The impact of regulations on overheating risk in dwellings

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Abstract

Many new and emerging regulations and standards for buildings focus on climate change mitigation through energy and carbon reduction. In cool climates, such reductions are achieved by optimising the building for heat retention. It is increasingly recognised however that some degree of climate change is now inevitable and new and existing buildings need to consider this to ensure resilience and an ability to adapt over time. In this context the current approach to regulation which largely remains focused on the 'point of handover' may not be fit for purpose.

This paper focuses on a 'typical' dwelling designed to a range of standards, representing current or emerging approaches to minimising energy use, using a range of construction methods, where a number of adaptations are available to occupants. It considers, through the use of building performance simulation, how each configuration is likely to perform thermally over time given current climate change predictions.

The paper demonstrates that the current approach to assessing overheating risk in dwellings, coupled with the regulatory focus on reducing energy consumption, could result in significant levels of overheating. This overheating could, in the near future, present a risk to health and result in the need for significant interventions.

Keywords: Adaptation, Building Regulations, Building Simulation, Climate Change, Dwellings, Overheating

Introduction

The Committee on Climate Change (2014) noted that one fifth of homes in England could already experience overheating (in a mild summer) and that this percentage is likely to increase in a warming climate and therefore called for new building standards to be developed to address the overheating risk in dwellings. Parry, Canziani, Palutikof, van der Linden and Hanson (2007) reported that the 2003 heat wave in Europe accounted for in the region of 35,000 excess deaths. This increased mortality was related to high internal temperatures over an extended time period (Wright, A., Young, A. & Natarajan, S., 2005) and affected the most vulnerable in society, such as the elderly, infants and those with underlying health problems (Johnson et al., 2005). If such events are to become more common (which is predicted, with a similar event affecting southern Europe in 2007), this could have significant consequences for health, housing design (Wright, Young & Natarajan 2005) and arguably the regulatory framework in the built environment.

The building regulations primary focus is one of health, safety and wellbeing. The growing realisation though, that CO_2 emissions associated with the built environment can have a significant negative impact on the environment and contribute to climate change (in 2009 buildings were responsible for 43% of all CO_2 emissions in the UK (Department for Communities and Local Government [DCLG], 2015)), has resulted in the requirements of national and regional legislation (such as the UK Climate Change Act and The European Energy Performance of Buildings Directive) being interpreted through building regulations. In recent years building regulations in the UK (UK Part L revisions 2010 and 2013) (see **Figure 1**), EU (European Energy Efficiency Directive) and indeed globally (Dubai Green Building Regulations and Specifications, Green Building Code of Peoples Republic of China) have increasingly sought to set more stringent energy performance targets. In cool or temperate climates such as mid-latitude and northern Europe, characterised by extended winter heating seasons, these regulations aim to mitigate the worst effects of climate change by reducing CO_2 emissions and

optimising buildings for heat retention. However, as noted by McLeod, Hopfe and Kwan (2013) it is being increasingly recognised that higher global emissions scenarios are becoming more likely, increasing the risk of greater levels of warming. As a result, it has been suggested that dwellings in cool climates may in the future suffer from overheating and indeed there is evidence that this may already be happening (Dengel & Swainson, 2012). De Wilde and Coley, (2012) in a review of the implications of climate change for buildings, point out that the rationale and requirements of the building regulations in relation to overheating are largely based on historic data and may not therefore enable a realistic assessment of the potential future overheating risk.

Taking this into consideration this paper explores the idea that the current focus of increased levels of insulation and other heat loss reduction measures for new or recently constructed dwellings may, at least during warm periods, be counterproductive. As noted by Eames, Kershaw and Coley (2011) overheating could have severe health implications and as such could result in uninhabitable buildings that are technically obsolete due to the 'locked-in' (de Wilde & Tian, 2011) impacts of climate change. The paper, supported by detailed probabilistic predictions, demonstrates the level of overheating that could be experienced depending on the standard or regulation the dwelling is constructed to and suggests how an alternative, more robust approach, to overheating risk assessment could be developed.

Figure 1 Timeline of energy related regulations and emerging standards (UK) including energy reduction targets

Background

Evidence of Overheating

Until recently the general assumption in relation to domestic overheating has been that older dwellings were more vulnerable, with increased levels of insulation protecting new dwellings from such issues (Dengel & Swainson 2012). However, there is now increasing evidence that new and low energy dwellings may suffer significant problems in the future and indeed that many such dwellings may already experience high levels of overheating (Dengel & Swainson 2012, Mavrogianni, Taylor, Davies, Thoua & Kolm-Murray 2015, Peacock, Jenkins & Kane 2010, Rodrigues, Gillott & Teltow, 2013). It has been suggested that light weight, air tight dwellings with little access to cross ventilation (such as single aspect flats) may be at a particularly high level of risk of overheating (Dengel & Swainson 2012).

What is clear is that overheating presents a significant risk to dwellings and occupant health and that this could impact a wide range of buildings and building types. Using probabilistic assessment, Jenkins et al. (2014) found that by the 2030s up to 76% of flats and 29% of detached dwellings could be at risk of overheating. Furthermore, Rodrigues et al. (2013) in a study considering the performance of a low-energy steel frame house design under current and future weather scenarios found that the building could be uncomfortably warm for 30% of the year.

As noted by de Wilde and Coley (2012), there appears to be at least some debate in relation to highly insulated buildings with Crawley (2008) noting greater resilience and Wang, Chen and Ren (2010) noting less resilience to the impacts of climate change. Gupta and Gregg (2012) cite the Passiv-on project which found that the high levels of insulation is Passive House buildings in southern Europe worked to keep the building cool during warm weather. However, McLeod et al. (2013) cites a number of studies (Larsen & Jensen 2011, Mlecnik et al. 2012, Schnieders 2005) in relation to Passive House dwellings in several European locations where it is noted that there may be a risk of overheating in the current climate unless a number of alterations including active cooling

were implemented. McLeod et al. (2013) does however point out that Passive House dwellings may offer marginally more protection from overheating than other highly insulated options (Findings for the 2050s heavy weight passive house greater than 25°C for 6.6% of the year whereas a heavy weight 'well insulated' building greater than 25°C for 8.2% of the year). The core reasons for these differences are unclear, although Gupta and Gregg (2012) when considering a range of 'typical' dwelling types in Oxford found insulation position to be of importance. As such insulation may be a 'double edged sword' (Hacker, Holmes, Belcher & Davies 2005) with increased insulation reducing winter heat loss but increasing overheating risk especially in air tight buildings where it is difficult to dissipate internally generated gains. This is further supported by Orme and Palmer (as cited in Dengel & Swainson, 2012) who noted that increasing the level of insulation in dwellings resulted in higher levels of overheating.

Peacock et al. (2010) note the potential for increased internal gains through the proliferation of electronic devices in the home which could lead to higher internal temperatures. They go on to note that despite this climatic effects are still likely to be more influential than internal gains and for the UK such internal gains are likely to remain useful throughout the heating season. Building on this, it can be argued that measures designed to mitigate future climate change must also take account of the impact these measures may have on overheating risk, the research presented in this paper attempts to take this into consideration. There is evidence that behavioural and technical adaptations may at least in some part be able to address overheating risk (Coley, Kershaw & Eames, 2012) however, as noted by Hills (2012) for low-income households any requirement for technical intervention through artificial cooling may result in summer fuel poverty. This is particularly important for countries like the UK as installed cooling capacity remains low (Hulme, Beaumont & Summers, 2011).

Overheating Adaptation

A number of authors have explored potential solutions to overheating in domestic buildings (for example see Gupta & Gregg, 2012, Porritt, Cropper, Shao & Goodier, 2012, van Hoff, Blocken, Henson & Timmermans, 2015). These studies found that adaptation measures such as shutters and fixed shading, reductions in solar/fabric gains, increased surface albedo and the use of thermal mass may help reduce future overheating, although the magnitude of the influence of thermal mass has been questioned (Kendrick, Odgen, Wang & Baiche 2012). Gupta and Gregg (2012) found that user controlled shading, surface albedo and thermal mass, could help reduce overheating risk although it was also found that no 'passive' measures alone could completely remove the risk and that behavioural and active measures may also be needed. Jones, Mulville and Brooks (2013) set out an approach to adaptation planning related to the potential impact of climate change where the lifecycle of the building is taken into consideration. It suggests that where risks are identified at the design stage an adaptation plan can be developed and where such adaptations in the future may otherwise prove prohibitively expensive, preparatory or enabling works can be carried out during the construction phase to enable the future adaptation. As noted by Gupta and Gregg (2012) mitigation measures to reduce the contribution of the built environment to climate change, and adaptation measures, to allow the building to adapt to climate change that does occur, should not negatively impact on the performance of the building. Combining the adaptation planning approach suggested by Jones et al. (2013) with the measures that have been shown to reduce overheating risk may have the potential to ensure the buildings can perform over time. In such a scenario adaptation measures are enabled at the design stage but only implemented when needed, therefore not having a negative impact on current performance (such as increasing winter heat load due to increased solar shading).

Literature Review

The Regulatory Framework

In the UK, building regulations do not stipulate a single maximum temperature in the workplace or in the home. For domestic buildings, checks are required at the design stage, comparing mean summer internal temperature to a threshold temperature (using the Standard Assessment Procedure (SAP)) to assess the risk of overheating (Zero Carbon Hub, 2015). Further guidance, which does refer to specific temperature is provided by the Chartered Institution of Building Services Engineers (CIBSE, 2015), but this is beyond the requirements of the regulations. The UK Workplace (Health, Safety and Welfare) regulations (Health and Safety Executive, 2013) specify minimum but not maximum temperatures in the workplace, the same standards do not exist for private residential buildings but minimum and maximum temperatures may apply to other residential type buildings (see for example Northern Irelands Residential Care Homes, minimum standards (Department of Health, Social Services and Public Safety, 2011)).

By way of comparison, for new dwellings, the Danish Code for Indoor Thermal Climate (DS 474), sets a maximum of 100 hours not in excess of 26°C and not more than 25 hours above 27°C calculated using a simple software tool (BE10) (Kunkel, Kontonasiou, Arcipowska, Mariottini & Atanasiu, 2015) similar to the UK SAP. The Swedish Building Code sets minimum room temperatures and maximum surface temperatures, but not maximum room air temperatures (Krunkel et al., 2015). The Republic of Ireland follows a similar approach to that of the UK with the Dwelling Energy Assessment Procedure (DEAP) used to carry out an overheating risk assessment (Sustainable Energy Authority of Ireland, 2013), although this assessment is optional and not mandated by regulation. The Norwegian building regulations have implemented requirements for the consideration of solar gains in non-domestic buildings, but not domestic buildings (Schild, 2009). As can be seen from the above comparisons, set maximum summer temperatures for dwellings in cool climates are still uncommon.

Where such standards do exist the assessment method used tends to be simplistic in nature and as will be discussed below, may not be fit for purpose.

Metrics

There remains considerable discussion in regard to the most appropriate metrics for defining overheating (de Dear, Kim, Candido & Deuble 2015, de Wilde & Tian 2011, Hacker et al., 2005, Nicol & Spires, 2013) with the merits of single temperature exceedance or traditional approach versus adaptive comfort standards (Nicol & Spires, 2013), considerations of potential health and mortality impacts (Dengel & Swainson 2012, Jenkins et al. 2014) along with considerations of the relevant importance of night time temperatures (Dengel & Swainson 2010, Peacock et al., 2010), forming the main points of discussion.

The main criticism of the single temperature exceedance method (which set an allowable exceedance of 1% of occupied hours above a given temperature) is that there is evidence of a correlation between acceptable internal temperatures and the external temperature (Nicol & Humphreys, 2010) and as such the comfort range is in reality a moving target that a single temperature criterion cannot take account of. Furthermore, a single temperature criterion does not give an indication of the severity of overheating experienced while the adaptive comfort approach considers both severity and length of exposure (Nicol & Spires, 2013). Length of exposure is of particular importance in relation to potential health impacts with, as previously noted, many of the premature deaths associated with the 2003 European heat wave being related to the extended period of high temperatures (Wright et al., 2005). The adaptive thermal comfort approach as detailed by Nicol and Humphreys (2010) is built on field studies that note the ability of occupants to adapt to climatic changes, whereas the temperature exceedance approach, it could be argued assumes a more passive approach taken by occupants. However, as noted by Beizaee, Lomas and Firth (2013), EN15251 which forms the basis of the adaptive comfort approach for 'free running' buildings was developed primarily for commercial buildings and the adaptations available for

occupants of dwellings are significantly different to those of an office. Furthermore, Mavrogianni et al. (2015) question how under such conditions vulnerable and potentially immobile people may be able to adapt. It has been noted (Roaf, Brotas & Nicol, 2015) that the single temperature exceedance method (in comparisons to the adaptive comfort method) would appear to overestimate the overheating risk and that in reality the risk may be lower than many studies in this field have predicted. With the potential health risks associated with overheating such assertions need to be approached with caution and as suggested by Mavrogianni et al. (2015) it may be wise to combine the adaptive comfort approach with a static overheating criterion.

What is clear from the literature is that high temperatures in bedrooms overnight are a significant risk (Naughton et al. 2002 as cited in Peacock et al., 2010) and that temperatures above 24°C may begin to impair sleep and have other associated health impacts (Dengel & Swainson 2012). With the lack of a clear definition of overheating in dwellings, studies in this area are as a result subject to a degree of uncertainty (Dengel & Swainson 2012).

Overheating Assessment Methods

In addition to a lack of clarity regarding the appropriate metrics used to define overheating there is evidence that the current methods of assessing overheating risk in dwellings may not be reliable (Jenkins, Ingram, Simpson & Patidar, 2013). It has been noted that much of the data used to analyse current overheating risk comes from the past (de Wilde & Coley, 2012) and therefore does not make allowance for the potential impacts of a changing climate. The overheating prediction method currently used in the Standard Assessment Procedure (SAP) (Department of Energy and Climate Change [DECC], 2014) assigns a level of risk to potential overheating, where higher levels of overheating are detected the assessor has the option to use window opening to alleviate these problems (window opening may help to reduce overheating by increasing the ventilation rate, which will reduce the ambient room temperature where outside air is cooler and can also help aid personal

cooling through the evaporation of moisture form the skin). Although this may be suitable in rural areas, in areas subject to high levels of pollution and noise (Mavrogianni et al. 2015) this may be unrealistic and in both cases (urban and rural) such an approach may present a security risk (Mavrogianni, Wilkinson, Davies, Biddulph & Oikonomou 2012). This is supported by the findings of Skinner and Grimwood (2005) who note that 54% of dwellings in the UK during the day-time and 67% during night-time are exposed to noise levels in excess of World Health Organisation (WHO) guidelines. In addition there are strong safety related arguments for the inclusion of restrictors on upper floor windows (McLeod et al. 2013) which reduce the potential for increased ventilation. As such, the reliance on window opening may be over optimistic and furthermore as suggested by several authors (for example see Peacock et al. 2010 and Roaf et al. 2015) there may, in the future, be an upper limit to the effectiveness of window opening in reducing overheating.

The Passive House Standard, as developed by the *'Passivhaus Institut'* (Cotterell & Dabeby, 2012) (http://www.passiv.de), uses a separate method of overheating risk assessment administered through the Passive House Planning Pack (PHPP). Although, like the other standards discussed here, the data contained in PHPP is from the past, the exceedance limitation of 25°C for a maximum of 10% of the year (Feist, W. 2013) assessed through PHPP, would appear to be more robust than the SAP assessment method (below 23.5°C) as it is not based on a reliance on window opening.

Building Performance Simulation

In most cases of overheating risk assessment at the design stage, there is some form of building performance prediction, usually through building performance simulation (such as the compliance assessments used in SAP and PHPP or dynamic simulation more commonly used in research such as that of Coley at al. (2012)). Although widely used, there are some significant uncertainties that must be taken into account when considering building simulation based performance assessments. As

noted by de Wilde and Tian (2011) this includes modelling, numerical and specification uncertainty along with scenario uncertainties related to occupant behaviour and, when considering performance over time, predicted climatic conditions and likely renovation scenarios. Future weather files are a key component of any climate change impact study using building simulation. In the UK, the data used to generate such weather files (as used in building simulation studies) originates from the UK Climate Change Projections (UKCP) (Jenkins et al. 2009). It has been argued that due to the inherent difficulty in predicting future weather scenarios a probabilistic approach should be taken (de Wilde & Tian, 2011) and in that sense the UKCP09 offers a significant advantage over the previous UKCP02 as it offers a wide range of probabilistic scenarios. This has the knock on impact of introducing additional complication to such prediction due to the required processing. With the goal of addressing this, the PROMETHEUS project at the University of Exeter developed a range of weather data files based on the UKCP09 predictions which represent a range of probabilities (10th, 50th and 90th percentile for low, medium and high scenarios) for three timescale (2030s, 2050s and 2080s) producing both Test Reference Years (TRYs) to represent a 'normal' year and Design Summer Years (DSYs) to represent a 'near extreme' year. The methods used to develop the files are detailed by Eames et al. (2011). Several studies considering domestic overheating have used these weather data files (for example see Coley et al., 2012, Gupta & Gregg, 2012, Mavrogianni et al., 2012) and although the methods used to develop the files reduces the computing needed some considerations remain in relation to how the files are implemented in climate change impact studies. Gupta and Gregg (2012) suggest that climate impact studies carried out using worst case scenarios (90th percentile) would ensure resilient designs. Coley et al. (2012) however, suggest that a more median approach (50th percentile) with allowance only for 'hard' adaptations to resolve any overheating, as this would allow designers to avoid potentially unnecessary and costly adaptations. Jenkins et al. (2013) suggest that both the DSYs, which is intended to test the building for overheating and TRYs, used to represent more normal conditions for energy estimates, be used so that both 'near extreme'

and higher probability scenarios can be represented. This in turn allows for at least some of the probabilistic capabilities of UKCP09 to be realised, although as noted by Coley et al. (2012) for some UK cities DSYs may show a cooler climate than TRYs and use of DSYs therefore should be approached with caution.

Methodology

For this research, five building standards were chosen to represent a range of construction specifications, requiring increasing levels of energy savings. This included the regulatory minimums of Part L 2006 and 2010, the voluntary standards of the Code for Sustainable Homes (CfSH) levels four and five and the Passive House Standard. **Figure 1** depicts how the energy consumption predictions for each standard noted relate to each other. As can be seen they follow the push towards *'net zero carbon'* dwellings in the UK (National House Building Council Foundation, 2009) and although this has recently been put on hold (Her Majesty's [HM] Treasury, 2015) it is likely to remain a long term goal.

Once the relevant standards were established a 'typical' UK dwelling was developed based on a dwelling stock analysis of England and the wider UK. This indicated that since 2001, 66% of dwellings constructed were houses (DCLG, 2014a and National House Building Council 2014), approximately one third of these were semi-detached, with an average of three bedrooms and an average floor area of 91.7sqm (DCLG, 2014b). Of the total dwelling stock in England and Wales (24.6 million, DCLG, 2014c and Statistics for Wales, 2015) 30% or 7.38 million are semi-detached houses (Office of National Statistics, 2011). Although flats/apartments and particularly single aspect flats have been shown to be at high risk of overheating (Mavrogianni et al. 2015) and several studies have explored these issues (Dengel & Swainson 2012), detailed exploration of the impact on houses are less prevalent and given the volume of dwellings involved (7.38m) consideration of the potential impacts

on these units is merited. Following this, a three bedroom semi-detached property aligning with

these criteria, with a glazing ratio of 22.5% and layout based on Roberts-Hughes's (2011) 'case for

space' guidelines was chosen to represent the 'typical' dwelling.

The dwellings did not include solar shading, other than in places where the regulation or standard in

question required it. It is accepted that details of design will have a significant impact on overheating

risk and it is a limitation of this work that the 'typical' case presented here cannot be fully

representative of the stock of semi-detached dwellings. The criteria used aim to ensure that the

'typical' case reflects the likely approach to delivering such dwellings built to the standards and

regulations under consideration in this paper.

The fabric specifications of the dwellings were developed in accordance with the relevant

compliance assessment for the given standard (SAP (DECC, 2014) for Part L, Passive House Planning

Pack (Feist, 2013) for Passive House and the DCLG (2011) recommendations for the Code for

Sustainable Homes for CfSH level four and CfSH level five). For each specification three variants were

established, representing three levels of thermal mass, and three different construction methods:

low mass ~100 kJ/m²K, medium mass ~250 kJ/m²K and high mass ~450 kJ/m²K, based on SAP 2012

(DECC, 2014). Predicted internal loads were then established in accordance with CIBSE Guide A

(CIBSE, 2015). Details of the specifications used can be found in **Table 1**.

Table 1 Model Input Parameters

This 'typical' building was then modelled in 3D using the Ecotect® software (Marsh, 1996), before

being exported to the Heat Transfer in Buildings 2 (HTB2) software (Lewis & Alexander, 1990) for

thermal performance simulation and analysis. Exporting to HTB2 was necessary as this software

allows for more in depth analysis and also simulates the building dynamically as opposed to the admittance or steady state method used in Ecotect®.

Once the various versions of the buildings had been developed, models were run using current and future probabilistic reference years based around the UKCP09 weather generator as developed by the PROMETHEUS project at the University of Exeter and detailed by Eames et al. (2011). For the purposes of this study the 50th percentile predictions of the median scenario where used for both TRYs (representing the more likely prediction) and DSYs (representing near extreme predictions). It is accepted that using a range of predictions (10th, 50th and 90th percentiles for low, medium and high scenarios) would give a wider indication of probability, however as Coley et al. (2012) note using the 50th percentile provides a more median result, allowing for consideration of overheating risk while avoiding designing to the worst case scenario. Such an approach also reduces the risk of interventions made now, to avoid future overheating risk, increasing current energy use.

As building occupants are likely to adapt to warmer climates, four 'anytime' window opening scenarios (closed, slightly open, half open, fully open) and two night-time purge ventilation scenarios (half or fully open) were included in the simulations, with associated ventilation rates for each (see **Table 1**). The findings of the 'night purge' window positions are only included for the high thermal mass scenarios where they had the greatest impact. In each case the software used enabled the window opening position to be triggered by internal temperatures of 23.9°C. This aligned to the work of Jenkins, Patidar, Banfill and Gibson (2011) who suggested that 23.9°C was the temperature at which occupants are likely to begin to adapt.

Along with building standard, thermal mass and ventilation rate (window position), orientation can be expected to have an impact on overheating risk. For this study two possible orientations were considered (North-South and East-West). These were chosen to reflect potential extremes of solar gain (high gains for South facing, but easier to control versus the East-West scenario). It is a

limitation of the study that a wider range of orientations could not be considered, which arguably would be more representative of the as built stock.

Overall five building standards, built using three thermal mass variations, in two orientations with up to six possible window positions were simulated (see **Table 2**), along with some additional simulations for comparison between London and Edinburgh (a full set of scenarios/models were run for London with a selection for Edinburgh for comparative purposes) which resulted in 1788 individual model runs.

Table 2 Sample Modelling Plan (Part L 2010 – Model Images included for Illustration)

As discussed previously, there is some debate regarding the most appropriate metrics to be used for predicting overheating in free running dwellings. To allow for further comparison between the two most common approaches (single temperature exceedance and the adaptive comfort method) both were included in this study. Overheating criteria one, two and three are based on adaptive comfort standards as detailed by Nicol and Spires (2013) while criteria four and five are based on the more traditional single temperature exceedance criteria, the specifics of each of the criteria can be found in **Table 3** . For each of the adaptive comfort criteria the threshold used is a function of the relationship between the running mean outdoor temperature and the indoor temperature. As the software used was not capable of calculating a running mean of temperature (directly at least) the data generated was exported and manually analysed to create a running mean thus allowing for consideration of the adaptive comfort measures. As noted by Nicol and Spires (2013), exceedance of any two of these criteria is considered to represent overheating.

Table 3 Traditional and Adaptive Comfort Overheating Criteria

Results

Figure 2 displays the findings of the building simulations carried out for London (with a comparative for Edinburgh included in the 2080s) combining the building standard, thermal mass, window position and climatic scenario for a dwelling with either a North-South or East-West aspect. Although as noted by Coley et al. (2012) for some UK cities DSY (for testing near extreme) may show a cooler climate than TRY (for a more normal climate) this was not found to be an issue in this scenario as TRY was consistently cooler than DSY. As a result of this the findings presented in this section are based on DSYs only.

Figure 2 Overheating Risk Assessment (semi-detached house, cross ventilation possible)

A number of initial observations can be drawn from the analysis, such as an increase in overheating over time, as can be seen in **Table 4**. Taking the CfSH level four, medium thermal mass, North-South orientation with slightly open windows possible and measured against exceedance of two of the three adaptive comfort criteria (criteria 1-3) no overheating occurs in the base case, however, for the 2030s exceedance occurs 7.8% of the time, 11.1% for the 2050s and 27.4% for the 2080s. Interestingly, when measured against the more traditional steady state criteria (criteria 4), predicted overheating increases significantly (Base 25.2%, 2030s 54.8%, 2050s 64.8% and 2080s 75%) highlighting as noted by Roaf et. al. (2015) that the traditional criteria predict higher levels of overheating than adaptive comfort standards. This research did not explore the merits of the adaptive comfort versus traditional steady state overheating criteria in detail, for clarity the remainder of this study focuses on the adaptive comfort standards.

Table 4 CfSH level four: Overheating Risk as a percentage, during summer months (May-Sept)

Secondly, buildings with higher thermal mass are at less risk of overheating than more light weight buildings when construction standard built to is kept constant (for instance built to CfSH level four, but thermal mass varied) (see **Table 5**). Taking Part L 2010 as an example, in the 2030s higher thermal mass can help to reduce incidents of overheating by up to 15%, 15.6% in the 2050s and 19.6% in the 2080s (all based on slightly open windows when temperatures are appropriate to take advantage of thermal mass). Furthermore, thermal mass becomes more important as insulation levels increase, while at higher levels of insulation (CfSH level five and Passive House) the benefit of thermal mass reduces between the 2050s and 2080s as the climate warms. This is based on the difference in percentage of overheating observed between the low and high thermal mass versions across the building standards as noted in **Table 5**.

Table 5 Overheating Risk as a percentage of occupied hours during summer months (Slightly open wins –N/S)

This reduction in the benefit of thermal mass is likely a result of the decrease in diurnal temperature ranges over time and, as can be seen in **Figure 3**, the general reduction in the difference between internal and external temperatures. This has the impact of reducing the ability of ventilation and thermal mass to store or transfer energy to the cooler outside air. **Figure 3** also demonstrates that along with the potential for increased overheating over time, temperatures in excess of 24°C in bedrooms at night time may be regularly experienced from the 2030s onwards, which presents a particular cause for concern.

Figure 3 Internal to External Temperature Difference (high thermal mass)

When considering the performance of the buildings across the range of standards (Part L 2006 to the Passive House Standard), during peak temperatures (taken as the month of August) it was found that as the levels of insulation increase and external temperatures increase over time, increasing levels of fabric gains are observed overnight (see **Figure 4**). This overnight gain maybe a contributory factor in high night-time bedroom temperatures. **Figure 4** is based on mean daily temperature ranges for August, showing a comparison between the 2050s and 2080s for dwellings built to the Part L 2006 and CfSH level five building standards.

Figure 4 Gains & Losses (2050 and 2080 comparing Part L 2006 and CfSH level five)

As previously noted, the adaptive comfort criteria include an assessment of the severity and duration of the overheating (criteria two in this study). As can be seen in **Figure 2**, in the low and medium thermal mass scenarios, as higher levels of insulation are introduced (CfSH level four and five and Passive House) from the 2030s onwards this criteria is regularly exceeded unless windows are in the half open position. Such window opening as previously noted may be impractical due to noise, pollution and security issues. Consistent exceedance of this criteria is an additional cause for concern as persistent exposure to elevated temperatures can result in serious health impacts, particularly when they occur at night-time (Dengel & Swainson 2012). This criteria does not consider longer term exposure to higher temperatures (beyond the length of time within a single day) which although of importance was beyond the scope of this paper.

Using the adaptive comfort criteria, a cross analysis between the five building standards (see **Table 5**) found that, for the slightly open window position in the 2030s (near future) and low thermal mass construction, the 2006 building overheats 5.9% of the time, the 2010 building overheats 15% of the

time, CfSH level four 18.2% of the time, CfSH level five 35.9% of the time and the Passive House building 31.3% of the time, all measured during the summer months (May to September inclusive).

Building on this, and extrapolating the data in **Table 5**, it can be said that in the above scenario building standard (assuming thermal mass is kept constant) can increase potential incidents of overheating by up to 11.7% in the base case (11.7-0), for the 2030s this can increase to 30% (35.9-5.9), 30.7% in the 2050s (41.8-11.1) and for the 2080s 48.4% (61.4-13). It is worth noting that although the fabric specifications of CfSH level five and the Passive House Standard are similar (when in 'free running' mode) there is evidence that the overheating assessment criteria in the Passive House Standard are more robust. Reductions in incidents of overheating of 6.6% were observed for the 2030s, 6.8% for the 2050s and 7.2% for the 2080s for the Passive House standard in comparison to the CfSH level five, all based on a medium thermal mass scenario with slightly open windows (data stated but not presented in separate table). As noted below however, orientation presents a significant overheating risk for the Passive House standard, which if shading is not carefully considered, may reduce or reverse the benefit.

As can be seen from **Figure 2**, changing the orientation of the building from North-South to East-West has a noticeable impact on the incidents of overheating across all standards, when measured against the adaptive comfort criteria. This highlights the importance of solar shading and the impact it can have on overheating (East-West orientations are more difficult to shade than North-South orientations due to the low sun angle). For the East-West orientation, in line with the findings from the North-South orientation, further increases in incidents of overheating are experienced as the building standard increases (greater levels of insulation and reduced infiltration), and the building is optimised for heat retention.

For comparative purposes, thermal performance simulations were also carried for Edinburgh in the 2080s (see **Figure 2**). Unsurprisingly, this resulted in significantly reduced levels of predicted

overheating, with in all scenarios, only the low thermal mass version of CfSH level four and all thermal mass versions of CfSH level five and the Passive House standard presenting significant overheating issues. By comparison, for London all standards exhibited at least some incidents of significant overheating, with the low thermal mass version (excluding the 2006 version) experiencing this across all window opening positions.

Implications

The preceding results suggest that the current standards used in relation to overheating risk in dwellings in cool climates may not be fit for purpose. The lack of regulation in relation to maximum allowable temperatures and the opportunity for designers to utilise potentially unrealistic adaptations at the design stage, such as window opening, results in unreliable predictions. Coupled with this, the use of historic climatic data means that the current approach is not able to make predictions about likely overheating risk beyond the point of handover, thus ignoring the lifecycle of the building and potential impact of climate change. As noted by Meikle and Connaughton (2006) new and existing housing is predicted to have to last for an extended period and in many cases this may be beyond the end of the century. In this context an alternative approach is required if the regulatory framework is to ensure the delivery of comfortable and healthy dwellings that offer resilience to predicted climate change.

In addition to the issues raised with the approach to assessing overheating risk in dwellings, the drive to reduce energy use in new dwellings through current and emerging regulations and building standards (thus optimising the building for heat retention) has the potential to increase the overheating risk. The high proportion of CO_2 emissions that have been linked to the built environment (43% of all CO_2 emissions in the UK, DCLG 2015), and the link between this and anthropogenic climate change, creates a particular challenge for regulation in the built environment,

where increased short or near term energy savings must be balanced against increased long term overheating risk.

The approach outlined in this paper and the findings as presented in **Figure 2** could be used as the basis of an alternative risk based overheating assessment method that takes account of predicted climate change. This would require a careful definition of how exposure to high temperatures for a specific period of time constitutes an unacceptable overheating risk, which would provide clarity and allow methods to be developed and refined accordingly.

In addition to this, such an approach could also incorporate climate change adaptation planning at the design stage, as outlined by Jones et al. (2013), thus ensuring that short or near term energy efficiency is not compromised for longer term comfort (by for instance adding shading now, that may reduce future overheating risk, but also increase current heating loads).

Conclusion

Although the current drive within the regulatory framework of the built environment to reduce heat loss (in cool climates) is not without its merits, as levels of insulation increase and infiltration decreases, there is increasing risk of summer time overheating linked to climate change, particularly in urban areas. Furthermore, there is a risk of extended periods of overheating and unacceptably high temperatures in bedrooms overnight. The current standards used for predicting overheating risk may not be fit for purpose as they are based on historic data taking no account of potential climate change, and make unrealistic assumptions in terms of occupant adaptations. Higher levels of thermal mass and the potential for increased ventilation rates offer benefits, however these may reduce over time as internal to external temperature differences decrease.

Predicting overheating in buildings, given the range of variables involved, is complex and subject to a degree of uncertainty. Instead of a single temperature or hours of exceedance metric requiring

complex building simulation to predict overheating, a risk based scale may be more appropriate. This risk based assessment, embedded in regulations and standards, could take account of the duration of the high temperatures experienced and the predicted impact of climate change (taking account of not only increased temperatures, but the reduced ability of thermal mass and ventilation to minimise overheating). The approach to climate change risk assessment in dwellings as detailed in this paper could be expanded upon to provide such a design stage risk assessment for a range of dwelling types. This approach presents a clear role for standards and regulations in defining anticipated scenarios in relation to overheating risk linked to climate change with the aim of ensuring resilience in both the predicted 'normal' future climate and during 'extreme' events.

This research must be considered in the context of a number of limitations. Future predictions of overheating risk based on building simulation are subject to uncertainty and rely on a number of assumptions in relation to variables that cannot be easily predicted (such as internal gains, occupancy patters and occupant adaptations). The paper has tried to reduce this uncertainty through the use of 50th percentile climate predictions (using weather data files produced from the PROMETHEUS project), offering a range of possible adaptations (window opening) and taking conservative predications in relation to internal gains, in order to avoid more extreme and potentially less realistic predictions. The research presented is based on a single building type, namely a semi-detached dwelling where cross ventilation is possible, but consideration of a wider range of buildings using the same methodology would be of benefit. Further granularity could be added to the predictions by considering a range of shading configurations. For all standards considered the buildings are assumed to be in 'free running' mode, as such this ignores the potential for a Passive House dwelling with a mechanical ventilation system and summer by-pass to implement purge ventilation, although as noted, the benefits of increased ventilation may reduce over time.

Further research is needed to consider how occupants of dwellings, particularly vulnerable occupants, may adapt to overheating. This could include further research in relation to window opening patterns in urban areas where noise, pollution and security may place restrictions on such adaptations.

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