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The problem of overheating in European dwellings

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Abstract
The awareness of climate change and the increasingly urgent need to reduce carbon emissions in buildings and cities is growing in parallel with concerns with the comfort of occupants due to the rising temperatures. Recent comfort theories have acknowledged the interaction between people and their surrounding environment. BS15251 and TM52 have suggested a methodology that addresses comfort and overheating in naturally ventilated buildings. However, criteria need to be easily applied, overheating should be easily quantifiable. This paper looks at the criteria from CIBSE TM 52 and discusses their applicability to a typical archetype located in a set of cities in Europe. This follows work assessing the energy performance and thermal comfort of dwellings for morphed climates for the year 2020, 2050 and 2080. However, there are a set of variables that can significantly modify the results of an overheating assessment. In particular, the occupancy profile can significantly influence criterion 1 of TM 52 because it is couched in terms of occupied hours. Likewise, criterion 2 due to its weighted calculations on a daily basis is deemed to be difficult to apply. There is a danger that simplifications are made and criterion 1 prevails as the sole criterion to apply. A clear set of profiles may minimize this deficiency. An attempt to suggest a weekly profile for criterion 2 is also discussed.

Keywords: Overheating, climate change, comfort, resilience

1 Background
1.1 Temperature rise
There is growing evidence that the global climate is changing and that this is a result of human activities. Increased levels of greenhouse gas emissions and other forms of environmental degradation such as the increase of waste in landfills and destruction of rainforests help cause global warming, acid rain, depletion of the ozone layer and increased frequency of extreme weather events. Natural resources, such as energy and water, could be at risk if no action is taken to reduce demand, adopt renewable as against finite resources, reuse and recycling of materials and recovering part of the damage already made (IPCC, 2014).

Concerted actions have been promoted to tackle the problem of global warming and as much as possible minimise man-made contributions to an aggravated scenario. In particular, there is a real need to reduce urban carbon emissions to prevent temperatures rising to unprecedented levels. The recent Climate Change summit COP21 held in Paris in December 2015 emphasised the urgent need to limit temperatures rises well below 2K - and if possible attempt to limit it to 1.5K. This is an important climate deal that commits all countries to cut emissions after the Kyoto protocol comes to an end in 2020. Another factor in the deal is the requirement for nations to assess their progress towards meeting their climate commitments and submit proposals for revision of their own defined targets (non binding) every 5 years

(COP21, 2015). This may avoid the need to strike perennial deals and is expected to minimise delays in its implementation. The need for frequent revisions will hopefully make governments and people move from simple awareness's to more tangible actions.

1.2 Green agenda

Buildings account for 40 % of total energy consumption in the European Union (EPBD, 2010). Therefore, it is imperative to reduce the use of fossil fuel energy that is contributing to green house gas emissions whilst promoting the use of renewables. Recent energy supply uncertainty (threats of blackouts) and price rises have been a drive to nearly zero carbon buildings (ZCH, 2009). Reducing heating losses, increasing energy efficiency and adopting renewable energy have been at the forefront of most EU regulations (EPBD, 2010; EED, 2012). However, an increasing use of new technologies and an interest in comfort cooling associated with global warming has counterbalanced the expected reduction of carbon emissions and in some cases has even aggravated its growth.

The Energy Performance of Buildings Directive (recast) has imposed that all new buildings should be nearly Zero Energy-Buildings from 2020 (EPBD, 2010). The directive is to be transposed to the state members which can define the parameters and the method they will use to achieve the European target of 20% reductions in energy and inherent carbon emissions, 20% increase in energy efficiency and 20% increase in the renewable sector, all by the year 2020. In the UK buildings are responsible for almost 50 per cent of the countries' carbon emissions. So ambitious plans for new dwellings to be zero carbon by 2016 have been proposed by the UK government and are aligned with the European Policy.

However, European regulations still mainly address the heating season. Emphasis on reducing heat losses by building fabric and infiltration is promoting compact buildings, lightweight, very airtight and sometimes relying on mechanical ventilation albeit with heat recovery. While these solutions are effective at minimising heating loads while providing comfortable temperatures in the cold spell, they can have an aggravating impact in the hotter periods. Consideration for passive solutions for heating and cooling need to be taken in parallel, even in mild climates. This means that buildings and cities need to become resilient to more frequent extreme weather events and to heat-waves in particular.

Design solutions for new and refurbished of buildings need to be low energy whilst envisaging the present requirements and needs without compromising the needs in the future and as much as possible contributing to sustainable buildings and cities. This grows in parallel with concerns about the comfort of the occupants and the opportunities available to restore or maintain acceptable environments. These are primary defences against the effects of climate change (Nicol *et al*., 2012; Roaf *et al*., 2015). Furthermore, low energy design becomes even more relevant in scenarios of instability in the energy supply. It is also important to take into account the needs of an ageing population and the problem of fuel poverty even in industrialised countries.

Regulations, Standards and Guidelines are good references to access and quantify the impact of changes in buildings. In Europe, EN 15251 (BSI, 2007) and its current redraft look at thermal comfort in naturally ventilated buildings using the Adaptive Comfort approach. More recently CIBSE Technical Memorandum TM52 (2013) has provided criteria by which to judge overheating risk in buildings. While more real data is still needed to validate these models, recent developments in dynamic building simulation software give an opportunity to test future scenarios.

2 Overheating in dwellings

Studies indicate that overheating is already a problem in a prototype tested across different climates in Europe (Brotas and Nicol, 2015). This is also indicated by others (Psomas *et al.*, 2016; AECOM, 2012; Mavrogianni *et al.*, 2014). There are also records which suggest that European dwellings which have been refurbished to improve the thermal performance in winter are now facing overheating problems in summer. This is also identified in new buildings designed to achieve the PassivHaus standard (Psomas *et al.*, 2016).

See Figure 1 for a representation of the energy consumption for heating and cooling for a mid-floor flat in different countries in Europe and for climate predictions of 2020, 2050 and 2080 (Brotas and Nicol, 2015). Whilst this model has high internal gains (assumed as representative of an increasing use of appliances in dwellings), this clearly highlights the predominance of cooling loads even in mild climates. This can be further exacerbated with climate change aggravated emissions scenarios and Urban Heat Island phenomena (Santamouris, 2014; Lafuente and Brotas, 2014; Kolokotroni *et al.*, 2010). Moreover, it can influence in the way passive technologies such as natural ventilation are viable options to mitigate the impact of climate change in buildings (Kolokotroni *et al.*, 2006; Santamouris and Kolokotsa, 2013; Santamouris, 2014). The rapid urbanisation of cities, the pressure associated with land cost and scarcity of space, has resulted in a more compact urban landscape with high and dense constructions and materials and less open/green spaces. All these factors can aggravate or even prevent the possibility of adopting design solutions and strategies that can be effective in avoiding or reducing the need for mechanical systems for cooling and increasing the proportion of the year during which neither heating nor cooling is required.

While dwellings have been less prone to adopting such active systems to deal with temperature rises, there is a growth in sales of air-conditioning units or energy inefficient cooling devices across Europe. Unprecedented recent heat waves particularly affecting vulnerable populations, raise awareness of the impact of overheating on people's health (WHO, 2009). Heat-waves characterized by long duration and high intensity have the highest impact on mortality (Santamouris, 2015; WHO, 2009).

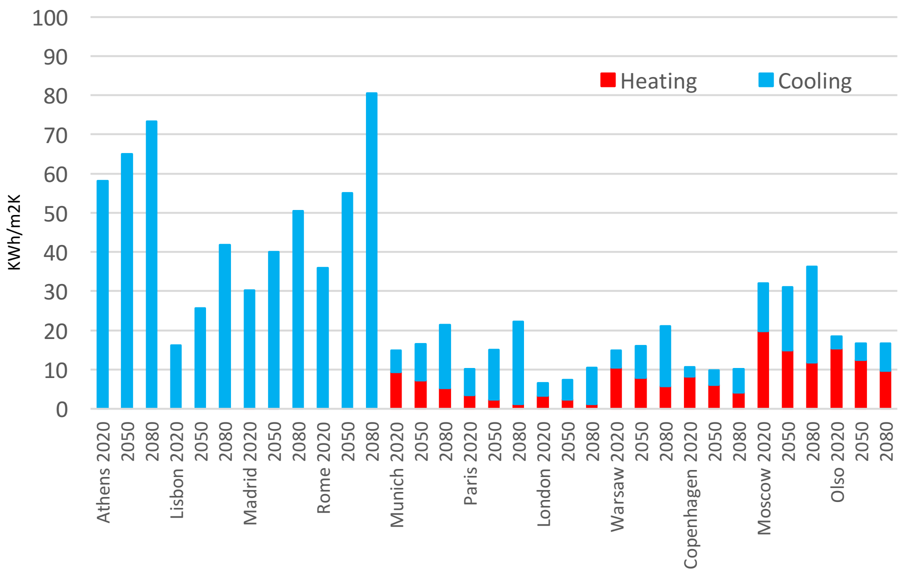

Figure 1. Heating and cooling energy consumption for a dwelling in cities in Europe at 2020, 2050 and 2080

2.1 Method to assess the likelihood of overheating

The methodology suggested in European Norm and British Standard BS 15251 (2007) to address the environmental parameters in naturally ventilated buildings is described in Nicol and Humphreys (2010). This was largely based in field studies undertaken in European cities, mostly in office buildings under the European project SCATs (McCartney and Nicol, 2002). This is acknowledged in the goals of the standard, but casts doubt on the suggestion that "The standard is [thus] applicable to the following building types: single family houses, apartment buildings, offices, educational buildings", etc. (BS 15251, 2007).

While its applicability in domestic buildings can be questioned there is little evidence of contradictory indications. Oseland's paper from 1995 comparing comfort perceptions in homes, offices and climate chambers highlighted that people are less sensitive to temperature variations in their home (Oseland, 1994). It also identifies that offering occupants control over the temperature, by allowing an interaction with the building (i.e. opening windows) or personal attitudes and behaviours (i.e. dress code) is the optimum strategy for energy efficiency and comfort in buildings. Nicol (2016) presents evidence that the limits for comfort in free-running residential buildings are typical of the general building stock but suggests the use of mechanical temperature conditioning to control temperatures is used in a different way to that assumed for non-residential buildings.

A key aspect is the establishment of indoor environmental parameters for building system design and energy performance calculations according to a set of categories of buildings that are defined based on the expectations of the occupants in relation to the space requirements. This differentiates free-running from mechanically ventilated buildings in their associated acceptable temperature ranges. In its essence this embodies the 'adaptive method' already acknowledged in International standards across the globe (BS 15251, 2007; ASHRAE, 2010), suggesting that the temperature that occupants will find uncomfortable relates to the outdoor conditions in a predictable way. The range of acceptable temperatures can be narrower in free-running buildings which have more sensitive occupants and other buildings are likewise defined by the nature of the building.

The TM52 (CIBSE, 2013) follows this research in particular addressing overheating and providing guidance to designers to identify overheating in naturally ventilated buildings. A commonly used approach to identify overheating has been to look at the proportion of occupied hours with temperatures above a certain threshold. In the UK, following guidance from the superseded CIBSE guide A (2006), overheating was likely to occur if operative temperatures exceeded above 28^{o}C for more more than 1% of occupied hours. However, this limit was set irrespective of the outside conditions. Conditions for naturally ventilated buildings were set to be more flexible than under conditioned spaces but the occupant behaviour and the local climatic conditions were not fully considered. More recently it suggests the use of the criteria proposed in TM52 (CIBSE, 2015; CIBSE, 2013: Nicol *et al.*, 2009).

The likelihood that a building will overheat can be predicted using monitoring or simulation. The simulation tool used should be able to calculate Operative Temperature, T_{op} and Running Mean Outdoor Temperature, T_{rm} to account for the adaptive model. It should be able to account for a realistic occupancy pattern of the building and the adaptive behaviour of the building occupants. However, there is clearly a lot of uncertainty especially in predictions with future climate scenarios. Other studies have highlighted problems associated with the reliability and variability of results for different climates, the morphing of future climates, the assessment of embodied energy and life cycle in the selection for solutions and materials, internal gains, occupancy profiles, operation modes and even the experience of the researcher in representing a model accurately (de Wilde *et al.*, 2008: Hacker *et al.*, 2008; Din and Brotas, 2016; Taylor *et al.*, 2014). These uncertainties are beyond the scope of this paper which presents a case study in various scenarios to discuss trends. It focuses on the pitfalls of trying to predict overheating in buildings and discusses solutions and criteria for more thorough analysis in future studies.

2.2 TM52 overheating criteria

Criteria by which the danger of overheating can be assessed or identified in free range buildings have been proposed base on previous studies in particular research undertaken for the project SCATs. A relationship between the indoor comfort temperature calculated from the data and the running mean of the outdoor temperature was derived from a broad survey of buildings in free-running mode (Nicol and Humphreys 2010):

$$T_c = 0.33T_{rm} + 18.8\ (^{o}C) \tag{1}$$

Where T_c is the predicted comfort temperature when the running mean of the outdoor temperature is T_{rm}.

According to TM52 the designer should aim at remaining within the category II limits: Normal expectation (for new buildings and renovations) with a suggested range of ± 3K (BS 15251, 2007) of the comfort temperature T_c. This limit has been updated in the EN16798 (2016) rewrite as +3K for the upper limit of the indoor operative temperature and -4K for the lower limit. Then from equation (1) it follows that the upper limit of the range is T_{max} where

$$T_{max} = 0.33\ T_{rm} + 21.8\ (^{o}C) \tag{2}$$

Simply exceeding T_{max} momentarily cannot be a reasonable justification to classify a building as overheating. Likewise, for criteria to be easily applied, overheating should be easily quantifiable.

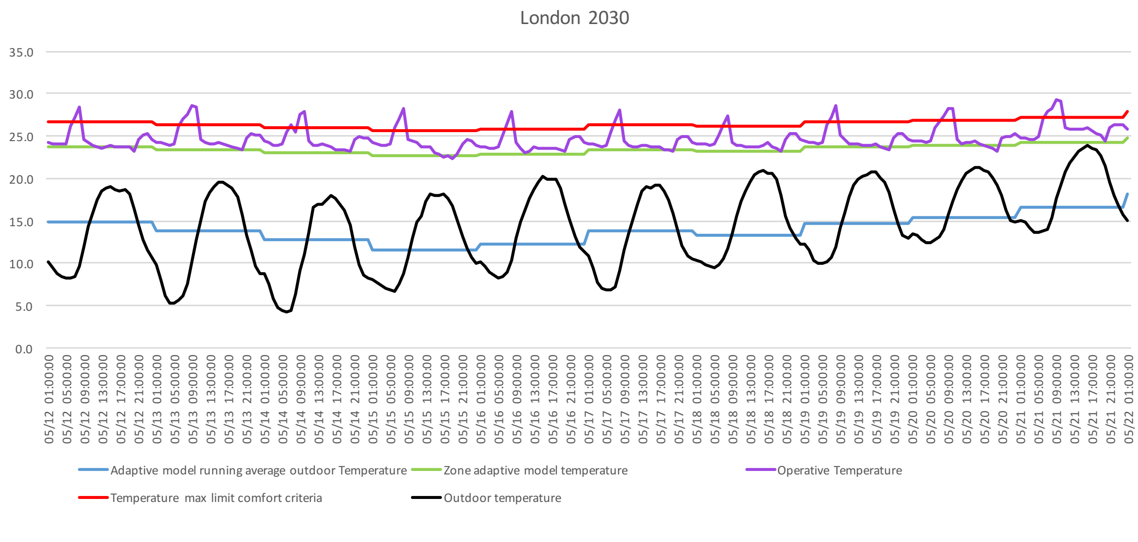

Figure 2. Temperatures to assess overheating criteria

Figure 2 presents the operative temperature of a living room (with kitchen) and the comfort temperature and threshold upper limit comfort criteria. The operative temperature is clearly above the adaptive model temperature. But are the few instances where indoor temperatures are above the threshold enough to characterize this as an overheating space?

It can be noticed as well that the amplitude of outdoor temperature is fairly regular. Yet, the adaptive running average outdoor temperature reaches its lowest of 12°C at 15/05 at 14:00 and increases by two or three degrees in a short period. As the temperature upper limit comfort criteria is dependent on this plus 3K, it may be the hysteresis temperature to pass or fail a limit of comfort.

The three criteria defined in TM52 (CIBSE, 2013) provide a proposed method by which the danger of overheating can be predicted. The method was developed by the CIBSE overheating task force and the description of the method given below is from CIBSE TM52 (CIBSE, 2013)

The first criterion sets a limit for the number of occupied hours that the operative temperature can exceed T_{max} during a typical non-heating season, assumed for the TM52 as between 1 May to 30 September. The second criterion deals with the severity of overheating within any one day, which is given in terms of temperature rise and duration and sets a daily limit for acceptability. The third criterion sets an absolute maximum acceptable temperature for a room (CIBSE, 2013)

The criteria are all defined in terms of ΔT the difference between the actual operative temperature in the room at any time (T_{op}) and T_{max} the limiting maximum acceptable temperature calculated as shown in Equation 2.

$$\Delta T = T_{op} - T_{max} \qquad (3)$$

ΔT is rounded to the nearest integer. ΔT will be negative unless the room is overheated. The three criteria for assessing whether a building is overheating are listed below.

***Criterion 1: Hours of exceedence* (*He*)**

The number of hours (*He*) during which Δ*T* is equal to or greater than one degree (K) during the period May to September inclusive shall not be more than 3 per cent of occupied hours.

If data are not available for the whole period (or if occupancy is only for a part of the period) then 3 per cent of available hours should be used.

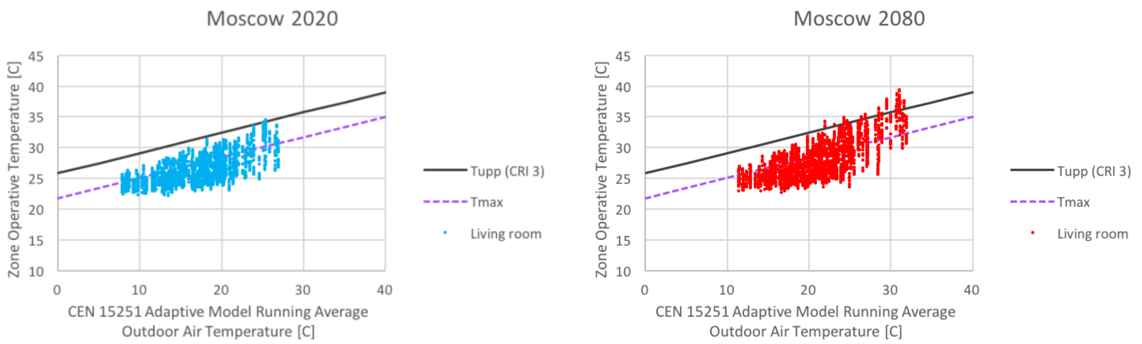

Figure 3 Likelihood of overheating with exceeding thresholds of Operative temperature versus Running Average Outdoor air temperature for Moscow in 2020 and 2080

Figure 3 shows the maximum and upper thresholds for the operative temperature with reference to the running average outdoor air temperature. This provides a visual indication of the range of temperatures achieved in a space as well as the likelihood of these exceeding the reference thresholds.

Quantifying the number of hours that the operative temperature indoors exceeds a maximum (T_{max}) and a upper limit (T_{upp}) for a certain period, can provide an indication of whether the space is likely to be overheating. The 'hours of exceedence' criterion adopts a concept similar to the percentage of hours above a certain threshold previously suggested in CIBSE Guide A. The 3% maximum limit of occupied hours is suggested in BS EN 15251 (2007).

***Criterion 2: Daily weighted exceedence* (W_e)**

To allow for the severity of overheating the weighted exceedence (W_e) shall be less than or equal to 6 in any one day where:

$$We = \sum(h_e \times w_f) = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3) \quad (4)$$

where the weighting factor $w_f = 0$ if $\Delta T \leq 0$, otherwise, $w_f = \Delta T$, and h_{ey} is the number of hours when $w_f = y$.

An indication that the temperatures of a space are above a certain value may not be enough to assess the severity of overheating. If this exceedance is not significantly higher than the limit it may not be perceived as discomfort, as adaptive mechanisms may take place. However, if this exceedance is significant or for a period longer than a few hours it becomes problematic.

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

To set an absolute maximum value for the indoor operative temperature (T_{upp}) the value of ΔT shall not exceed 4 K.

$$(T_{upp} \leq T_{max} + 4) \quad (5)$$

The threshold or upper limit temperature is fairly self-explanatory and sets a limit beyond which normal adaptive actions will be insufficient to restore personal comfort and the vast majority of occupants will complain of being 'too hot'. This criterion covers the extremes of hot weather conditions and future climate scenarios (CIBSE, 2013).

2.3 Uncertainty factors influencing the criteria

The TM52 memorandum suggests an applicability across Europe. The data on which the adaptive standard developed were mainly conducted in offices throughout Europe. While it may be argued that the diversity of latitudes and climates across Europe may require a similar variety of periods of assessment, the five hottest months will give a reasonable indication of the likelihood of overheating in local buildings.

A second aspect that seems relevant in the criteria is the method used to account for occupied hours. It is reasonable to expect that overheating in buildings is a problem when it occurs in occupied periods. Conversely, temperatures on the other end of the spectrum (cold weather) can affect occupants and cause significant degradation to the building i.e. interstitial condensation, mould growth, eventually compromising its integrity or cause aggravated health problems to the occupants.

It is therefore interesting to discuss the impact the occupancy pattern has on the assessment of the overheating criteria. Buildings that are occupied during daytime hours are more likely to fail the criteria as the assessment considers the hotter period of the day. Likewise, assuming a permanent occupation of 24hrs all year will spread and may dilute the impact of a high percentage of overheating hours that occur during day. It is not unheard of that consultants may extend the occupancy profile for an hour or so to avoid a building being classified as overheating. Another situation that frequently occurs in domestic buildings is that they are unoccupied during day hours at least in week days. Adopting a predominantly night profile plus weekends can potentially reduce significantly the risk of failing criteria. Thinking about possible future trends towards working from home and of the ageing of populations, it is reasonable to assume a permanent occupation on domestic buildings with more than a single occupancy. This was the adopted option on this study.

According to the above British Standard 15251 and Technical Memorandum, the criteria to assess overheating are applicable when the running mean outdoor air temperature is between 10 and 30^{o}C during the period of assessment. The 30^{o}C limit is related to the conditions which applied in the data on which the standard is based. In mild climates, it is unlikely that the running mean outdoor temperature will exceed the upper threshold. Conversely, the lower range defines the need to heat not cool. However, with global warming, temperatures may well begin to reach this limit in many European cities. Questions that may arise when assessing overheating include:

How to quantify the hours when the T_{rm} is above 30^{o}C? Is this assumed as a threshold where active systems for cooling will need to be put in place? Then how it this moderated? Or shall it be assumed as an immediate overheating hour? This can easily be adopted for Criteria 1 and 3. But how to quantify the range of exceedance for Criterion 2? As the limit of 6 degree-hours? or shall it be accounted in terms of ΔT? Results from the case study presented will give an insight into this discussion.

3 Model

The present case study is located in the city of London. A base case model of a mid-storey flat (67m^2) is adopted based on statistics of housing stock broken down by type and in line with a rapid urbanisation of cities.

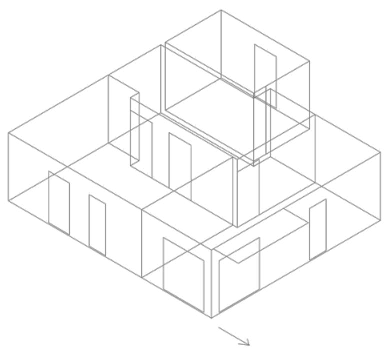

Figure 4 Wireframe model thermal zones

The main façade is oriented east and the secondary faces north (see Figure 4). The thermal characteristics of the envelope comply with the Minimum Fabric Energy Efficient Standard (FEES) for 2016 from UK Part L1A regulations: external walls (U-value 0.18 W/m^{2}K), party walls (0 W/m^{2}K), semi-exposed wall (0.17 W/m^{2}K) and windows (U-value 1.4 W/m^{2}K and G-value 0.63). The layout and further details from the building envelope, ventilation and systems specifications are defined after Zero Carbon Homes (ZCH, 2009; ZCH, 2012). The occupancy profile is defined for 3 people in a domestic environment, assuming one person is permanently at home. This agrees with future trends towards home-working and an ageing population that may stay indoors most of the time. However, the assessment of overheating will account in scenario "occupancy day" a period of occupancy between 8am and 6pm for 7 days in the week between 1st May and 30th September. This selected period is to account for the hotter period of the day. Scenario "all" will assess overheating on a 24hr occupancy for 7 days a week. Please note this assessment is independent of the actual occupancy of the space. This is acknowledged as a conservative value for the periods the space is unoccupied, and will therefore attract lower internal gains.

The assessment of 24hours dissipates the impact of peak periods over longer hours. Conversely, it should be kept in mind that high density materials commonly found in cities can delay the impact of UHI in buildings for a couple of hours. So early evening hours may experience higher temperatures.

The initial base case assumes an infiltration specified as 0.3 ac/h as design level. A single side night cooling ventilation (driven by wind and stack effect) influence individual rooms is activated when indoor temperature is above 24°C and the delta differential to the outdoor is less than 2°C. An internal blind shading device with 0.1 visible and solar transmittance is activated when the indoor temperature rises above 24°C and solar radiation incident on the window is above 120 W/m^2. The thermal characteristics of the base model and adopted strategies are already fairly sustainable and energy efficient to a very good standard.

The second combination of strategies is a result of previous studies, to be published elsewhere, and in line with the findings by other authors. Shading, ventilation and thermal mass are identified as first line strategies to mitigate temperature rises in dwellings (Gupta and Gregg, 2012; Mavrogianni *et al,* 2014; AECOM, 2012). The second model assumes a cross ventilation defined as a multizone airflow network driven by wind direction, speed, orientation of the opening and temperature difference between indoors and outdoors. As before the night cooling ventilation is activated when the indoor temperature is above 24°C and the delta differential to the outdoor is less than 2°C. While this replicates an automatic system it can also represent to some point an occupant opening the windows when he feels hot and leaving them open until the space cools down to a perceived comfort.

This model also integrates an external shading device with similar transmittance characteristics and operating profile as the previous internal device. The selection of solutions was based on realistic proposals that would not significantly interfere with land scarcity and high real state value in cities or could eventually be adopted in a refurbishment. No restrictions from listed areas were considered in the adoption of external devices. However, the window opening is reduced to 30% to account for security measures or opening just a fraction of the window.

A third model assumes internal gains being significantly reduced. Data for operation and power for lighting (low energy) and equipment (energy efficient) was retrieved from the Guide A from CIBSE (2015). Internal gains are assumed for this model to be relatively low in line with the idea that appliances must become more efficient in the near future, if we are to achieve the CO_2 reduction targets for mitigating climate change (EED, 2012).

All the dynamic simulations were made with EnergyPlus software, version 8.4.0. The criteria for the assessment of overheating were compiled in a spreadsheet. Weather data was retrieved from the climate generator predictor from The University of Southampton (CCWorldWeatherGen, 2013).

4 Results and Discussion

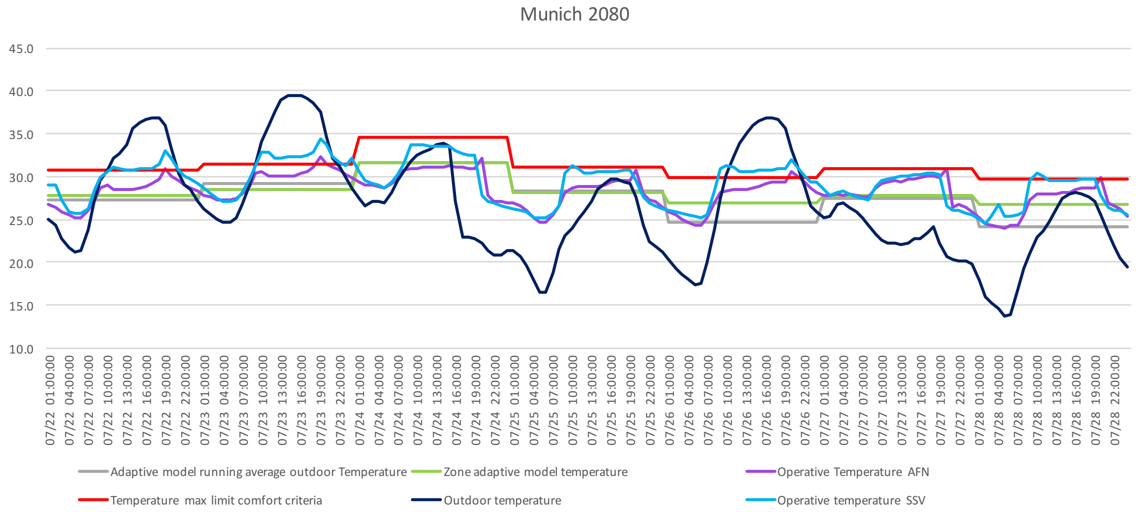

Figure 5. Extreme week for Munich for the year 2080. Operative temperature for model with cross ventilation (AFN) and single side ventilation (SSV).

Figure 5 shows the operative temperature for model 1 assuming single side ventilation and an internal blind (SSV) and for model 2 optimised with cross ventilation and an external shutter. In terms of the TM52 criteria both models pass the criteria (see Table 1 for details).

Table 1. TM 52 Criteria for both models under analysis

	C1 %	C2 days	C3 occurrences
SSV	**2**	**0**	**5**
AFN	**0**	**0**	**0**

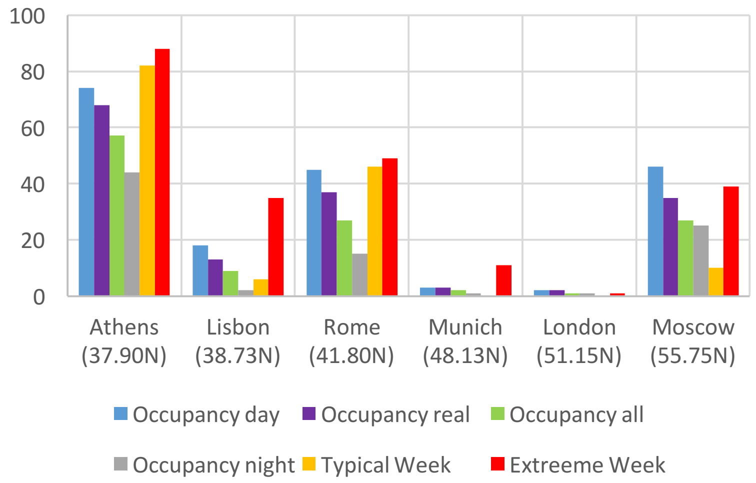

Figure 6. Criterion 1 (3% above threshold) for different locations and reference periods with the 2080 climate

Figure 6 presents results for criterion 1 for varying occupancy profiles, from 9am til 6pm, the real occupancy of that particular room (8 till 11pm), a permanent 24 hour schedule and a night occupancy form 0 till 8am and 7pm till midnight. A Typical Summer Week (nearest average temperature for summer) and an Extreme Summer Week (nearest maximum temperature for summer) have been retrieved from the EnergyPLus weather files. They vary for the different climates presented (see Table 2 and Table 3 for an indication of the dates). Results presented for these week periods are based on a 24 hours' permanent occupancy (all). Longer hours of occupancy result in a reduction of the percentage of overheating. Moscow presents a reduced reduction between the permanent and the night occupancy. This may be a result of a lower daily amplitude or the impact of UHI.

Some weather files present very unusual peak temperature periods. These may compromise compliance with criteria 2 and 3. While the adoption of the adaptive running outdoor average temperature may attenuate this phenomena, there is an ongoing discussion about whether criterion 2 instead of a 6 degree-hours per day should not be extended to a week period. This would avoid failing criteria on certain climates by a very small margin. This could eventually be twisted by selecting the start week day of the simulation and planning for these peaks to fall on an unoccupied period (i.e. weekend for services). A week assessment would prevent these omissions and attenuate its impact for the criteria.

The typical and extreme weeks do not seem to present a consistent variation amongst the climates here presented, though there are some similarities of the week criterion assessment between Athens and Rome and between Lisbon, Munich and Moscow. The results from adopting a particular week in the summer period for the criterion 2 do not seem to be very consistent. Preliminary data not presented here further recognises this difficulty.

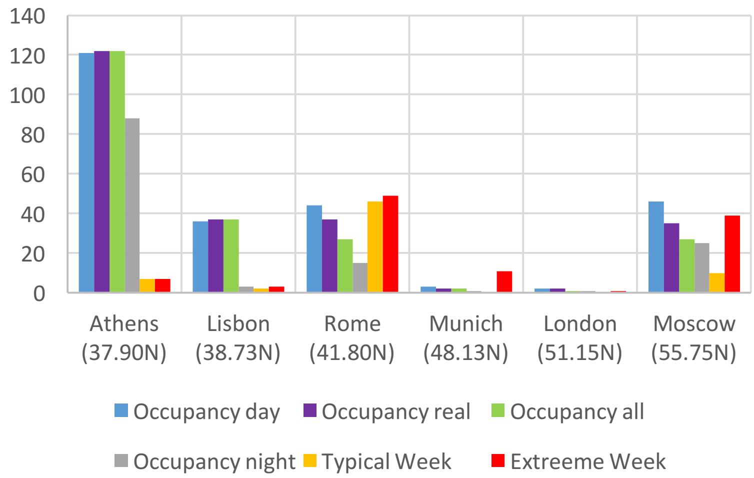

Figure 7. TM52 Criterion 2, number of days the daily temperature-weighted exceedance W_e is greater than 6 degree-hour

Figure 7 presents the Daily weighted exceedence W_e for different occupancies at various locations in Europe with a climate file morphing 2080. Figure 8 presents a similar method but accounting for a week period of exceedance above 21 degree-hours. This approach is meant to simplify the collation of data and will account for possible periods that fall outside a typical or extreme reference week. A comparison between the two periods suggests that the daily period will be more sensitive to small variations. While a method should be relatively easy to apply (hence 24 hours during 7 days) its accuracy is also important as it may compromise sensitivity analysis between different variables. This is important as the TM52 criteria can be a good mechanism to evaluate the impact of different design solutions to minimise overheating.

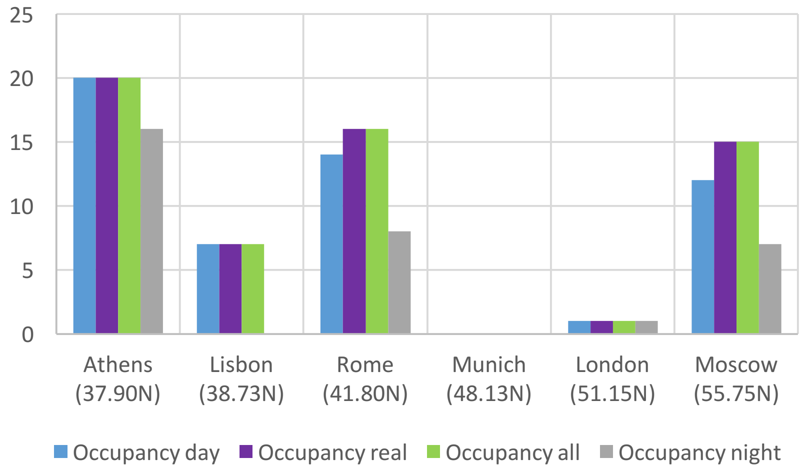

Figure 8. Overheating criterion over a week period when it exceeds 21 degree-hours, for different locations across Europe for the climate 2080.

Figure 9 presents results for criterion 3 for different occupancy profiles. As before caution should be taken to define the occupancy profile as it may strongly influence the validity of results obtained. Unlike the first two criteria the third criterion tends to exaggerate the effect of extended hours of occupancy. This defines a maximum temperature limit threshold, beyond which adaptive opportunities may not be sufficient to restore comfort.

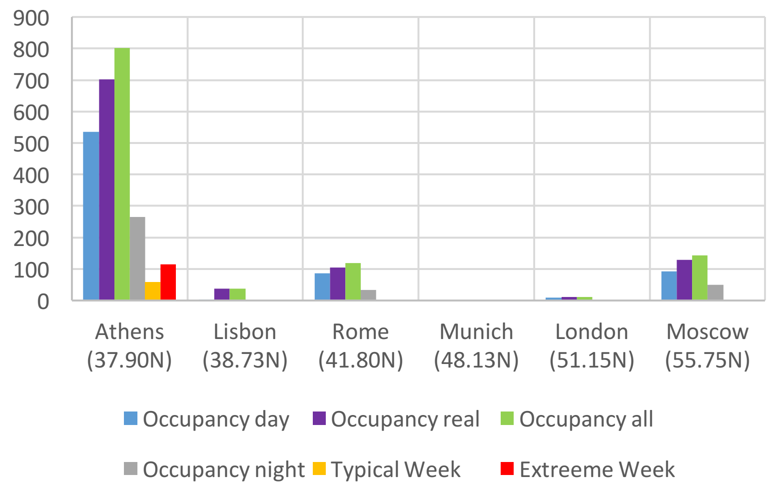

Figure 9. Criterion 3 for different occupancy solutions at different city locations across Europe for the climate of 2080.

Tables 2 and 3 show the combination of the three TM52 criteria to a prototype simulated at various cities on Europe. While this particular model has been selected as representative of an overheating scenario in most of the climates, it also raises questions whether the three criteria would need to be checked. Likewise, can a building failing two criteria out of three for a small number of instances (Lisbon and London) be at risk of overheating? The representation of possible alternative approaches in terms of length of the period under assessment is the start of an ongoing project. It still needs a significant compilation of different simulation models or monitoring data to derive sensible conclusions.

Table 2. TM52 criteria for different periods for analysis in Athens, Lisbon and Rome. Highlighted in green are the TM52 criteria that passes for the day occupancy and in orange the misses.

	Athens (37.90N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	52	89	14	119
	day	44	90	16	138
	Occupancy all	34	90	16	138
	night	20	45	9	19
	Typical week (29 Jun - 5 Jul) all	51	6		8
	Extreme week (3 - 9 Aug) all	61	6		39
2050	Occupancy 9-18	63	105	18	311
	day	55	105	19	378
	Occupancy all	44	105	19	391
	night	31	70	13	80
	Typical week (29 Jun - 5 Jul) all	67	7		29
	Extreme week (3 - 9 Aug) all	73	7		86
2080	Occupancy 9-18	74	121	20	536
	day	68	122	20	703
	Occupancy all	57	122	20	802
	night	44	88	16	266
	Typical week (29 Jun - 5 Jul) all	82	7		59
	Extreme week (3 - 9 Aug) all	88	7		114

	Lisbon (38.73N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	1	1	1	8
	day	1	2	1	10
	Occupancy all	1	2	1	10
	night	0	1	0	2
	Typical week (5 - 11 Aug) all	0	0		0
	Extreme week (15 - 21 Jul) all	0	0		0
2050	Occupancy 9-18	1	2	1	8
	day	1	2	1	10
	Occupancy all	1	2	1	10
	night	0	1	0	2
	Typical week (5 - 11 Aug) all	1	0		0
	Extreme week (15 - 21 Jul) all	1	0		0
2080	Occupancy 9-18	18	36	7	4
	day	13	37	7	37
	Occupancy all	9	37	7	37
	night	2	3	0	1
	Typical week (5 - 11 Aug) all	6	2		0
	Extreme week (15 - 21 Jul) all	35	3		0

	Rome (41.80N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	13	21	4	11
	day	10	23	4	11
	Occupancy all	7	23	4	11
	night	4	6	2	0
	Typical week (24-30 Aug) all	0	0		0
	Extreme week (27 Jul - 2 Aug) all	2	0		0
2050	Occupancy 9-18	23	38	7	41
	day	18	41	7	45
	Occupancy all	13	41	7	45
	night	7	12	2	4
	Typical week (24-30 Aug) all	12	2		0
	Extreme week (27 Jul - 2 Aug) all	27	4		0
2080	Occupancy 9-18	45	75	14	86
	day	37	78	16	104
	Occupancy all	27	78	16	119
	night	15	27	8	33
	Typical week (24-30 Aug) all	46	6		0
	Extreme week (27 Jul - 2 Aug) all	49	7		0

Table 3. TM52 criteria for different periods for analysis in Munich, London and Moscow. Highlighted in green are the TM52 criteria that passes for the day occupancy and in orange the misses.

	Munich (48.13N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	2	2	0	0
	day	2	2	0	0
	Occupancy all	1	2	0	0
	night	0	0	0	0
	Typical week (15 - 21 Jul) all	0	0		0
	Extreme week (22 - 28 Jul) all	1	0		0
2050	Occupancy 9-18	2	2	0	0
	day	2	2	0	0
	Occupancy all	1	2	0	0
	night	0	0	0	0
	Typical week (15 - 21 Jul) all	0	0		0
	Extreme week (22 - 28 Jul) all	2	0		0
2080	Occupancy 9-18	3	4	0	0
	day	2	5	0	0
	Occupancy all	2	5	0	0
	night	1	0	0	0
	Typical week (15 - 21 Jul) all	0	0		0
	Extreme week (22 - 28 Jul) all	11	0		0

	London (51.15N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	2	3		
	day	2	3	1	3
	Occupancy all	1	3	1	3
	night	1	3		
	Typical week (29 Jun - 5 Jul) all	0	0		0
	Extreme week (17 - 23 Aug) All	0	0		0
2050	Occupancy 9-18	2	3	1	9
	day	2	3	1	9
	Occupancy all	1	3	1	9
	night	1	2	1	0
	Typical week (29 Jun - 5 Jul) all	0	0		0
	Extreme week (17 - 23 Aug) All	0	0		0
2080	Occupancy 9-18	2	3	1	10
	day	2	3	1	12
	Occupancy all	1	3	1	12
	night	1	2	1	2
	Typical week (29 Jun - 5 Jul) all	0	0		0
	Extreme week (17 - 23 Aug) All	1	0		0

	Moscow (55.75N)	C1	C2		C3
		%	days (6 degree-hr)	weeks (21 degree-hr)	occurrences
2020	Occupancy 9-18	26	45	8	3
	day	21	47	10	3
	Occupancy all	15	47	10	3
	night	7	8	2	0
	Typical week (6 - 12 Jul) all	11	2		0
	Extreme week (29 Jun - 5 Jul) all	26	3		0
2050	Occupancy 9-18	29	48	10	17
	day	25	52	13	22
	Occupancy all	18	52	13	22
	night	10	14	4	5
	Typical week (6 - 12 Jul) all	8	1		0
	Extreme week (29 Jun - 5 Jul) all	34	4		0
2080	Occupancy 9-18	46	62	12	93
	day	35	70	15	130
	Occupancy all	27	70	15	143
	night	25	38	7	50
	Typical week (6 - 12 Jul) all	10	1		0
	Extreme week (29 Jun - 5 Jul) all	39	5		1

5 Conclusions

Climate change is creating more and more potentially devastating and unpredictable events at a global scale. A green agenda is a required global trend towards sustainability, addressing resilience to combat climate change (COP21, 2015). In particular overheating is already a problem in some locations and building types across Europe. It is therefore relevant to clearly identify a common methodology to assess its magnitude. The application of TM52 criteria, based on the adaptive comfort method and the relationship of the operative temperature to the running outdoor mean temperature seems to be a step forward on previous suggestions of a fix threshold.

This paper raised some problems associated with the application in practice with using simulations tools as the assumptions to be made.

An important aspect is associated with the increase in global temperatures and the limit of applicability of the criteria to 30°C. Similar approaches have been developed in the USA by de Dear and Brager (2002) and in hot climates like Pakistan by Nicol *et al.* (1999) and suggest a broader range of applicable temperatures. Except for extreme heat wave events, most of the climates in Europe do not reach such high temperatures, so the limiting thresholds may be safe. Nevertheless, climatic file predictions up to the year 2080 are already affected. As they are being used more and more when assessing long term impacts of solutions, it is timely to address these questions. Adaptive opportunities and climatic adaptation may mean that Europeans may well behave as other populations from hotter climates already do. This will then mean the formula suggested at BS 15251 and TM52 may be extended without significant rises in discomfort.

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