not appropriate for all climates and that, in order to achieve thermal comfort, the target indoor temperature should reflect the outdoor temperature at the time [15].

Adaptive thermal comfort standards provide comfort envelopes which change with the external temperature. Nicol et al. [15] suggest that occupant discomfort is related to ΔT, the difference between the actual operative temperature (T_{op}) in the room and the comfort temperature (T_c) in a free-running building ($\Delta T = T_{op} - T_c$).

Based on European Standard EN 15251 [39], the comfort temperature (T_c) in summer is calculated from Equation 1:

$$T_c = 0.33Trm + 18.8 \quad \text{(Equation 1)}$$

where T_{rm} is the running mean of the outdoor temperature which is calculated from Equation 2.

$$T_{rm} = (T_{od-1} + 0.8\,T_{od-2} + 0.6\,T_{od-3} + 0.5\,T_{od-4} + 0.4\,T_{od-5} + 0.3\,T_{od-6} + 0.2\,T_{od-7})/3.8 \quad \text{(Equation 2)}$$

where Tod -1 is the daily mean external temperature for the previous day
Tod -2 is the daily mean external temperature for the day before and so on.

BS EN 15251 [39] defines that the risk of building overheating relates to the comfort temperature as well as the type of building and occupants. Building Category I is considered to include buildings where the occupants are particularly sensitive and fragile (vulnerable group), whereas Building Category II is considered for normal expectations in new or renovated buildings. Equations 3 and 4 show the maximum allowable temperature (i.e. thermal comfort) in Building Categories I and II respectively.

$$\text{(Category I)} \quad T_{max} = 0.33T_{rm} + 21.8 \quad \text{(Equation 3)}$$

$$\text{(Category II)} \quad T_{max} = 0.33T_{rm} + 20.8 \quad \text{(Equation 4)}$$

Following the new way of evaluating comfort temperature according to the adaptive approach, in CIBSE TM 52, Nicol [38] suggests a new guideline to evaluate the overheating occurrences for European buildings. According to this guideline the following three criteria should be assessed. A room is overheated if any two of the three following criteria fail:

- **Criterion 1: Hours of exceedance (H_e)**

The first criterion sets a limit for the number of hours that the operative temperature can exceed the threshold comfort temperature (this refers to the upper limit of the range of comfort temperatures) by 1K or more during the occupied hours of a typical non-heating season.

The number of hours (H_e) during which ΔT is greater than or equal to 1K during the cooling season (May to September) should not be more than 3% of the total occupied hours.

According to CIBSE TM 52 [38], if data are not available for all of the cooling season (or if occupancy or monitoring applies only to part of the period) then 3% of the available hours should be used as a limit.

- **Criterion 2: Daily weighted exceedance (W_e)**

The second criterion deals with the severity of overheating within any one day, which can be as important as its frequency. The severity of overheating that occurs in one day is a function of the sudden temperature rise and its duration. This criterion sets a daily limit of overheating which it states is acceptable during a single day.

The daily limit set for weighted exceedance (W_e) shall be less than or equal to 6 in any one day to allow for the severity of the overheating. The equation used to calculate weighted exceedance (W_e) is as follows:

$$W_e = (\sum h_e) \times W_F = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3) \quad \text{(Equation 5)}$$

where:

h_e is the number of hours.

The weighting factor $W_F = 0$ if $\Delta T < 0$, otherwise $W_F = \Delta T$, and h_{ey} is the time (in hours).

- **Criterion 3: Upper limit temperature (T_{upp})**

An absolute maximum daily temperature for a room is set by the third criterion. Temperatures which exceed the absolute maximum temperature are deemed unacceptable.

The absolute maximum value for an indoor operative temperature is set as follows: the value of ΔT should not exceed 4K.

In this standard the absolute maximum temperate is one in which adaptive actions are inadequate and cannot restore occupant comfort. Therefore, at no time during monitoring period should ΔT exceed 4K.

According to European Standard BS EN 15251 [39], in order for an adaptive method to apply, the living quarters should be equipped with operable windows which open outdoors, can be readily opened and adjusted by the occupants of the spaces and there should be no mechanical cooling in operation anywhere else apart from the living quarters. In the summer, mechanical ventilation with unconditioned air may be used, but opening and closing windows shall be of primary importance as a means of regulating thermal conditions in the living quarters. In addition to opening and closing the windows, there may be other low-energy methods that can help control the indoor environment, such as fans, shutters, night ventilation, etc.

The adaptive thermal comfort model as defined by European Standard BS EN15251 [39], was applied in this study to help analyse the occupants' thermal comfort. The reason for using this model is that the bypass mode of the MVHR system used in Passivhaus during the summer provides unconditioned ventilation and also gives occupants access to windows which open.

3. Methodology

3.1 Case study

This study investigates overheating risk in social housing flats built to the Passivhaus standard. The case study development is located in the Sampson Close Coventry, West Midlands, UK. This development comprises 23 social housing units built to Passivhaus Standards. The development has 18 flats and 5 houses constructed by Orbit Heart of England Housing Association (OHE) (Figure 1).

Figure 1: Sampson Close development by Orbit, reference will be added

3.2 Indoor temperature and occupancy pattern:

Orbit Housing undertook a systematic monitoring programme of Samson Close where indoor environmental parameters (i.e. indoor temperature, humidity, CO_2 etc.) were monitored in 23 dwellings. The analysis in this paper is based on an evaluation of flats' indoor air temperature. Given the thermally lightweight nature of Passivhaus dwellings, air temperature is likely to be reasonable proxy for operative temperature. Flats included in this analysis were selected based on the availability and quality of monitored data. Table 1 shows the number of flats selected and monitoring period for each year between 2011 to 2013.

In this paper the analysis focusses on the overheating in the living rooms of these flats. The selection of living rooms for analysis is due to the daytime use of the space and the higher likelihood of overheating during the day when both temperature and solar radiation are at their peak. Living rooms also have the highest potential for internal gains during the day and the largest south facing aperture.

Table 1: Summary of the monitoring information

Monitoring period	Year	Period of monitoring	Number of monitored days	Number of monitored flats
A	2011	17 Aug – 30 Sep	45	11
B	2012	3 Jul – 5 Aug	34	9
C	2013	1 May – 30 Aug	122	5

The occupants of all selected flats were surveyed by OHE about their occupancy pattern. The responses from the occupants reveal the majority of the flats are occupied all day. Therefore, for the purpose of this study, due to the high likelihood of living rooms being occupied during the day and considering the occupancy pattern of livings rooms used in similar studies [10, 40], an occupancy pattern of 8.00-23.00 was used to evaluate overheating risk in the selected living rooms. Hence, based on the assumed occupied hours and the number of monitoring days (Table 1), the total numbers of occupied hours monitored for each flat were 657, 510 and 1830 in 2011, 2012 and 2013 respectively.

3.3 Outdoor temperature and solar irradiation:

Outdoor temperatures and solar irradiation information were taken from the local weather station (Coventry Coundon weather station) [41].

Figure 2 shows the average mean and maximum outdoor temperatures during the selected monitoring periods since 2002 [42]. It indicates that the outdoor average mean temperature during monitoring periods in the summers of 2011 and 2013 was slightly higher (by 4% and 3% respectively) than the historic temperature of the same period. Whilst 2012 had a slightly lower average mean temperature (a 2% decline). These results indicate that the temperatures experienced during the three monitoring periods are in line with those that might typically be expected in this location.

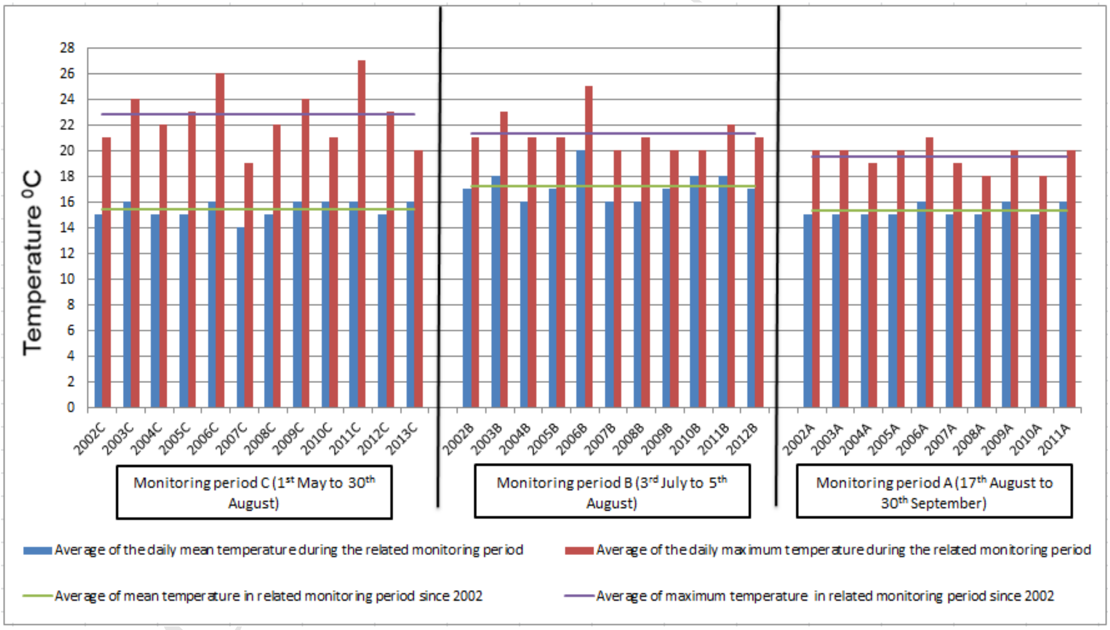


Figure 2: Coventry's average mean and max outdoor temperatures since 2002 in the selected monitoring periods

Further to this historical comparison of outdoor temperature, the environmental factors that affect indoor temperature and overheating (outdoor temperature and solar irradiation) for the three monitoring periods are compared and presented in Figure 3.

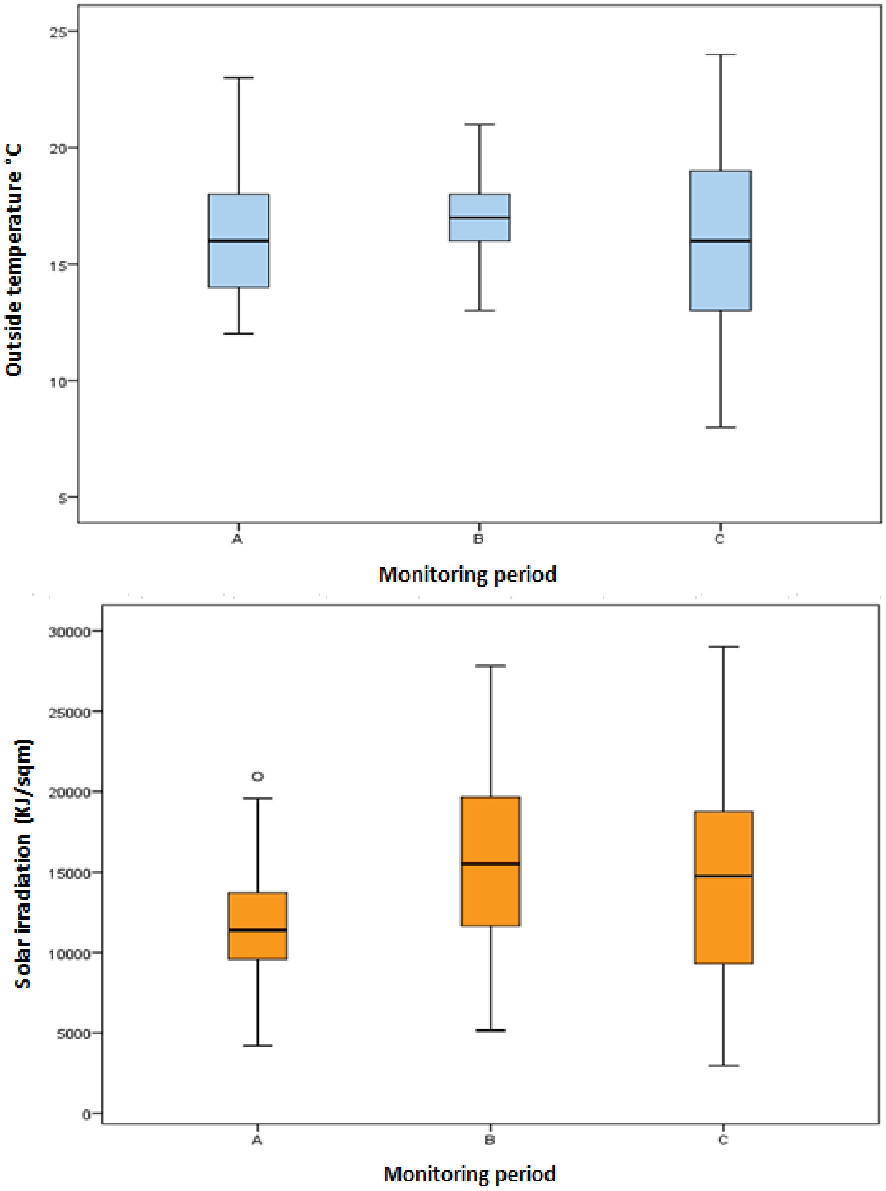
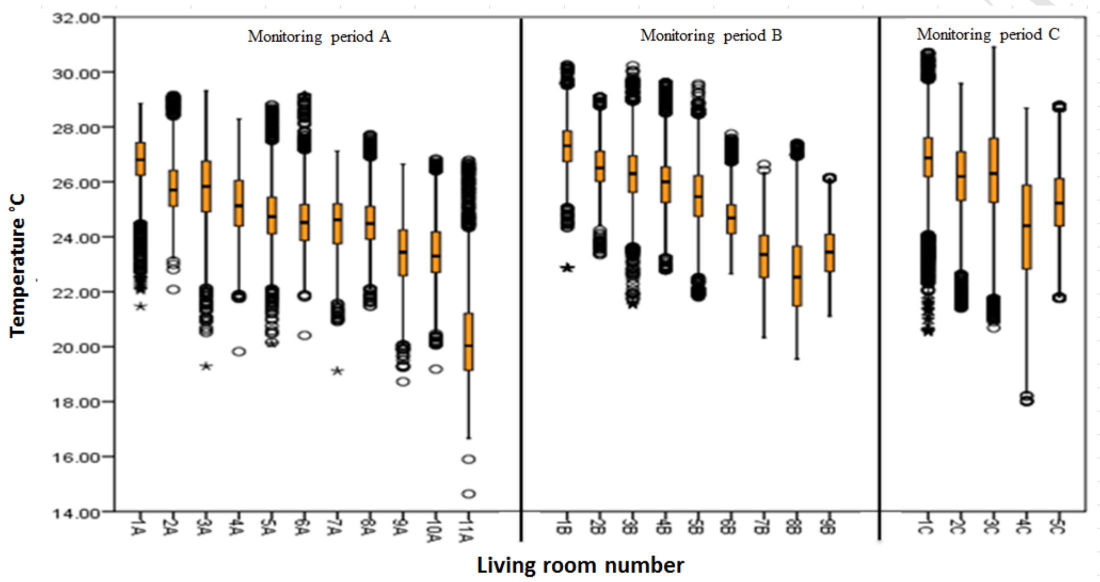


Figure 3: Comparison of the monitoring periods (Outside temperature and Solar irradiation)

As it can be predicted based on the number of monitored days, monitoring period C has the biggest range of outside temperature and solar irradiation. Comparing three monitoring periods, monitoring period B and A have the smallest range of outside temperature and solar irradiation respectively and B has the maximum average outside temperature and solar irradiation.

4. The results

Recorded temperatures during occupied hours in all living rooms are summarised for the all monitoring periods in Figure 4. This shows the range of temperature variations is significant. However judgment about the actual overheating requires in-depth analysis using the selected overheating benchmarks outlined above and which are used for data evaluation in the following sections.



[1] Asterisks and circles in box plot graphs show the out range data

Figure 4: Recorded temperatures during occupied hours in all living rooms during all monitoring periods

4.1 Overheating evaluations based on the Passivhaus benchmark

Passivhaus overheating criteria were used to analyse the data in order to assess the risk of overheating and the thermal comfort in the flats.

As noted above, the criterion states that it is not acceptable for temperature in the living area to exceed 25°C for more than 10% of the total annual occupied hours.

One limitation of the study from which the data were generated is that it was conducted on a limited number of days during three cooling seasons; therefore, it cannot show the actual risk of overheating based on the Passivhaus benchmark.

In order to calculate any rise in the annual elevated temperature above 25°C and indicate whether flats based on the Passivhaus criteria do indeed overheat, two percentages of overheating were calculated. To begin with, the annual overheating percentage was calculated, based on the actual number of hours with elevated temperature during the monitoring period. Second, assuming occupant behaviour to be consistent throughout the year, the likely number of occupied hours that each flat would have had a temperature higher than 25°C in the rest of the cooling season was calculated based on the actual cooling degree hours recorded during the monitored

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[1] Asterisk (*) represents extreme outliers where a data point is more extreme than Q_1-2× Step or Q_3+2×Step.
Where Q_1= first quartile, Q_3= third quartile, IQR (Interquartile range) = Q_3-Q_1 and Step=1.5× IQR
Circle (O) represents mild outliers where a data point is more extreme than Q_1-Step or Q_3+Step, but are not extreme outliers.

and unmonitored periods of each cooling season. These anticipated hours were then used to calculate the annual overheating percentage in the unmonitored period of the cooling season. The sum of these two percentages was then used for comparison with the Passivhaus overheating limit.

Figure 5 represents the result which illustrates the significant risk of overheating in these flats, based on Passivhaus criteria.

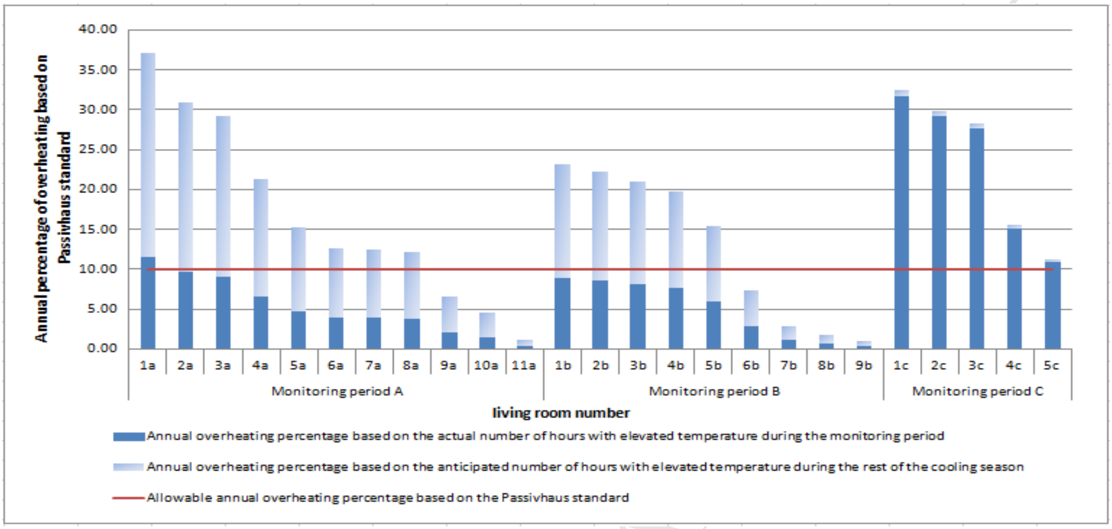

Figure 5: Overheating evaluation for all available living rooms and in all monitoring periods, based on Passivhaus Criteria

4.2 Overheating evaluations based on the adaptive benchmark

In order to assess the occurrence and severity of overheating, the adaptive comfort threshold temperature for each category was calculated, based on the daily outdoor temperature. The daily values of T_{rm} were calculated from the daily mean outdoor temperature (Equation 2) and then T_{max} for Categories I and II were calculated using Equations 3 and 4.

Figure 6 shows the daily mean outdoor temperature (T_{out}) and the values of T_{max} for building Categories I and II during all monitoring periods.

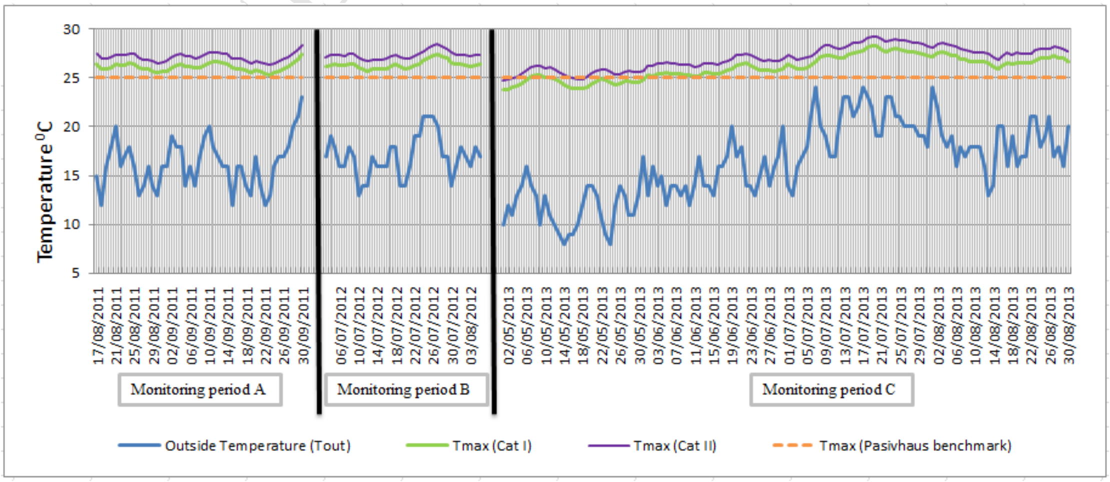

Figure 6: Daily mean outdoor temperature (T_{out}) and maximum adaptive thermal comfort temperature (T_{max}) for building Categories I and II during all monitoring periods

Although the Passivhaus thermal comfort threshold (fixed) and the adaptive thermal comfort benchmark are not directly comparable due to the difference in their overheating evaluation criteria, Figure 6 clearly shows that the adaptive thermal comfort thresholds are significantly related to the outside temperature and vary according to it.

In order to evaluate overheating in the monitored living rooms, all three criteria were investigated separately and then the results were combined to determine the occurrence of overheating in each living room. In addition to Category II (this is the suggested category for new houses and for normal expectations), an analysis was also made of Category I buildings to examine the suitability of these flats for vulnerable occupants.

4.2.1 Criterion 1:

As outlined above, Criterion 1 investigates the frequency of overheating in living spaces. The analysis of results based on this criterion is presented in Figure 7. In 2011, 3 living rooms failed Criterion 1 based on both building categories and 1 living room based on only Category I. In 2012, 5 living rooms out of the 9 did not meet the requirements of this criterion in both categories. In 2013, all living rooms failed Criterion 1 based on building Category I and three of them failed based on building Category II as well.

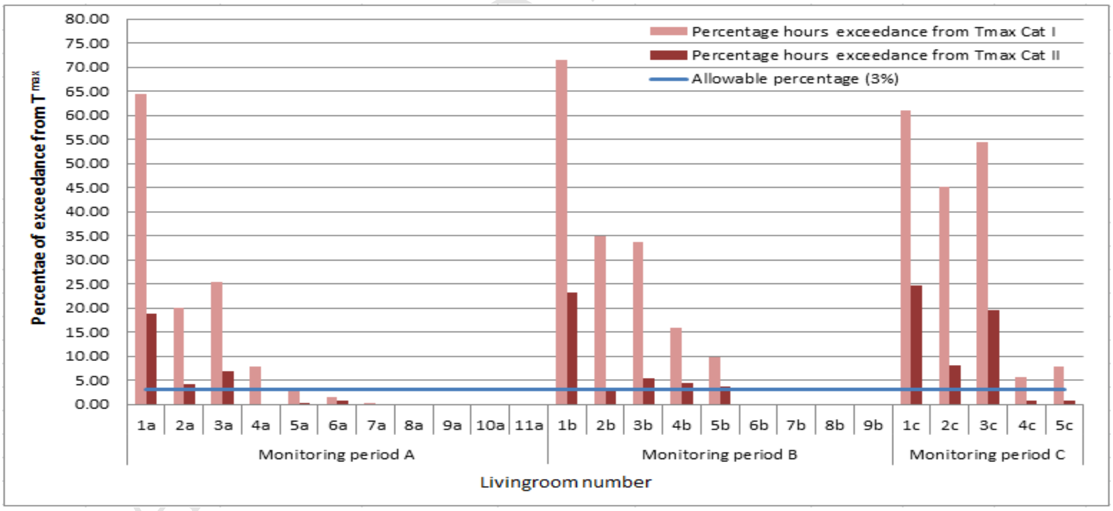

Figure 7: % hours of exceedance from Categories I and II threshold comfort temperature during the monitored occupied hours in all monitoring periods

4.2.2 Criterion 2

Criterion 2 considers the severity of overheating within any one day. During each day of monitoring, the weighted exceedance (W_e) was calculated for all monitored living rooms. Figure 8 reveals the total number of days that W_e was greater than 6 for each living room, on the basis of Categories I and II during all monitoring periods. The results indicate that nearly all the living rooms that failed Criterion 1 had at least one day (amounting to more considerable number of days in some cases) where W_e was higher than 6 and did not meet the requirement of Criterion 2.

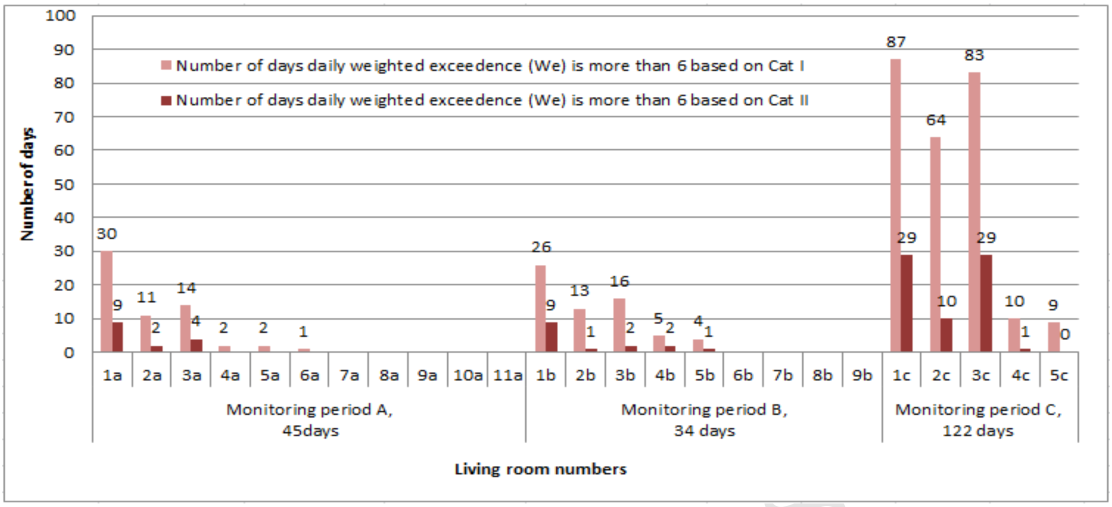

Figure 8: Number of days where the weighted exceedance was more than 6 from Categories I and II threshold comfort temperatures during all monitoring periods

4.2.3 Criterion 3

Criterion 3 establishes a maximum value for an indoor temperature. During all the monitoring periods, the ΔT values were calculated for all living rooms. The results show that in nearly all living rooms, ΔT was less than 4 K, only for three days in 2013, two rooms failed this criterion based on building Category I.

4.2.4 Summary of the results

Table 2 summarises the data analysis based on all three criteria for 2011, 2012 and 2013. According to CIBSE TM 52 [38], the room is classed as overheated when at least two of the three criteria have failed.

Table 2: Summary of the results for both adaptive and fixed benchmarks

Category	Monitoring period	A (17^{th} Aug to 30^{th} Sep 2011)											B (3^{rd} Jul to 5^{th} Aug 2012)									C (1^{st} May to 30^{th} Aug 2013)				
	Living room number	1a	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	1b	2b	3b	4b	5b	6b	7b	8b	9b	F1	F2	F3	F4	F5
I	Meets Criterion 1	x	x	x	x	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	x
	Meets Criterion 2	x	x	x	x	x	x	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	x
	Meets Criterion 3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	x	√	x	√	√
	Overheated (at least two criterion failed)	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
II	Meets Criterion 1	x	x	x	√	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	√	√
	Meets Criterion 2	x	x	x	√	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	√
	Meets Criterion 3	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	Overheated (at least two criterion failed)	Yes	Yes	Yes	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	No	No

5. Discussion

5.1 Indoor temperature variation

The recorded indoor temperatures of all the flats are shown in Figure 4. In order to compare the indoor temperatures experienced in different living rooms, the Passivhaus discomfort temperature threshold is used (without any endorsement or judgment about the suitability of this threshold) to calculate and evaluate the elevated temperatures and their frequencies from this baseline. The percentage of hours in which the temperature exceeded 25^{o}C is shown in Figure 9 for the monitored living rooms for all monitoring periods.

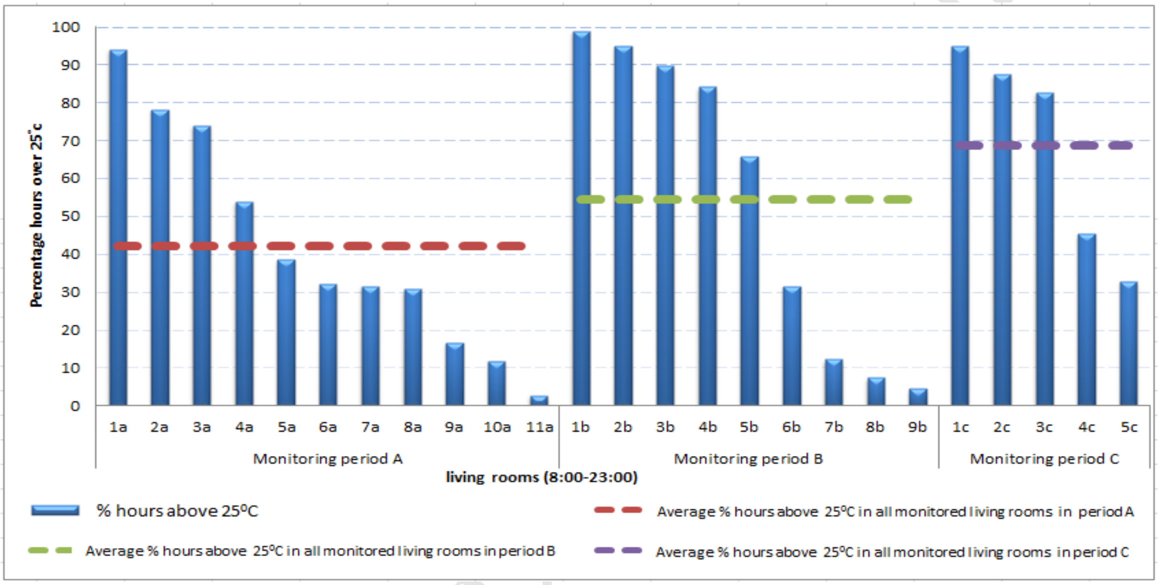

Figure 9: Percentage of occupied hours with measured temperatures over 25°C in all living rooms during all monitoring periods

The results reveal significant variations in the elevated temperature in different living rooms. The percentages vary from approximately 94% to 3% in 2011, from 99% to 5% in 2012 and from 94% to 33% in 2013.

As discussed, different factors (outdoor temperature, solar gain, ventilation, thermal mass and internal gains) have significant effects on the indoor temperature range and overheating of a room.

In general, the results suggest that in the monitoring period of 2013 monitored living rooms experienced more elevated temperatures, since the average percentage of hours above 25^{0}C was 68% in 2013, 54% in 2012 and 42% in 2011. The daily averages of percentage hours with temperatures over 25 ^{o}C in all flats for all monitoring periods are represented in Figure 10.

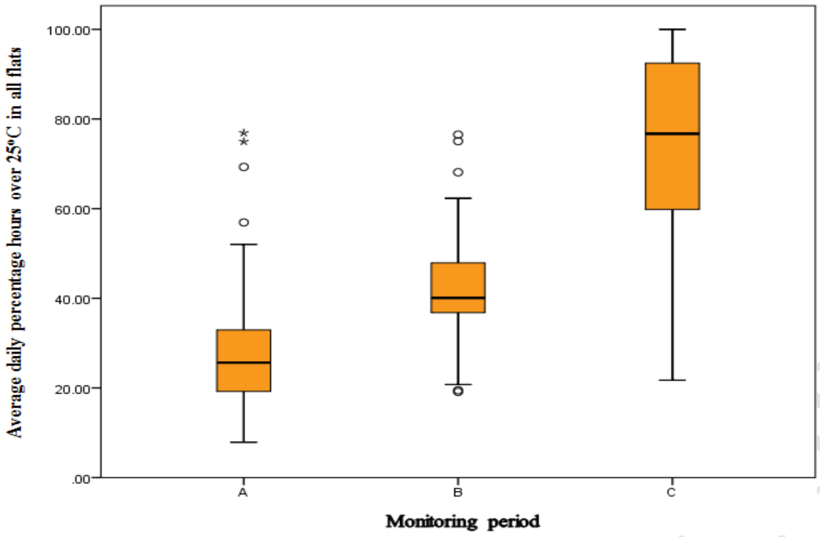

Figure 10: Daily comparison of average daily percentage hours with temperature over 25 °C in all flats during three monitoring periods

A comparison of external environmental factors and average daily percentage hours with temperature above 25°C in all flats (Figures 3 and 10), suggests no direct relationship between such factors and the overheating experienced in different flats. However, in order to understand the significance of the factors that did cause the variation, an in-depth analysis has been carried out. To assess the significance of the effective factors on temperature variations and overheating experienced, separate linear regression analyses were carried out for each flat.

Hourly outside temperature and solar irradiation were identified as the environmental factors that affect indoor temperature and were considered as the two input factors in each regression analysis.
It should be noted that solar gain on each vertical surface is affected by solar irradiance (direct and diffuse data) on the related orientation [43]. Many meteorological stations in the world measure global irradiance on a horizontal surface; however, only limited number of them measure the solar component on vertical surfaces [44]. Available solar data for this study (obtained from UK Metoffice) is also global radiation on horizontal surface. Some methods to predict vertical global solar irradiation based on the horizontal value have been suggested by different researchers; however, most of them are complicated and their applications are debatable [43, 45, 46]. Therefore, as this study is concerned with the relative effect of solar irradiance, data for horizontal surfaces are used and are considered simply as being representative of the potential solar irradiation on vertical surfaces.

Occupant behavior, thermal mass, orientation and size of window aperture are the other factors that affect indoor temperature [34]. Occupant behavior in this study is defined as:

- Amount of natural ventilation and mechanical ventilation through MVHR bypass mode,
- Actual amount of solar gain affected by shading devices used by occupants,
- Actual internal gain.

Since the regression analysis was carried out separately for each flat, factors such as thermal mass, orientation and aperture which remained constant during the monitoring period will not affect the proposed regression model. Hence, the regression model in each flat can directly show the relative significance of the two input factors (environmental conditions) and also indirectly the significance of missing input factor (occupant behavior) (Table 3).

Table 3: Results from the regression analysis in each living room

Monitoring period	Flat Number	Environmental factors impact on inside temperature (R^2 value (%) of the regression model)	Occupants' behaviour impact on inside temperature ($100 - R^2$)
A	1a	5.0	95.0
	2a	33.7	66.3
	3a	15.6	84.4
	4a	21.5	78.5
	5a	21.2	78.8
	6a	22.3	77.7
	7a	14.6	85.4
	8a	28.9	71.1
	9a	10.8	89.2
	10a	42.4	57.6
	11a	62.8	37.2
	Average	25.3	74.7
B	1b	13.3	86.7
	2b	39.2	60.8
	3b	32.1	67.9
	4b	26.2	73.8
	5b	39.3	60.7
	6b	33.9	66.1
	7b	38.7	61.3
	8b	51.6	48.4
	9b	23.3	76.7
	Average	33.1	66.9
C	1c	30.8	69.2
	2c	45.0	55.0
	3c	60.8	39.2
	4c	55.6	44.4
	5c	32.8	67.2
	Average	48.1	52.0
Average		32.1	67.9

Table 3 shows the impact of environmental factors (R^2) and also the significance of occupant behavior ($100- R^2$).

Although the result shows a range of R^2 values in different flats from 5% to 62.8%, in a majority of cases, the R^2 is less than 50% and in terms of the average of all monitoring periods, this value is 32.1%. This indicates that in most cases, less than 50% of the indoor temperature variations are explained by environmental factors (parameter in model) which means the impact of occupants behavior as defined (missing factors in the model) on indoor temperature variations is greater.

The results from this investigation therefore show that occupant behavior has a significant impact on temperature variation and overheating. Also, comparison of the results in three monitoring periods (Table 3 and Figure 10) shows that where the average daily percentage hours with elevated temperature is lower, the average impact of occupants behavior on temperature variation is higher, which suggests that occupants have a considerable role in controlling overheating. Consequently, it is likely that occupant behavior can increase the risk of overheating even in cases where the environmental factors are not very severe, it also suggests that even in cases when the environmental factors are severe, effective occupant behavior can have a significant impact on reducing overheating risks in these flats. Therefore, it is essential for the occupants to know how to run their homes and control overheating in thermally efficient buildings such as Passivhaus. This highlights the importance of educating occupants about ways they can reduce the risk of overheating.

5.2 Overheating assessment

5.2.1 Passivhaus benchmark

The results from the overheating evaluation show that in 2011, and for only 45 monitored days, two flats reached the overheating limits of the Passivhaus standard (10% of annual occupied hours) and two flats overheated more than 5% of occupied hours over the whole-year. In general, taking account of the anticipated overheating hours for the rest of the cooling season, 8 out of 11 monitored flats overheated on the basis of the Passivhaus benchmark, which represents more than 72% of the case studies.

In 2012, during the 34 days of monitoring, overheating in three flats was more than 8% of the annual occupied hours and about 6% in two flats. After considering the anticipated overheating hours for the rest of the cooling season, 5 out of the 9 monitored flats overheated according to the Passivhaus benchmark, which represents more than 55% of all the case studies.

In 2013, flats were monitored during most of the cooling season and all of them exceeded the annual Passivhaus overheating limit. Some of the flats experienced overheating based on Passivhaus standard during most of the occupied hours monitored.

The average annual percentage of elevated temperatures in all monitored flats was 16.6%, 12.6% and 22.9% in 2011, 2012 and 2013 respectively and 72% of these flats (18 out of a total of 25 flats in 3 monitoring years) failed to meet their design criteria in terms of overheating. Therefore, according to the Passivhaus criteria, most of these flats face significant risks of overheating.

5.2.2 Adaptive benchmark

As discussed in section 2.4, there is a consensus that the statistical benchmarks which define overheating, such as the Passivhaus benchmark, are increasingly restrictive. In contrast, adaptive thermal comfort benchmarks can provide better understanding and prediction of overheating. However, the results from this study indicate that the criteria for defining overheating based on adaptive thermal comfort benchmark as defined in CIBSE TM52 [38] can help identify overheated spaces in different categories, but they are relatively weak and limited in terms of determining the frequency, intensity and severity of overheating between categories I and II.

The results from this study indicate that nearly all the living rooms that overheated based on Category I evaluation were also deemed highly likely to overheat when evaluated based on Category II. However, on the basis of a detailed analysis of Criteria 1 and 2, it should be noted that the intensity and severity of overheating based on Category I were significantly higher than those based on Category II. In order to explore this in more detail and assess the significance of overheating in each category, a statistical analysis was conducted for both categories as summarised in Table 3. In this analysis, the daily average percentage hours exceedance from T_{max} (Criterion 1) and also the daily average weighted exceedance (W_e) (Criterion 2) for both categories, across all flats, are compared for all monitoring periods. This analysis indicates that on average, occurrence of overheating in terms of Category I is approximately 8.31, 14.01 and 26.27 percent higher than this occurrence in terms of Category II in the monitoring periods of A, B, and C and in each of these cases there are lower and upper limits based on 95% confidence interval as shown in Table 4. The statistical analysis shows that the results of each criteria based on each category are significantly different (Sig <0.05). Similarly, on average the daily average weighed exceedance was about 1.7, 2.81 and 5.85 percent higher in Category I than the occurrence based on Category II in the monitoring periods A, B, and C. Hence, both the frequency (comparison of Criterion 1) and the severity (comparison of Criterion 2) of overheating in terms of Category I are significantly higher than Category II.

Table 4: statistical analysis of Criteria 1and 2 in the two monitoring periods

Criterion	Comparing pair	Monitoring period	Paired Differences				Sig. (2-tailed)
			Mean	Std. Deviation	95% Confidence Interval of the Difference		
					Lower	Upper	
1	-Daily average percentage hours exceedance from Tmax Cat I in all living rooms during monitoring period -Daily average percentage hours exceedance from Tmax Cat II in all living rooms during monitoring period	A (2011)	8.31	4.90	6.84	9.78	0.000
		B (2012)	14.01	7.61	11.35	16.67	0.000
		C (2013)	26.27	14.80	23.61	28.92	0.000
2	-Daily average weighted exceedence (We) from Tmax Cat I in all living rooms during monitoring period -Daily average daily weighted exceedence (We) from Tmax Cat II in all living rooms during monitoring period	A (2011)	1.70	1.03	1.39	2.01	0.000
		B (2012)	2.81	1.73	2.21	3.42	0.000
		C (2013)	5.85	2.87	5.34	6.37	0.000

Apart from this general comparison, and in order to demonstrate these differences in all overheated living rooms, the same statistical analysis was undertaken for each overheated individual living room separately. A summary of the results can be found in Tables 5 and 6.

Table 5: Statistical analysis of Criterion 1 for all overheated living rooms

Comparing pair	Monitoring period	Living room number	Paired Differences				Sig. (2-tailed)
			Mean	Std. Deviation	95% Confidence Interval of the Difference		
					Lower	Upper	
- Daily percentage hours exceedance from T_{max} Cat I during monitoring period - Daily percentage hours exceedance from T_{max} Cat II during monitoring period	A	1A	45.25	33.65	35.14	55.36	0.000
		2A	15.77	21.96	9.18	22.37	0.000
		3A	18.40	26.78	10.35	26.44	0.000
		4A	7.83	13.80	3.69	11.98	0.000
	B	1B	48.36	33.83	36.56	60.16	0.000
		2B	31.82	28.33	21.94	41.71	0.000
		3B	28.35	32.10	17.15	39.55	0.000
		4B	11.52	20.77	4.28	18.77	0.003
		5B	6.03	12.11	1.80	10.25	0.007
	C	1c	36.35	32.36	30.55	42.15	0.000
		2c	37.09	34.21	30.95	43.22	0.000
		3c	35.02	24.83	30.57	39.47	0.000
		4c	4.82	15.66	2.02	7.63	0.001
		5c	5.47	14.27	2.35	8.59	0.001

Table 6: Statistical analysis of Criterion 2 for all overheated living rooms

Comparing pair	Monitoring period	Living room number	Paired Differences				Sig. (2-tailed)
			Mean	Std. Deviation	95% Confidence Interval of the Difference		
					Lower	Upper	
- Daily weighted exceedence (We) from T_{max} Cat I during monitoring period - Daily weighted exceedence (We) from T_{max} Cat II during monitoring period	A	1A	9.83	6.67	7.82	11.83	0.000
		2A	3.06	4.32	1.76	4.36	0.000
		3A	3.87	5.57	2.19	5.54	0.000
		4A	1.19	2.10	0.56	1.83	0.000
	B	1B	10.92	5.74	8.91	12.92	0.000
		2B	5.32	4.75	3.66	6.97	0.000
		3B	5.15	5.66	3.17	7.12	0.000
		4B	2.43	4.43	0.88	3.97	0.003
		5B	1.50	3.50	0.28	2.72	0.018
	C	1c	9.33	5.78	8.29	10.36	0.000
		2c	6.90	6.17	5.79	8.00	0.000
		3c	8.31	4.96	7.42	9.20	0.000
		4c	0.87	2.81	0.37	1.37	0.001
		5c	0.94	2.48	0.40	1.48	0.001

These separate analyses also reinforce the results from general analysis of the average values. The statistical analysis shows that the results of each criteria based on each category for all overheated living rooms are significantly different (Sig <0.05). The range of the difference for daily percentage hours is from approximately 5 to 45 percentage (mean values) and this range for daily exceedance is about 1 to nearly 11 degree hours (mean values) in different flats.

5.2.3 Suggestions for revising Criterion 2 and comparison of the benchmarks

It is noted above that Criterion 2 used in the adaptive benchmark sets a daily limit for the severity of overheating (weighted exceedance). As discussed in section 2.4, to meet the criterion, this daily limit, which is expressed as weighted exceedance (W_e), must be less than or equal to 6 in any given day. The number 6 is based on the assumption that similar occupancy patterns exist in all the spaces being investigated for overheating. In fact, this number in CIBSE TM52 [38] is considered with the assumption of having a room with 8 hours of occupancy. Obviously, in a room with higher hours of occupancy, this number can increase and a higher W_e can be acceptable. In order to investigate the effect of a higher acceptable W_e in overheating evaluation, Criterion 2 was tested over the W_e of 11 degree hours. The number 11 is based on adjusting W_e proportionally in line with the difference between the actual occupied hours of 15 and the standard, assumed, occupied hours of 8.

All the living rooms that failed against Criterion 2 were tested again using the new weighted exceedance of 11. The results of the initial and revised investigation of Criterion II are presented in Table 7. The results of the new overheating evaluation for all living rooms are also presented in this table.

The results show that according to this modified limit, in the monitoring period A, one flat based on Category I and one based on Category II are not classified as overheated. The difference in monitoring period B is more considerable: four flats based on Category II are no longer classified as overheating. It can be seen that in in monitoring period C one flat based on Category I is not classified as overheating according to the modified criterion. This clearly shows the importance of selecting an accurate weighted exceedance limit for the assessment of overheating. This study suggests that this number should be in accordance with the actual occupied hours rather than a fixed number.

In all monitoring periods, 18 out of out of 25 living rooms, were classified as overheated based on the Passivhaus benchmark. Interestingly, most of these living rooms are classified as overheated when assessed according to the adaptive benchmark of Category I. However, when assessed according to Category II criteria, significantly fewer of these spaces are identified as overheated.

Therefore, although considerable numbers of these flats failed against the Passivhaus criteria of overheating, when the adaptive thermal comfort model is applied, this risk is quite different and is based on occupant type. The results from this study show that the risk of overheating for vulnerable occupants (Category I) is considerable, while this risk is not as significant for occupants with normal expectations (Category II).

As previously explained in detail in section 2.1, the social housing sector has the most vulnerable occupants (both in terms of affordability and age profile) in the UK. Hence, the results from this study show a significant risk of overheating in Passivhaus social housing flats built in the UK under current climate condition.

In order to have a clear picture of the summer performance of social housing flats built to the Passivhaus standard, not only the current performance but also the future performance of these dwellings in an uncertain future climate should be investigated and assessed. Also, determining the flats with higher risk of overheating (related to orientation and position of the flat within a block, etc) will help social housing developers to house their tenants appropriately and prioritize accommodation of vulnerable occupants in dwellings less susceptible to overheating. This strategy can avoid or reduce the risk of overheating occurrences based on type of occupant.

Therefore, determining the flats with higher risk of overheating and assessing the summer performance of these dwellings under future climate condition are the future focuses of this study.

Table 7: Summary of all overheating assessment

Category	Monitoring period	A (17th Aug to 30th Sep 2011)											B (3rd Jul to 5th Aug 2012)									C (1st May to 30th Aug 2013)				
	Living room number	1a	2a	3a	4a	5a	6a	7a	8a	9a	10a	11a	1b	2b	3b	4b	5b	6b	7b	8b	9b	1c	2c	3c	4c	5c
Cat I	Criterion 1 (Percentage hours of exceedance)	64.44	25.36	20.07	7.83	2.95	1.49	0.22	0.00	0.00	0.00	0.00	71.60	34.86	33.75	15.91	9.84	0.00	0.00	0.00	0.00	61.15	45.23	54.49	5.70	7.77
	Meet the Criterion	x	x	x	x	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	x
	Criterion 2 (Number of days with daily weighted exceedance of more than 6)	30	14	11	2	2	1	0	0	0	0	0	26	13	16	5	4	0	0	0	0	87	64	83	10	9
	Meet the Criterion	x	x	x	x	x	x	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	x
	Revised Criterion 2 (Number of days with daily weighted exceedance of more than 11)	26	4	7	0	0	1	0	0	0	0	0	24	7	8	5	2	0	0	0	0	66	44	61	4	0
	Meet the Criterion	x	x	x	√	√	x	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	√
	Criterion 3 (Number of days with ΔT more than 4k)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0
	Meet the Criterion	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	x	√	x	√	√
	Overheated	Yes	Yes	Yes	Yes	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
	Overheated (Revised Criterion 2)	Yes	Yes	Yes	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No
Cat II	Criterion 1 (Percentage hours of exceedance)	18.83	6.96	4.30	0.77	0.11	0.00	0.00	0.00	0.00	0.00	0.00	23.24	5.40	4.39	3.81	3.04	0.00	0.00	0.00	0.00	24.81	8.14	19.47	0.87	0.89
	Meet the Criterion	x	x	x	√	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	√	√
	Criterion 2 (Number of days with daily weighted exceedance of more than 6)	9	2	4	0	0	0	0	0	0	0	0	9	1	2	2	1	0	0	0	0	29	10	29	1	0
	Meet the Criterion	x	x	x	√	√	√	√	√	√	√	√	x	x	x	x	x	√	√	√	√	x	x	x	x	√
	Revised Criterion 2 (Number of days with daily weighted exceedance of more than 11)	3	0	2	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	24	4	11	0	0
	Meet the Criterion	x	x	√	√	√	√	√	√	√	√	√	x	√	√	√	√	√	√	√	√	x	x	x	√	√
	Criterion 3 (Number of days with ΔT more than 4k)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Meet the Criterion	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
	Overheated	Yes	Yes	Yes	No	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	No	No
	Overheated (Revised Criterion 2)	Yes	No	Yes	No	No	No	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No	Yes	Yes	Yes	No	No
PH benchmark	Overheated based on PH ceriteria?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes

6. Conclusion

Considering global environmental and energy concerns and the UK movement towards more energy efficient homes, the housing industry and social housing developers in particular are under pressure to deliver energy efficient dwellings. In the social housing sector which has a high percentage of vulnerable occupants, the increase in the cost of new housing delivery as a result of new regulations and the increasing demand for new dwellings due to population increase, will make it more challenging for this sector to meet this new regulations.

New standards, design and construction methods are undeniably needed to comply with new regulations. One of these is the German Passivhaus standard. Evidence suggests that new energy efficient dwellings are at risk of overheating in the UK and the north of Europe. Considering the limited monitored data for the actual performance of Passivhaus dwellings in the UK, the ability of this standard to provide suitable thermal comfort conditions during cooling seasons is one of the main concerns. This risk is exacerbated in dense social housing flats built to Passivhaus standard.

In order to evaluate overheating in Passivhaus, it is essential to have a clear appreciation of the occupants' thermal comfort requirements and apply an appropriate benchmark to assess the risk of overheating.

The results of the analysis of in-use data for flats built to Passivhaus in the UK highlight a considerable risk of overheating based on the Passivhaus benchmark, where 72 percent of all monitored flats failed their designed criteria.

The result of a regression analysis indicates that user behavior is the most significant factor in increasing or decreasing the risk of overheating. This emphasizes the importance of occupant's awareness of the implication of their actions in the thermal performance of their homes and also developing targeted education packages.

Statistical benchmarks to define overheating such as the Passivhaus benchmark have been criticized with greater emphasis now being placed on the adaptive thermal comfort model. An initial assessment of the results of the overheating analysis using the adaptive thermal comfort model does not show significant difference from the Passivhaus benchmark in the number of overheated rooms, when the associated threshold for vulnerable and normal occupants was applied. However detailed analyses of all criteria and the statistical analysis of the differences show significant differences in terms of both the occurrence and severity of uncomfortable indoor temperatures experienced for these two types of occupant.

Modifying the intensity of daily uncomfortable indoor temperatures, known as weighed exceedance (W_e), the actual occupied hours results in a considerable difference in the number of overheated rooms based on occupant type, showing about 50% of the livings rooms overheated for vulnerable occupants while about 25% overheated for normal occupants. The use of the new assessment reveals significant differences between the risk of overheating for vulnerable and normal occupants.

Occupants' vulnerabilities in social housing dwellings due to both financial capacity and age of occupants demonstrate the significance of this risk.

This study highlights the risk of overheating in social housing flats built to Passivhaus standards under current climatic conditions. Identifying flats with higher risk of overheating both now and under uncertain future climate will also help the social housing developers to house their tenants appropriately and reduce or avoid the risk of overheating based on the occupant type.

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- Overheating risk is more related to occupant behavior in Passivhaus (PH) flats
- There is a significant risk of summer overheating based on PH benchmark
- Adaptive model is better in representing the overheating risk in PH flats
- Based on above model risk of overheating is higher for vulnerable occupants