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Variance of future UK heat wave incidents with geographic implications on mitigation

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Abstract: The effect of heat waves on human comfort is an area of research that needs to be further investigated. Many of the parameters that deal with heat wave events have similar mitigation strategies to those used for overheating. This study examines weather files from 8 UK cities to identify heat wave periods which are then used to quantify the effectiveness of shading and thermal mass in a simulated prototype. Both heat wave and cooling season results are compared to highlight the differences in their characteristics. The effect of thermal mass and fixed shading in the building, based on a previously used prototype model, is assessed with EnergyPlus software. Results show that the number of heat wave days have no correlation with the city's population, a possible proxy for the heat island effect. A combination of thermal mass and shading can be 90% effective in reducing the impact of a heat wave event. The next best solution is thermal mass, then shading alone, which reduces heat wave impact by up to 50%. These roughly follow the results obtained for the cooling season but the proportion of overheating criterion given in TM52 for the cooling season and heat wave events show little relationship and require further investigation.

Keywords: Heat Wave mitigation, TM52, TM59, Future Climate, Overheating mitigation

1. Introduction

Heat waves are particular weather characteristics that may significantly influence the internal environment of buildings, but have not been given much thought in previous research. There is a lack of standards or guidance relating to the parameters and methodology required to model such occurrences. Designers should consider heat wave effects within their building design, as previous events have demonstrated they have a strong impact the comfort and well-being of building occupants.

Heat waves are by definition abnormal events that occur in the external environment. There will be an increase in the frequency of heat waves, as external temperatures and the temperature extremes rise in the future. The UK definition of a heat wave relates to emergency response plans (NHS, 2015) and is different from the international identification of a heat wave event. A conservative estimate derived on a previous study predicts a tenfold increase in heat wave occurrences in 60 years' time (Din and Brotas, 2016). This coincides with the lifespan of current new buildings according to the Building Research Establishment (BRE, 2018).

The particular impact of heat wave effects on occupants in comparison to (dis)comfort levels experienced in the rest of the cooling season has not been quantified in previous building studies. A key parameter in the definition of the building's thermal characteristics is the thermal capacity (mass) of the construction materials. This parameter has been shown to reduce heating and cooling requirements, as it acts as thermal storage reducing peak temperatures (CIBSE, 2016) and dissipating heat energy (Hacker, 2008).

The mitigation of heat waves follows the same strategies used to prevent overheating (ZCH, 2012). The three factors that have the most impact in minimising overheating in buildings are thermal mass, shading and air velocity. Modifying the air velocity was not considered in this study because the ceiling height of new build dwellings in the UK is too low to be effective for ceiling fans (passipedia, 2018). These would require higher floor to ceiling heights to allow for an effective velocity downdraft. Raising ceiling heights is not realistic in the current housing construction market in the UK, which is interested in maximising profit through dwelling density. The main priority has become cutting heat losses through the fabric, to reduce CO2 emissions in the heating season as a requirement of building regulations and planning applications.

Previous studies have shown the impact of shading on comfort (Din and Brotas, 2016) but do not take into account the combined effects of mitigating measures with thermal mass. Providing additional solutions may affect the overall mitigation result in a non linear manner. The use of mitigation measures may not be applicable in all the UK as it depends on individual local conditions. Although the UK is classified as one climate by ASHRAE (2018), building regulations define separate regions with different characteristics. Any overheating mitigation measure used should be defined according to its geographic significance.

Building designers should assess the resilience of the building over its lifespan (Jenkins et al, 2012) with the onset of climate change. Overheating and particularly extreme high temperature heat wave events will have a critical impact on the comfort of (alongside health dangers to) occupants within the lifespan of the building and their risk within a building design should be assessed.

The starting point to assess heat waves is to use current methods of assessing overheating such as BSEN 15251 (BSi, 2007), complemented by the Chartered Institute of Service Engineers (CIBSE) Technical Memorandum TM52 (2013). TM52 does not provide a definitive operative threshold but a range of conditions taking into account occupant's acclimatisation, i.e. adapting their comfort with historic weather conditions. The CIBSE Technical Memorandum TM59 (2017) adds to the previous methodology the definition of the parameters for equipment, occupancy and occupancy hours in dwellings. TM59 assesses the risk of overheating for a range of units within a housing development.

2. Aims

This study shows the variance in heat wave patterns from future climate files for different UK locations in different zones as defined by the UK building Regulations Standard Assessment Procedure, SAP (DECC, 2012). The main part of the study assesses the thermal mass and shading input to simulation software (Energy Plus v8.7.0).

The study shows the amount of overheating occurring under heat wave events in 2080 provides a future end point for new buildings and maximises the number of overheating events experienced. The weather files are from the Eames et al studies (2012) which have established probabilistic weather for future years based on climate change models for various locations in the UK. The study will show the impact of shading and thermal mass which are already recognised as overheating mitigation measures. The comparison of the impact of heat wave events on the internal comfort of occupants in comparison with the whole of the cooling season will show what types of overheating (as defined by TM52) are significant and any relationships that occur in terms of impact of mitigation and the geographic location within the UK.

3. Background

The assessment of overheating in the UK building regulations SAP is based on a simple calculation using climate data, the construction materials and solar gains. The internal environment of dwellings demands better criteria than a simple threshold temperature (Beizaee et al, 2013). Regulatory tools should assess the impact of heat waves. Despite their short term they have a disproportionately large impact (McLeod et al, 2013) to the comfort and well-being to the building occupants.

Previous overheating studies assessing the internal conditions of dwellings do not consider heat waves. Similarly, many heat wave studies do not quantify the heat wave impact on comfort of occupants inside a dwelling. TM52 assesses overheating using the adaptive comfort methodology, where the comfort temperature depends of the outdoor temperature rather than a fixed threshold temperature. Overheating is assessed accounting for the proportion of uncomfortable conditions that are experienced by building occupants. This is a development of the previously defined BS EN 15251 guidance. TM52 sets a relationship between the outside temperature, the occupant's behaviour, the activity and adaptive opportunities which affect comfort. Overheating is defined in three distinct criteria which have some interdependency in their calculation method:

1. The amount of degree hours more than 1K over the limiting comfort temperature (assessed from 1st May to 30th September) must be less than 3% of occupied hours;
2. The higher the temperature the more significant the overheating effect. This test quantifies the severity of temperature on a daily basis. The weighted excess of temperature must be less than 6 degree-hours on any one day for comfort to be achieved;
3. Reports heat stress events 4K above the limiting comfort temperature.

Occupants are likely to experience overheating if two or more of these conditions are not met. TM52 defines the amount of overheating over the whole cooling season. The conditions given above need modification to allow the comparison of short time periods with those over the whole cooling season

TM59 defines the model input requirements and technical specifications to assess the risk of overheating in a housing development. The guidance uses the TM52 classifications of overheating but also defines the type and future climate files to use to assess overheating risk. The guidance also defines a range of other influencing factors including setting the temperatures windows should be operated, the occupancy rates, schedules and specification of equipment allowed for each room. The guidance also specifies a fixed set point temperature similar to that used in BS EN 15251 for use in bedrooms. TM59 is good in defining aspects but a range of double accounting exists to increase the probability of identifying overheating risk. However, it does not provide the quantification of overheating which has been further developed in this paper. This study uses the TM59 as the backbone of model inputs but some inputs have been modified to give more realistic results. With such twofold inputs any errors will be internal to the simulation process and will not prevent a comparison between models in this paper.

Climate change model scenarios for low, medium, and high probability were retrieved from the Eames et al weather database. Each file has a 33, 50, 66 and 90th probabilistic percentile depending on the risk being assessed. Files are available in 20 year bands from a reference year to 2080. The climate output files are available in two forms of future weather files. Test Reference Year (TRY) which uses averages from the previous 20 years of data to produce a weather file and the Design Summer Year (DSY) uses 20 years of the peak summer condition to weight the weather file. From this range of options care has been taken to select the right file for use in this study.

Din and Brotas (2016) have shown for a case study in London that active cooling to prevent overheating in bedrooms is predicted to happen in the near future. The variation in overheating within living rooms is sensitive to daytime room occupation and solar gains. This creates the opportunity for the further investigation of the combination of overheating mitigation strategies as previously identified by the Zero Carbon Hub.

Heat wave weather periods have a relationship to mortality events (Zhang et al, 2013). Many major urban centres have defined a trigger temperature to activate the emergency services plan (Diaz et al, 2015). Studies have been conducted to classify inhabitants by location and social demographic to identify their vulnerability to heat wave events (Wolf and McGregor, 2012) for a trigger temperature of 28^{o}C. Existing heat wave definitions vary depending on geographic locations ranging in peak daytime temperatures from 26^{o}C to 40^{o}C (Scandinavia to Australia respectively) and a variance in the duration of days these temperatures are experienced from a daytime single event to being averaged over a specific number of consecutive days. Other heat wave definitions include night-time temperatures as part of the assessment occurring before or after the daytime threshold level to be classified as a heat wave.

Dense built up areas can aggravate the Heat Island Effect and rise of night time temperatures (Lemonsu et al, 2014). The current heat wave plan for England (NHS, 2015) defines a set point temperature of 32^{o}C for the day if the night before the temperature of 18^{o}C is exceeded. This threshold is an emergency response threshold and may be considered too high for a comfort analysis. Previous heat wave studies show actual observed data from a historic viewpoint (Porritt et al, 2012) as heat waves are defined as extreme random events historical data is currently the only methodology used to analysing such events. No studies define heat wave effects using future climate files.

A literature review on the influence of heat waves on the built environment is mainly concerned with the external urban environment rather than internal occupied areas. The built infrastructure influence on heat wave susceptibility for Europe is examined in Hintz et al (2017). The study identified the UK as the country most influenced by the 'grey infrastructure' that includes the external characteristics such as dark surfaces and green roofs and occupant behaviour, although these factors are not quantified.

The urban heat island of a site is compared to a surrounding countryside by Ward et al (2016). Comparative studies in Northern and Southern Europe show that urban heat island can be alleviated by urban green spaces. In Shanghai the building density and its elevated height create hot spots within the urban context (Chen et al, 2016).

The quality of the built environment is studied by Kim and Kim (2017) in which poor building standards are linked to higher heat wave events in deprived urban temperatures in Seoul, South Korea. These external studies are summarised in a study into heat wave mitigation strategies used in urban environments (Salata et al, 2017).

An inhabitant centric study conducted by Norbert and Pelling (2017) explores the vulnerability to discomfort. The study has been conducted using qualitative interviews to assess the speed of mitigation adoption amongst residents. Residents were given a range of external information such as television news reports. Elderly people were the least aware and tend not to modify their behaviour in a heat wave period, with possible negative health consequences.

Heat wave events are extreme events and have a low quantification within weather files which are based on 20 year averages. If a heat wave is identified to occur within a weather file then this would occur for every individual year within that 20 year sequence. Heat wave events defined by present-day standards will increase 20 fold by 2080 with one heat wave event a year as early as 2020 (Din and Brotas, 2017). Heat wave events that are quantified for 2080 may occur for a single year within the 2040s based on historic heat wave event projections.

The differences between Heathrow and Islington data in Din and Brotas (2016) leads to questions on the reliability of future weather files and the significance of consistently longer hotter periods evidenced in the Heathrow future projected data. This requires further investigation of the weather files and the Heat Island effect through geographic and population data.

4. Methodology

A typical flat layout shown in Figure 1 has been used in previous studies (Din and Brotas, 2016) as an archetypal model. The dynamic thermal software of Energy Plus 8.7.0 is used to simulate the internal temperatures which has been validated for the calculation of thermal mass effects by US department of Energy (2014) using the TARP algorithm within the energy balance calculations.

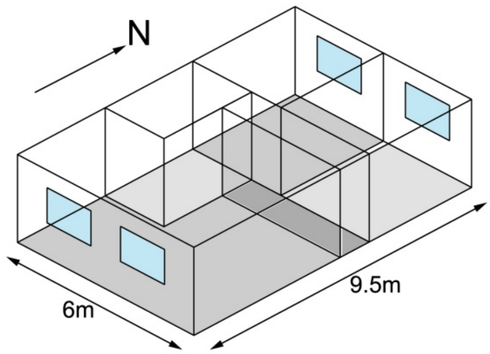

Figure 1. Two bed Flat configuration and dimensions

In the paper only the south facing living room is assessed with the rest of the flat providing adjacent spaces in which some thermal and radiative heat exchange occurs during non-occupied hours. The energetic configuration and loads need to be compared with TM59. Occupancy is identical apart from 3 people occupying the space from 7am to 7pm and then 2 people from 7pm to 11 pm to model a child going to bed. TM59 in contrast models continuous occupancy in the whole dwelling simultaneously in bedrooms and living areas.

The ventilation control is set to close the windows when the outside temperature is 5K higher than inside temperature. The lower limit when windows are also assumed closed is set to 18^{o}C rather than 22^{o}C as in TM59. Restrictors for night ventilation are in line with TM59.

The construction follows the specification of a PassivHaus: U value equivalent of 0.15 W/m^{2}K and an air tightness of 1m^3/m^2/hr. Internal Heat Gain (IHG) from people and lighting are in line with TM59 but appliances and their usage are given in more detail. Cooking occurs for 1.5 hours a day using a 1700W ceramic hob. Domestic appliances are taken from PassivHaus Planning Package (passipedia, 2018) at 210W for 10 hours a day.

Each modelled flat is applied with lightweight plasterboard to its innermost face as the base case. A 100mm dense concrete on the inner face acts as a thermal mass surface to the interior space (CIBSE, 2016), to model its effect. The density of thermal mass used was 2200kg/m^3 in line with CIBSE recommendations. Both models have similar windows and insulation levels. A 1 meter horizontal overhang to the whole of the south facade is applied to each model to determine the effect of shading on the results obtained.

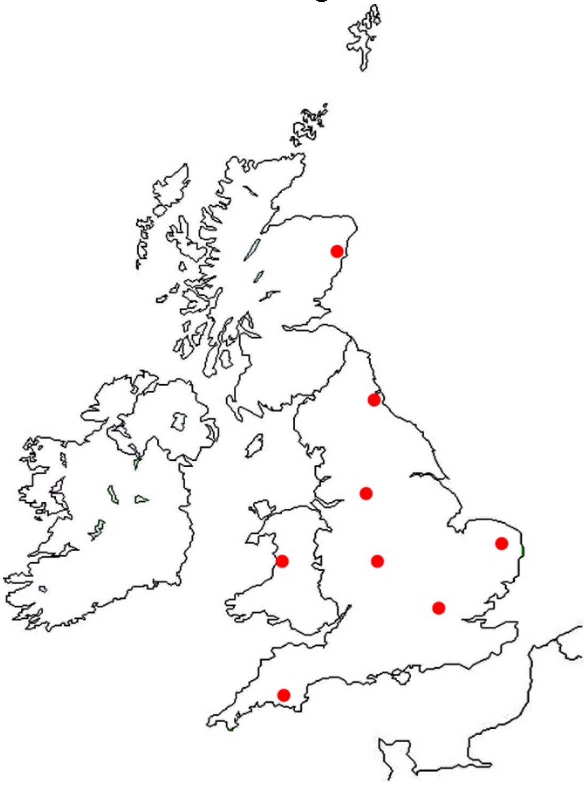

Figure 2. 8 cities investigated in the study. Each within a different weather zone in SAP

From future weather files (Eames et al, 2012) heat waves were identified in the 2080 high IPCC climate change scenario (business as usual), 66th percentile probabilistic data.

This is slightly higher than the 50th percentile recommended in TM59 but was used as the overheating demonstrated by 90th percentile has been shown to be exponentially higher than the 66th percentile weather files (Din and Brotas, 2017). Overheating is evaluated for the whole cooling season using Design Summer Year weather files in line with TM52 recommendations.

The process is carried out for 8 cities within the UK in differing weather zones as identified within the SAP methodology shown in Figure 2. These were Aberdeen 16, Aberystwyth 13, Birmingham 6, London (Islington) 1, Manchester 7E, Newcastle 9E, Norwich 12 and Plymouth 4. Each of the number codes beside the city specify the weather zone in SAP from 1 to 16. The building life is not relevant to this study however the dates for analysis coincide with that of the life of a new building, i.e. 60 years using BRE/NHBC guidelines.

Heat wave events are identified within the weather files and overheating is quantified for the 4 different construction models (lightweight, heavyweight with and without shading) for each city over any day that reaches over 28^{o}C and 18^{o}C the previous night. This follows a sensible day temperature definition from previous literature and the night time given from NHS guidelines. These periods match historic heat wave events in weather files. Discrete days and series of days are dealt with in the same way.

The cooling season is defined from 1st May to 30th Sept in line with TM52 guidelines for the 4 construction models and 7 cities within the UK. Each of the TM52 conditions is quantified on temperature frequency of the interior living room. This is a modification of TM52 but allows a comparison of the whole cooling season with a heat wave event, so that the criteria are modified to:

1. hourly above a threshold comfort temperature (hrs);
2. Amount of days over the daily weighted threshold of 6 deg-hrs (w);
3. number of hourly instances above the adaptive heat stress temperature (no).

This study deals with the quantification of each of the criteria, not requiring two conditions to be met to account for overheating. The time element is eliminated so not requiring annual occupied hours.

In summary heat wave periods are identified for 7 cities and compared to their population. Four construction types are modelled: lightweight (L), lightweight with shading (LS), heavyweight (H) and heavyweight with shading (HS). These are modelled over the heat wave periods for each of the modified TM52 criteria and then over the cooling season and the results compared. A comparison is made between the differing TM52 conditions previously identified. This is given as a proportion of the whole TM52 quantification in each case, to ascertain whether patterns on the conditions of TM52 that can be characterised for a heat wave period compared to that of a cooling season.

5. Results

Heat wave periods retrieved from the weather files are presented in figure 3. The number of days were plotted against the population of each of the cities to see if any relationship existed between the data. The population being a reasonable proxy against heat island effect the more populated the area the more hard surfaces and therefore a differential between the city and the surrounding countryside.

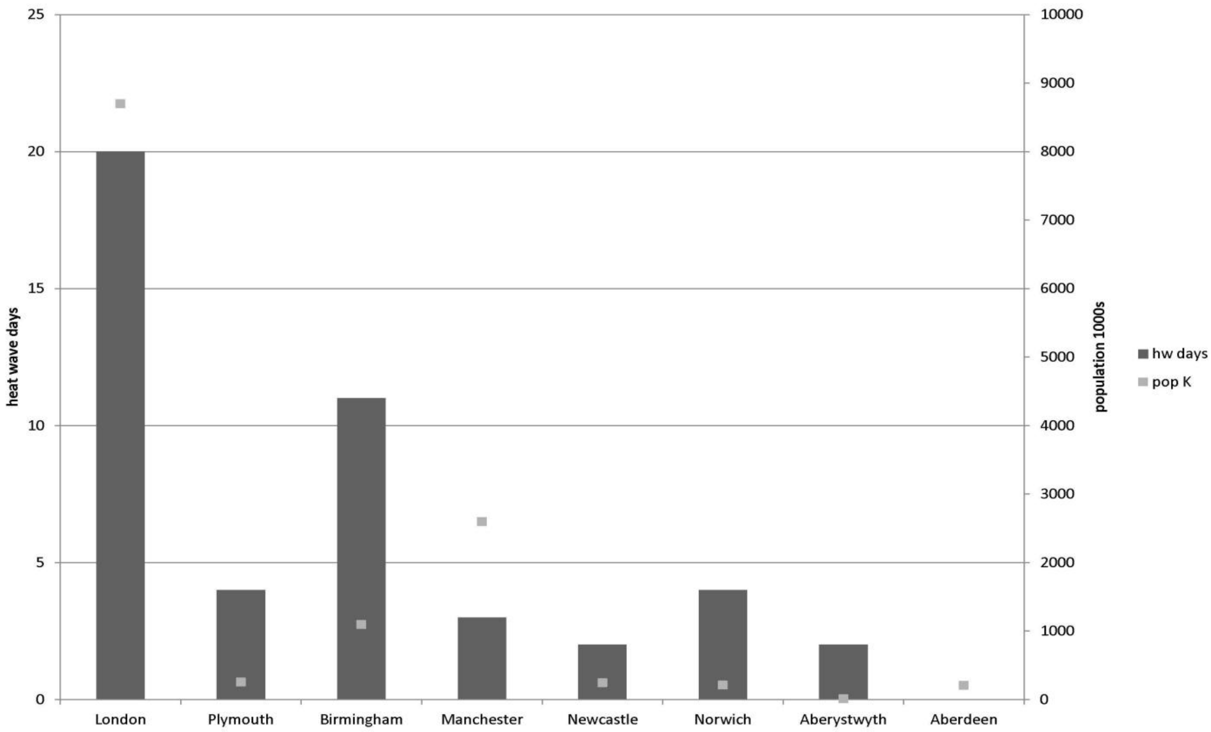

Figure 3. heat wave days and population of UK cities

The highest by some margin is London approximately double that of Birmingham in second place. The lowest is Aberdeen, which has no heat wave days as defined in the 2080 file. The quantification of heat wave days is not solely associated with the latitude of the city as Plymouth has less heat wave days than Birmingham. The link between heat wave events and population is unclear, with Manchester being more populated than Newcastle but not reflected in the heat wave days.

A large variation of the amount of heat wave events is shown, which globally is in the same ASHRAE climate zone and traditionally would be modelled with only two climate files, one for Scotland and one for England. The amount of heat wave days is not correlated with the population or the latitude of the cities.

Heat waves do not occur in the same time frame. At London they are mainly in August, at Plymouth in July, at Birmingham in August, at Manchester in August, at Newcastle between July and August, at Norwich in August and Aberystwyth in July. These clusters of dates are not random events and are different for different cities. This is not a simple translation error within the generated climate files. This matches previous findings in which a discrepancy within London city centre (Islington) and outskirt (Heathrow) was identified (Din and Brotas, 2016).

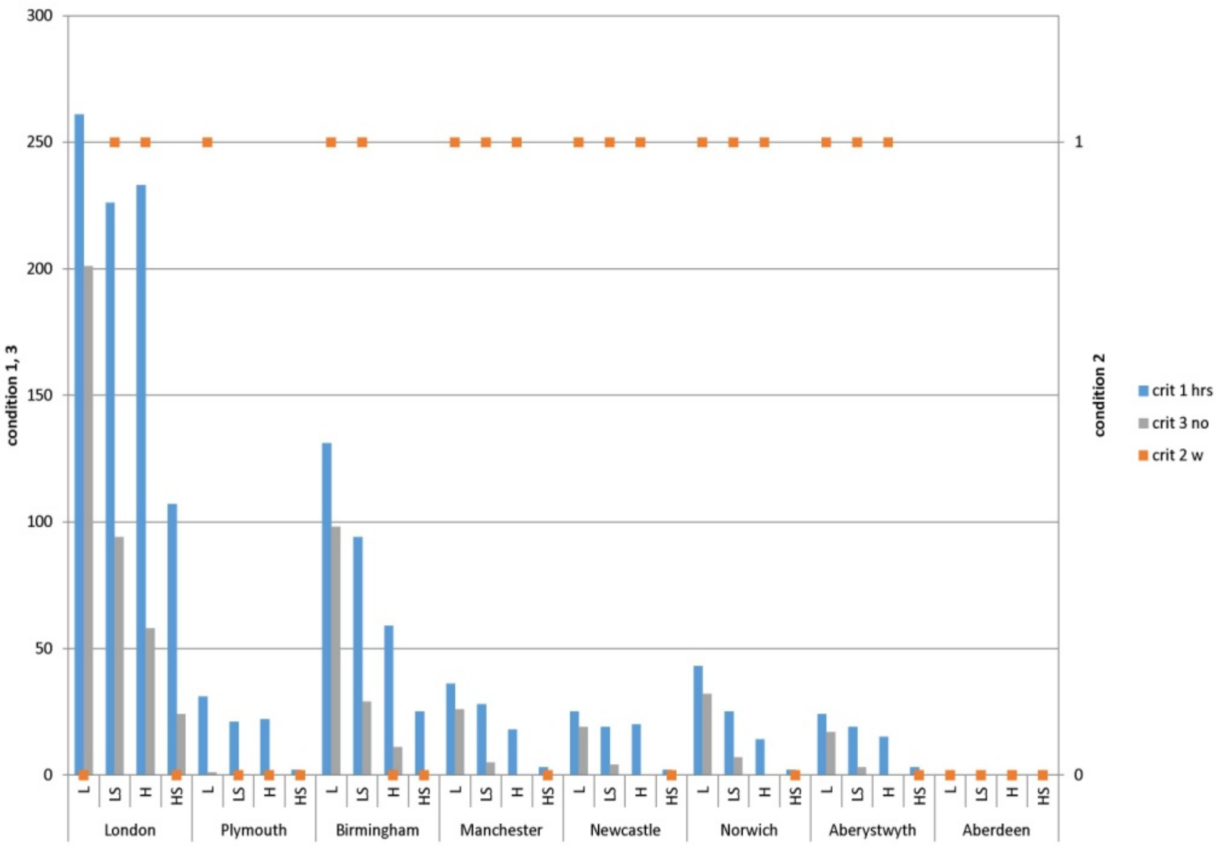

Figure 4. heat wave days and overheating events

Figure 4 shows a large variation in the amount of heat wave days and the effects that they bring to identical models placed within different UK cities. Again London is significantly higher than the second place, i.e. Birmingham. There is a trend however on how much each mitigation measure impacts on the amount of overheating experienced. Shading on a light weight construction results in a 25% drop in the amount of overheating hours (criterion 1) and about 50% more when considering heat stress events (criterion 3). This result is similar to those of a heavyweight construction in overheating hours in criterion 1. The most effective mitigation is experienced by a heavyweight construction and shading, which results in a 60% drop in overheating. It is worth mentioning that this is significantly less than the sum of the mitigation measures which would be greater than a 90% reduction of overheating under criterion 1 experienced.

The figures quoted above are not consistent across all UK cities and are largely based on the Birmingham results. A similar trend is seen for London but in lower count instances, in Newcastle the same conclusions cannot be made. Arguably only London and Birmingham require heat wave mitigation to take place, shading alone in Birmingham brings the number of overheating hours down to a similar level than the combined shading and thermal mass levels in London. The instances of Criterion 2 are of limited value in this analysis due to the short time periods involved.

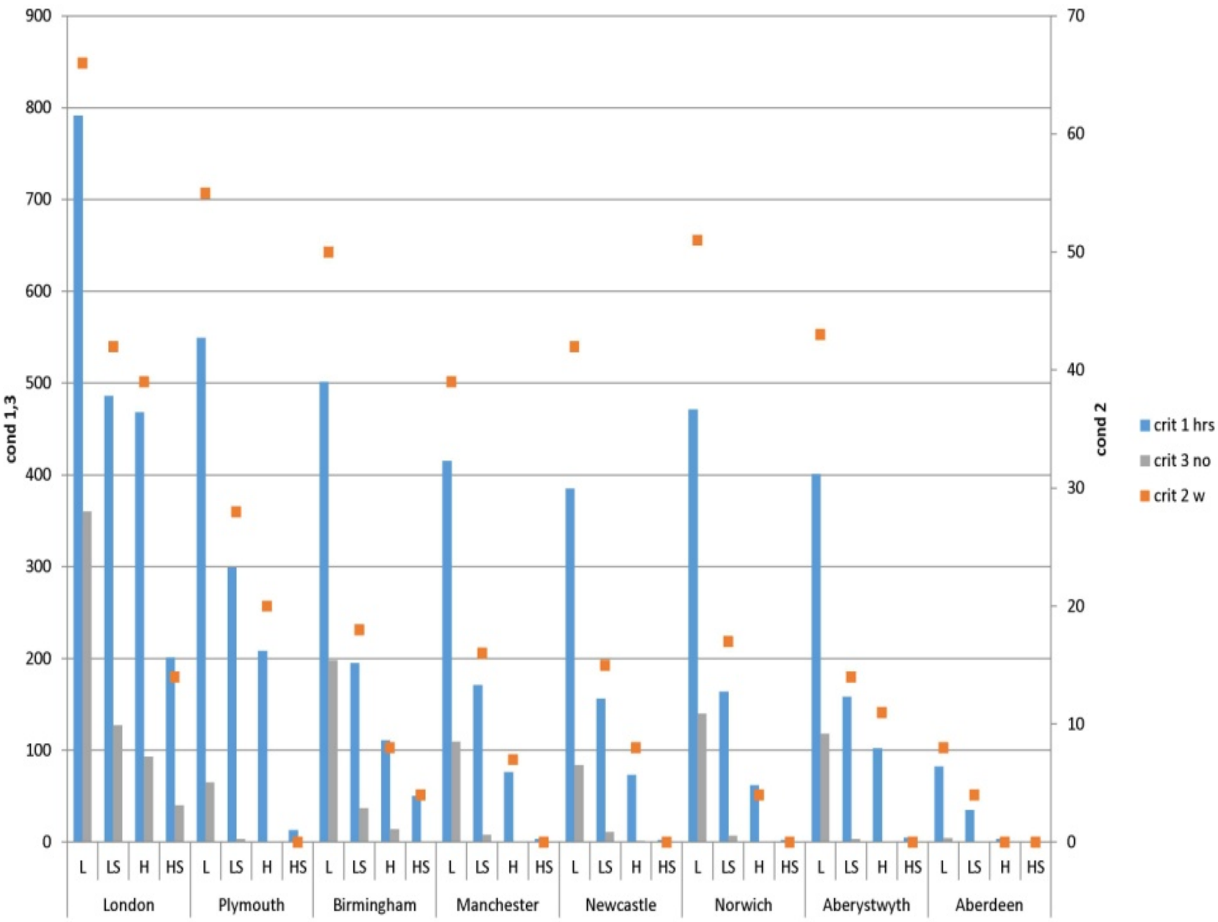

Figure 5. overheating events over the cooling season

Figure 5 shows the results over the whole cooling season as defined by TM52 for the same cities. Shading on a light weight construction results in a 60% reduction in criterion 1 overheating hours. Heavyweight construction results in 80% reduction in criterion 1 overheating hours and a combination of heavyweight and shading results in a 90% reduction in criterion 1 overheating hours. The trends for Criteria 2 and 3 show reductions with the addition of mitigation but again criterion 3 has the largest drop off and is significantly influenced by the addition of thermal mass.

The results for Plymouth and Norwich are significantly higher than those recorded from heat wave events which suggests that latitude has a higher influence over cooling season results. Uniform patterns are seen from the addition of mitigation apart from London which shows similar results for both shading on a lightweight construction and a heavyweight construction.

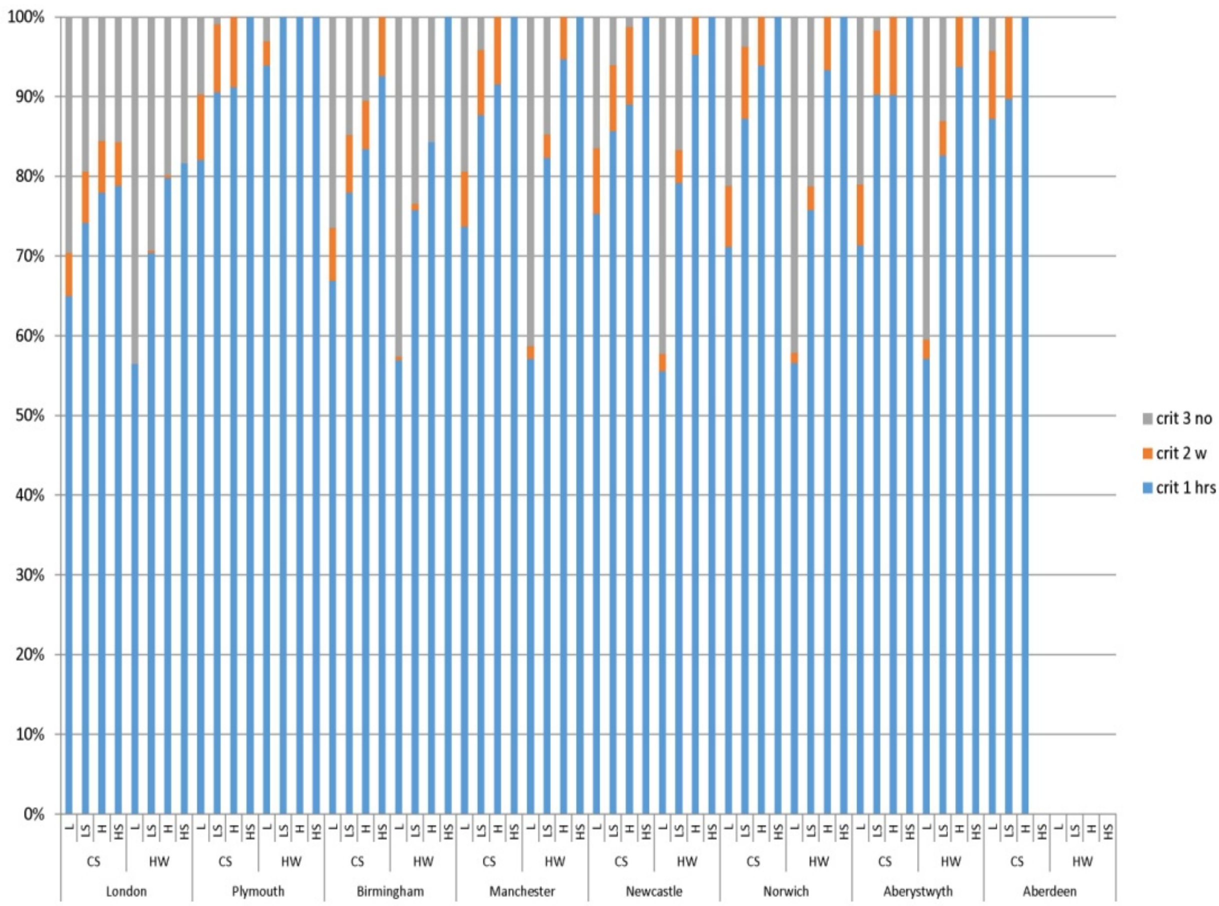

Figure 6. Proportion of TM52 criteria for both cooling season (CS) and heat wave (HW) events

Figure 6 presents all of the TM52 events combined. Although difficult to represent given the amount of models conducted Figure 6 shows that most results are dominated by the number of overheating hours (criterion 1) followed by criterion 3 and then criterion 2. With heat waves having short lasting effects, criterion 2 is not registered in most of the heat wave quantifications. As mitigation is applied the proportion of criterion 1 gets higher reinforcing previous graphs in which mitigation reduces the impact of heat stress events.

The impact of mitigation during heat wave events is more pronounced than that in a cooling season but this is largely a result of the number of instances recorded. Further trends should not be inferred by the graph which deals with proportions and not the quantification of the amount of overheating taking place.

6. Conclusions

Overall mitigation is effective in reducing the amount of overheating experienced in a modified TM52 technique. The inputs are in line with TM59 but are modified to give realistic results and not enhance them due to the additional loads imposed on the simulated rooms. Results from the heat wave and the whole cooling season should be dealt with separately as shading provides a 25% drop during heat wave events significantly lower than the up to 60% reduction during a cooling season. Thermal mass provides a 50% reduction during a heat wave compared to up to 80% during a whole cooling season. The combination of mitigation measures provides 60% reduction in heat waves rather than the 90% in a cooling season.

Thermal mass has to be planned at the start of the design process due to its structural implications in building design but shading can be placed as a retrofit option and provides significant results for south facing rooms.

In a heat wave the mechanism by which overheating occurs by the modified TM52 criteria is by criterion 1 with figures of 0 to 250 hours for UK cities in 2080. As demonstrated, criterion 2 is of limited use due to the short time periods allowing minimal quantification of daily weighted figure. Criterion 3 has a slightly lower range than condition 1 of 0 to 200 instances but when comparing back to the cooling season figures are 10 times higher than those experienced from the heat wave events.

Dealing with short term heat wave events has a similar approach to mitigating the thermal discomfort felt by occupants during a whole cooling season. The exercise has been useful in establishing the proportion heat wave effects contribute to the overall potential cooling season. The combination of thermal mass and shading provides the best mitigation against overheating. However, on a cost effective retrofit measure, solar shading provides the most cost effective mitigation solution. The qualification of results provides a method of comparison of differing periods of time although this cannot establish when overheating will occur as this requires a weighted mechanism as described in TM52. The models are internally compared and so are not influenced by the different inputs which result from TM59 approach.

7. Future implementation

The study provides a component towards a heat wave mitigation retrofit kit which could be issued in a cost effective way during heat wave events to reduce the number of heat stress and mortality events within existing buildings. To quantify the heat island effects within the weather files more real life surveys of the areas around the base weather stations whose files have been transformed is required to gain a greater level of certainty in calculating heat wave events. Further validation is required of the threshold temperatures used to define a heat wave event rather than the emergency service definition currently used in the UK. A further study is required to establish the impact of subsequent days in a heat wave period and its impact on the mitigation measures used rather than single days of heat wave effect.

A methodology is required to establish a probability from the calculations made such as first event 2035 with a one in 10 year return event to allow for future planning of these events on a risk basis.

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