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Research into overheating in new homes

Phase 1 report

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Introduction

In response to the recommendations in the Committee on Climate Change (CCC) Progress Report to Parliament in 2015, the government has commissioned research to better understand the overheating risk in new dwellings in England and the options to help industry and others mitigate this risk. This report presents the results from Phase 1 of the research which aims to gain a better understanding of the type of properties most at risk of overheating. It uses dynamic thermal modelling to assess this risk for different dwelling types and locations throughout England.

Definition of overheating

Overheating occurs when the local indoor thermal environment presents conditions in excess of those acceptable for human thermal comfort or those that may adversely affect human health.

The Chartered Institution of Building Services Engineers (CIBSE) TM59 definition of overheating has been used for this project. It specifically assesses the overheating risk for homes and has been developed through industry consultation. TM59 sets out two compliance criteria which both need to be met.

- Criterion A applies to living rooms, kitchens and bedrooms. It requires that the internal temperature does not exceed a defined comfort temperature by 1 °C or more for more than 3% of occupied hours over the summer period (1 May to 30 September).
- Criterion B applies to bedrooms only and requires that the internal temperature between 10 pm and 7 am shall not exceed 26 °C for more than 1% of annual hours.

The dwelling is deemed to have an acceptable risk of overheating if both TM59 criteria are met. If one or both of the criteria are not met, the implication is that mitigation measures are necessary to reduce the risk of overheating. Homes only need to overheat for part of the time for these criteria to not be met; to exceed Criterion B, a bedroom would only need to exceed 26 °C overnight for 33 hours per year which could occur during a week-long heat wave. The extent of the mitigation measures necessary depends on how much the criteria have been exceeded, taking into account the scale of the elevated temperatures and the duration and time-of-day that they occur.

Two key assumptions significantly affect the risk of overheating:

- To assess the risk of overheating over the lifetime of new homes, the analysis of internal temperatures should be based on predicted future weather data; this project has used 2020s Design Summer Year (DSY1) weather data. This weather data is intended to be representative of the time period 2011-2040 based on certain climate change assumptions. It aims to represent a moderately warm summer (i.e. warmer than a typical year) with around a 1-in-7 chance of temperatures being equal or hotter than a typical year.

- The overheating risk has been assessed based on ‘Category I buildings’, i.e. it assumes that the dwellings have a high probability of being occupied by vulnerable and fragile persons. This results in Criterion A being more stringent; the upper threshold for comfort temperature is reduced by 1 °C.

Overall, this approach results in a fairly rigorous test of overheating. It considers warmer than typical summers and looks to protect more vulnerable members of the population. More extreme weather events, such as heat waves, with temperatures significantly exceeding the running average offer limited opportunity to adapt to higher temperatures and would be expected to have a greater adverse impact on comfort and health.

Modelling overheating risk

The risk of overheating has been predicted using Dynamic Thermal Simulation modelling. IES Virtual Environment version 2016 has been used which is a commercially available software package.

Eight dwelling typologies have been assessed across five locations in England. The typologies consist of a mix of flats and houses and take account of building form, building size, aspect (e.g. single/ dual aspects), ventilation strategy, individual/communal heating system and construction type. All dwelling designs meet Building Regulations Part L 2013. The five locations comprise inner-city London, outer London, Southampton, Nottingham and Leeds.

Overheating risk by location and dwelling typologies

The modelling indicates that all dwelling typologies (including both houses and flats) in all five locations fail to comply with the TM59 overheating criteria. However, the degree to which dwellings exceed the criteria varies significantly by typology and location. The analysis identifies the greatest risk of overheating in London locations and generally a higher risk for flats compared to houses.

- Houses in the Midlands and northern locations only exceeded the allowable percentage of hours by around 10%. It is expected that relatively simple and low-cost measures could be effective in reducing the overheating risk.
- In the worst affected properties (flats in London), the allowable percentage of hours was exceeded by up to 600%. It is expected that more extensive mitigation would be needed. The core modelling assumed that occupants were able to open their windows; external factors (such as security, noise or air pollution) may limit the opening of windows and sensitivity analysis suggests that this would further significantly increase the likelihood of the building overheating.

Phase 2 of the project will examine the benefits and costs of applying alternative mitigation strategies to different building typologies and locations to reduce their risk to an acceptable level. This includes both modifications of the building design and occupant behaviour to reduce the risk of overheating. For example, sensitivity analysis undertaken as part of Phase 1 has shown the importance of the design and usage of window openings on internal temperatures.

Modelling assumptions

It would be valuable to further validate some of the modelling assumptions (e.g. occupant behaviour) and the modelled outputs, as well as the overheating criteria themselves. The analysis highlights that the overheating assessment is sensitive to the input parameters and assumptions, as well as the choice of modelling software itself.

However, government needs to consider carefully whether to delay action until the results of such research. Given the government's ambition for one and a half million new homes to be built by 2022 and without a significant consideration of mitigation strategies now, it may well result in more expensive and energy and carbon intensive retrofit measures later (e.g. occupants subsequently retrofitting air conditioning rather than developers designing in passive measures now). It is therefore recommended as beneficial to implement Phase 2 of this project now.

Early analysis for Phase 2

Phase 2 will comprise a cost benefit analysis of alternative strategies to reduce the risk of overheating and the production of guidance for use by house builders. Some early analysis has been undertaken in Phase 1 to aid work in Phase 2.

- A review of existing approaches to addressing overheating risk in existing housing in England and in other European countries has been undertaken to inform the mitigation strategies for Phase 2.
- A literature review has been undertaken on the likely uptake of residential air conditioning in the absence of alternative mitigation strategies. It is proposed to build from a model developed within the US based on uptake rates observed across a number of cities, with sensitivity analysis to allow for cultural and behavioural differences for residential air conditioning between the US and the UK.
- Overheating can have direct effects on health, safety, comfort and productivity. It can also disrupt sleep with consequential effects on health, safety, comfort and productivity. A literature review on sleep disruption has identified how its impact could be accounted for in the Phase 2 cost benefit analysis.
- It is proposed that Phase 2 includes the production of simple guidance for developers on mitigation strategies and their cost-effectiveness. This is based on feedback from developers and others within the project's Research Group. This could include a decision-making tool based on the dwelling type, location and other characteristics, and appropriate approaches to mitigation can be recommended depending on what decision path is followed. Given the number of potential variables that affect overheating, this may be best focussed on standardised designs for more common situations. Whether or not the government decides to regulate for overheating in new homes, this guidance should be useful to developers who are keen to mitigate the risk of overheating. Complementary guidance may be usefully disseminated to occupants to best adjust their behaviour to remain comfortable during summer months.

1. Introduction

The Ministry of Housing, Communities and Local Government (MHCLG) has commissioned AECOM and its consortium partners, London School Hygiene and Tropical Medicine and Studio Partington, to undertake research into overheating of new homes in England. The purpose of this research is to gain a better understanding of the types of properties most at risk of overheating, undertake a cost benefit analysis of mitigating measures to limit this risk, and to develop relevant tools and/or guidance for housebuilders. This report presents the results from Phase 1 of the project.

1.1 Research context

Overheating occurs when the local indoor thermal environment presents conditions in excess of those acceptable for human thermal comfort or those that may adversely affect human health. It can be limited to certain spaces within a home, or may affect all spaces. In addition, it can be intermittent, or sustained over time. The thermal environment includes air and radiant temperature, humidity and air movement, all considered in the context of reasonable or likely levels of clothing and physical activity.

Overheating in buildings has been highlighted as a key risk for the health and productivity of people and businesses in the UK. It is estimated that there are about 2,000 heat-related deaths each year in England and Wales. This number is expected to triple to over 7,000 by the mid-century, as a result of climate change (CCC 2015). At present there is no formal government or industry-wide guidance on how to identify the risk of overheating or how to apply effective preventative measures.

For new homes, the current criteria within Part L of the Building Regulations[1], which includes making provision to deal only with excessive solar gain in summer months, is not sufficient in mitigating these risks as Part L is concerned with the impact on energy performance rather than thermal comfort or health.

Although there is a range of measures known to mitigate overheating risk, there is a knowledge gap in terms of the assessment of which properties are most likely to overheat, and what combination of measures will be most cost effective in terms of mitigation.

The government's stated ambition is for one and a half million new homes to be built by 2022[2]. There is concern that most of these properties will be inhabited by 2080 when temperatures are projected to have risen by a range of 1.2 - 8.1 degrees in England under the medium emissions scenario[3] and, if no action is taken, by 2050, an estimated 7,000 people will die prematurely from heat-related causes (though not

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[1] https://www.gov.uk/government/publications/conservation-of-fuel-and-power-approved-document-l

[2] https://www.conservatives.com/manifesto; accessed August 2017

[3] http://ukclimateprojections.metoffice.gov.uk/23673?emission=medium; accessed August 2017

all in homes) annually (CCC 2015). The number of people using their home as their main place of work (1.5 million in Great Britain in 2014) or base is increasing. Overheating is likely to have an impact on productivity (Baglee et al 2012). Additionally, increases in the use of residential air conditioning will undermine Climate Change Act aspirations to reduce emissions and potentially put more strain on the electricity network.

The Committee on Climate Change Progress Report to Parliament in 2015 (CCC 2015) recommended that MHCLG should evaluate the latest evidence on overheating in new homes and subsequently introduce a new required standard or regulation to cover this by 2017. In response the government stated it would carry out research to understand better which new homes are at risk of overheating and the options to help industry and others address the risks. This research is being undertaken to meet this obligation.

1.2 Project scope

The research is broken down into two phases.

- **Phase 1** of the project focusses on assessing the risk of overheating in England. This includes defining what is meant by overheating and modelling the risk of overheating for different dwelling types and locations throughout England.
- **Phase 2** of the research focuses on the cost benefit analysis of alternative mitigation measures, including assessing relative benefits of mitigation packages on health and home-worker productivity. This analysis (along with the stakeholder engagement in Phase 1) will inform the development of a supporting tool/ guidance for housebuilders to assess overheating risk and to implement the most cost effective solutions.

A project Research Group consisting of representatives from academia, housebuilding industry, and industry bodies was set up at the commencement of the project to provide expert review and guidance to the project team. Two meetings were held with the Research Group in Phase 1; the first to discuss the overheating definition and the modelling methodology and the second to review key findings from Phase 1.

1.3 Report structure

This report sets out the findings from Phase 1 of the project, which covered the following tasks:

- Section 2 presents a working definition of overheating drawing on previous work by professional bodies and academia;
- Section 3.1 outlines the strengths and weaknesses of alternative methodologies/ tools to model the risk of overheating in new homes in line with agreed definition, and proposes the most relevant methodology/ tool to be adopted for this project;
- Section 3.2 summarises the modelling assumptions and inputs, including the representative dwelling locations, typologies and characteristics;

- Section 4 presents the results of the overheating modelling, including highlighting factors that are most likely to impact overheating risk;
- Section 5 summarises the findings from a high level literature review to understand the impact of overheating on home-worker productivity and on the uptake of mechanical cooling, which will be useful for the Phase 2 cost benefit analysis;
- Section 6 discusses the findings from the literature review on overheating risk in older housing in England and experience from other EU countries in addressing overheating risk in the residential sector.
- Section 7 identifies and initially evaluates options for a supporting tool/ method/ guidance to help housebuilders assess and mitigate overheating risk in new homes.

2. Definition of overheating

The project needed to agree early a clear quantitative definition of overheating, primarily for the purpose of modelling overheating risk in summer. It was agreed that there is benefit in adopting a definition that has been established independently through a wider industry consultation process. The project team reviewed existing definitions of overheating, in particular the definitions proposed by CIBSE both in TM52[4] and TM59[5], and consulted with several expert members of the Research Group. The Zero Carbon Hub material on overheating risk in residential buildings[6] was also reviewed though it does not add substantively to the CIBSE definitions.

2.1 The CIBSE definition of overheating

The TM52 overheating criteria

According to TM52, CIBSE recommends that new buildings should conform to Category II in BS EN 15251, which sets a maximum acceptable temperature (T_{max}) of 3°C above the comfort temperature for buildings in free-running mode (i.e. without use of mechanical cooling). For such buildings, T_{max} can be calculated as $T_{max} = 0.33\ T_{rm} + 21.8$ where T_{rm} is the running mean of the outdoor temperature.

TM52 sets out three criteria for overheating on the basis that they “provide a robust yet balanced assessment of the risk of overheating of buildings in the UK”. The criteria are all defined in terms of ΔT, the difference (rounded to the nearest °C) between operative temperature (T_{op}) in the room at any given time and T_{max} ($\Delta T = T_{op} - T_{max}$). A room or building that fails any two of the three criteria is classed as overheating.

Criterion 1 - Hours of exceedance: The number of hours (He) during which ΔT is greater than or equal to 1°C during the occupied hours of a typical non-heating season (1 May to 30 September) shall not be more than 3% 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% of available hours should be used.

Criterion 2 - Daily weighted exceedance: This criterion represents the severity of overheating within any one day, as a function of temperature rise and its duration, which can be as important as its frequency. Weighted exceedance (We) shall be ≤ 6 in any day, where:

$$\begin{aligned} W_e &= (\textstyle\sum he) \times WF \\ &= (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3) \end{aligned}$$

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[4] CIBSE Technical Memorandum TM52: 2013. The limits of thermal comfort: avoiding overheating in European buildings.

[5] CIBSE TM59:2017. Design methodology for the assessment of overheating risk in homes.

[6] Evidence Review Reports produced by Zero Carbon Hub. Available on ZCH website (accessed August 2017).

where the weighting factor WF = 0 if $\Delta T \leq 0$, otherwise WF = ΔT, and h_{ey} is the time (h) during which WF = y

The equation does not continue beyond h_{e3} because Criterion 3 would not be met if WF > 3. It is worth noting that it assumes no benefit from any cool periods among the hot periods.

Criterion 3 - Upper limit temperature (T_{upp}): The value of ΔT shall not exceed 4°C. This criterion, the absolute maximum daily temperature, covers the extremes of hot weather conditions and future climate scenarios.

TM52 (and therefore the above criteria) apply to buildings in general but are based largely on evidence from the occupants of non-domestic buildings.

The TM59 overheating criteria for homes

TM59 seeks to apply the same principles to dwellings. The CIBSE Domestic Overheating Task Force (DOTF) thought it necessary to keep the assessment as simple as possible while keeping it robust and relevant to homes. Criterion 1 in TM52 was seen to be the most important and so that was kept and made compulsory. In order to ensure sleeping comfort was considered, an additional criterion for bedrooms during the night was added.

For homes that are "predominantly naturally ventilated", compliance is based on meeting both of the following two criteria.

Criterion (a) for living rooms, kitchen and bedrooms - Hours of exceedance: This criterion is the same as TM52 Criterion 1. The assumed (summer) occupied hours for this criterion are 3672 for bedrooms (24 hours per day) and 1989 for living rooms (13 hours per day). So 3% of occupied summer hours is a total of 60 hours for living rooms and 110 hours for bedrooms.

Criterion (b) for bedrooms only, to guarantee comfort during the sleeping hours: T_{op} in the bedroom from 10 p.m. to 7 a.m. cannot exceed 26°C for more than 1% of hours over a full year. This means that 33 or more hours per year above 26°C during the period 10 p.m. to 7 a.m. will be recorded as a fail.

This research focusses on overheating in summer, and therefore "predominantly naturally ventilated" should be taken to mean not using mechanical cooling in summer. The dwelling may be heated in the winter months, and the adaptive method would then not be applicable in winter.

For homes that are predominantly mechanically ventilated (MEV) (i.e. with significantly limited opportunity to open windows), TM59 applies a single criterion that T_{op} should not exceed 26˚C for more than 3% of occupied hours in any occupied rooms. The criterion for mechanically ventilated homes is however not relevant to this project because most homes in England are not of this type. A significant minority of new homes (particularly flats) have mechanical ventilation but typically they would also have openable windows.

2.2 Proposed definition and application to homes

In discussion with MHCLG, it was agreed that the TM59 definition for naturally ventilated homes is to be used for the purpose of this research. It offers an approach to assessing overheating risk specifically for homes that has been developed through industry consultation.

The theoretical basis of the CIBSE criteria comes largely from research in non-domestic buildings (and therefore mainly the working-age population). It is important to understand how it might reasonably apply to homes. Adaptive opportunity should be greater in a person's own home than in non-domestic buildings because:

- more options will generally be available, particularly in relation to clothing and the timing and location of activities undertaken;
- householders should have greater familiarity with how their building performs, hence better opportunity to manage it to avoid overheating; and
- they do not generally need 'permission' to act, for example to open windows, draw curtains or sit outside in the shade.

If anything, therefore, applying the adaptive approach to homes should confer greater protection of thermal comfort in homes than in non-domestic buildings. Of course, this would however depend on the actual ability to adapt by knowing what to do and having the mental and physical ability to act. It cannot be assumed that every householder knows the best strategy (e.g. few people are likely to close windows during a very hot day rather than opening them). And the most vulnerable people can face physical or mental limitations (e.g. to open windows, get a cold drink or go outside). The ability to adapt may be further restricted as overheating takes effect on a person.

It is acknowledged that the TM59 definition has its limitations. For instance, Criterion (b) depends on limited evidence in relation to sleep disturbance. The criterion value of 26°C is based on a small sample (21 volunteers) in a pilot study conducted in 1975. At 26°C the volunteers were still using a sheet covering and (presumably) nightclothes; subject to cultural or personal barriers, further adaptation would therefore be possible. The TM59 definition also does not include any specific criteria on upper temperature limit similar to Criterion 3 in TM52. A short duration of very high temperatures could be as bad from a health perspective as a longer duration of temperatures that just exceed the other criterion levels. Criterion 3 may also be relevant to avoiding a situation in which adaptive opportunities are not sufficient.

2.2.1 Vulnerable persons

TM52 states that if a building is to be "occupied by very sensitive and fragile persons", the more demanding Category I occupancy can be applied, which sets T_{max} at 1°C less when calculating ΔT. The meaning of "very sensitive and fragile persons" is not expanded and the allowance of 1°C is not explained. TM59 also notes possible adjustments for homes with vulnerable occupants, including assumption of Category I occupancy.

Therefore, designing for vulnerable occupants is an option if using the CIBSE definitions. This could mean, for example, seeking to protect the health of the very young, seriously ill or fragile elderly. This project addresses the national future stock, which includes homes that are, or could be, occupied by vulnerable people. One of the questions considered was therefore whether to apply Type I occupancy in the modelling and/or make other adjustments to address the issue of vulnerable occupants.

The two options considered were:

- Apply the CIBSE criteria but with parameters that reflect the limited adaptive capability of the most vulnerable people. This approach should offer greater protection to the most vulnerable but at extra cost (possibly unnecessary cost) for others. It could also potentially increase unnecessary provision of mechanical cooling, with consequent implications for climate change.
- Apply the CIBSE criteria but with parameters that reflect the general population. Use the findings to guide the design of new homes and devise other ways of protecting them.

This is a matter of policy more than technical application. It was agreed with MHCLG that Category I occupancy is to be used in assessing overheating.

An additional consideration is that those with mobility problems may repurpose living rooms as bedrooms to avoid stairs or moving between rooms on the same level. So sleeping may not occur only in rooms designed to be bedrooms. This was not considered in the modelling but may emerge as an issue for impact assessment in Phase 2.

2.2.2 Shift workers

Most people sleep at night and this is reflected in Draft TM59 Method's Criterion (b). However, some people sleep during the day and therefore the effects of overheating on sleep are not limited to night-time conditions. This is most relevant to shift workers and it seems fair to offer them the same protection as everyone else, especially as some are working in life-critical occupations such as emergency services, health care and long-distance drivers.

Applying the bedroom criterion to daytime conditions in all homes would almost certainly create a much more extensive regulatory requirement. A counter-argument is that shift workers are, by definition, of working age (and possibly healthier than average) and maybe they will have found their own way of managing sleeping in warmer conditions. The project team does not have evidence relating to this counter-argument but recognise that people who live in warm countries do sleep and so there must be some doubt around placing clear limits on the required temperature range.

It was agreed with the Research Group not to account for shift workers in the Phase 1 modelling.

2.3 Other characteristics of overheating

Adopting the CIBSE TM59 definition does not answer all questions about the definition of overheating. In particular, TM52 notes that overheating depends not only on temperature (and its variability) but also on other indoor environmental factors (humidity and air movement). Therefore, there needs to be consideration on how to deal with environmental parameters other than T_{op} when modelling thermal conditions and/or the outcomes of the thermal conditions for occupants.

2.3.1 Indoor temperature variations

TM52 notes that radiant asymmetry can increase discomfort above what would be predicted by T_{op} alone. This is difficult to reflect in modelling because it depends critically on where a person is located in the room or building. Therefore it is probably necessary (and reasonable) to assume that people will usually keep away from uncomfortable locations or increase shading (e.g. by drawing curtains). On this basis, it was agreed with the Research Group that radiant asymmetry need not be taken into account in this work.[7]

Comfort is also affected not just by the current temperature but also by time-variation in temperature over short periods (up to a few hours). Again this is not reflected in the CIBSE definitions. In air-conditioned non-domestic buildings the variation can be rapid, annoying and difficult to deal with by changing clothing or location. This should not apply in most homes, where variation should be slower except when it arises from the occupants moving around the home. Hence it was agreed with the Research Group not to account for short-term time-variation in temperature.

One issue that needed to be considered was how to represent outdoor temperature when calculating ΔT according to the adaptive model, although the decision is expected to have relatively little effect on outcomes. BS EN 15251 uses the exponentially weighted running mean, which gives more weight to recent days. ANSI/ASHRAE Standard 55 uses a simple monthly mean but the current version also permits the use of a running mean. The exponentially weighted running mean is the recommended option to represent outdoor temperature. This is the approach taken for calculating overheating risk in the IES Virtual Environment modelling software.

2.3.2 Indoor humidity

Relative humidity (RH) affects thermal comfort, particularly at elevated temperatures, but the available models to predict temperature in dwellings do not include humidity as an output. TM52 states (based on evidence from “warm countries”) that the effect of high RH is equivalent to an increase in temperature of only around 1°C.

[7] TM52 states that it is “necessary that … the effects of solar radiation through windows are fully and realistically accounted for” but it is assumed that this relates to estimation of heat gains rather than the comfort effects of radiant asymmetry.

TM52 also notes that “The increased discomfort that is commonly experienced at high humidity may not be entirely experienced as feeling hotter”. This is important because humidity affects perceptions of ‘stuffiness’ and odour, and the mechanisms of thermoregulation can themselves be perceived as discomfort because they entail sweating, wet skin, ‘stickiness’, moist clothing and red skin. Shedding clothing can also cause psychological discomfort, thus limiting adaptation. This could differ between warm climates and the UK so humidity could have a greater effect on comfort (not just thermal comfort) than suggested in TM52.

Balancing this possibility, the sweating response to overheating is reduced in older people. Therefore, the more vulnerable people may be less affected by RH, especially when fully clothed, because they already have little benefit from evaporative heat loss. Also, in bed – even under a light cover – RH close to the skin will generally be high regardless of ambient levels.

The CIBSE definitions of overheating do not explicitly make allowance for RH. However, the adaptive method is based on surveys in the real world and this would include any effect of humidity (although mainly in relation to non-domestic buildings). On this basis, it was agreed with the Research Group not to make separate allowance for the relatively small thermal effect of RH. If Category I occupancy is assumed, resulting in a 1°C correction, it was agreed probably excessive to apply a further, say 1°C, correction for RH.

2.3.3 Indoor air movement

Air movement has a cooling effect at the temperatures generally encountered in the UK although it can have an adverse effect as air temperature approaches body temperature. To calculate T_{op} the CIBSE TM59 Method states that air velocity must be set at 0.1 ms^{-1} “where the software provides this option unless there is a ceiling fan or other means of reliably generating air movement. Elevated air velocity assumptions must be justified in the compliance report”.

The implication is that the modelling can include ceiling fans as a means of mitigation and the air velocity set accordingly. It should also be possible to assume higher air movement as a result of using other types of fan or opening windows. This is important because 0.5 ms^{-1} or more can be achieved with a fan, which TM52 shows as being equivalent to a temperature reduction of around 2°C. While T_{op} is affected by air velocity, it does not entirely account for its positive effects on comfort (e.g. via evaporative cooling) or any negative effect of draughts.

Ceiling fans are usually not currently provided in homes, and free-standing fans are not part of building design. It was agreed that it is not appropriate to include ceiling fans in the initial modelling. They are more relevant to evaluation of possible mitigation measures.

3. Assessing overheating risk

3.1 Methods and tools to model thermal performance

Phase 1 of this research project includes understanding the risk of overheating in new dwellings in England, based on quantitative computer modelling. Modelling will further be used in Phase 2 to assess the combination of measures that will be most cost effective in mitigating the risk taking into consideration dwelling design and operation. The modelling methodology therefore needs to take into account the full project requirements covering both Phases 1 and 2. It needs to be capable of adequately differentiating overheating risks between dwelling types and characteristics, locations, and occupancy characteristics. The methodology also needs to produce results in a form consistent both with the TM59 definition of overheating and the evaluations needed to inform the health and productivity assessments in Phase 2.

A brief summary of the assessment of alternative modelling methodologies is given below. Further details are provided in Appendix A.

1. Standard Assessment Procedure (SAP) – Appendix P: This supplements the building regulations carbon compliance process and provides an assessment of the risk of overheating in dwellings. However, the methodology is relatively simplistic. It is not suitable for assessing the overheating risk against TM 59 criteria; it calculates only mean monthly external temperatures whereas at least hourly calculations are required. Also, the overheating calculation in SAP is only undertaken for June to August whereas TM59 requires a whole year's assessment.

2. CIBSE Admittance method: There are various software packages that use the CIBSE or ASHRAE admittance methodologies to predict cooling loads for sizing plant (i.e. the CIBSE Admittance and ASHRAE Radiant Time Series methods). This method is designed to work with steady periodic inputs (i.e. cyclical design day profiles) and is not suited to using realistic annual-hourly weather data time series.

3. Dynamic Thermal Modelling (DTM) i.e. IES Virtual Environment (IES-VE), EDSL-TAS, EnergyPlus: These models are designed to work with hourly weather data and are able to model the impact of varying internal and external gains. IES-VE and TAS are the two main simulation packages used in the UK, and although both will satisfy various simple calibration tests (e.g. BS EN 13792, 15255, and 15265), their underlying methods for calculating the dynamic heat transfer through the building fabric are fundamentally different (i.e. IES-VE uses 'finite differences', while TAS uses 'response factors'). Similarly, the method used to model solar gain through glazing systems is slightly different.

4. Computational Fluid Dynamics (CFD): CFD is more suited to looking at detailed air movement and temperature distribution for a specific zone, typically using a set of fixed/steady-state boundary conditions. In general, CFD software poorly models solar gains through glazing systems and is a very inefficient tool for modelling multiple spaces simultaneously. Overall, this type of analysis is considered impractical for modelling transient analysis on the scale required.

For the purpose of this research project and in order to deliver robust assessments of the risk of overheating in homes, Dynamic Thermal Modelling (DTM) was selected as the most appropriate methodology.

As the most widely used building simulation package in the UK, IES-VE (2016 version) was used for this research.

Section 4.3 discusses the findings from the comparative modelling of overheating risk carried out by CIBSE using the three modelling software[8].

3.2 Modelling assumptions

The sub-sections below outline the dwelling locations, typologies and characteristics modelled to represent typical new building homes in England for the core analysis. Further sensitivity analysis was carried out to understand the impact of specific variables. All dwellings modelled meet Part L 2013 and the SAP overheating criterion.

3.2.1 Dwelling locations and typologies

Five locations (and associated weather data) were tested within England to understand potential geographical variations in overheating risk.

a. London weather centre (LWC) for inner city southern location (and accounting for heat island effect)
b. London Heathrow (LHR) for suburban southern location
c. Nottingham for mid-England climate
d. Leeds for northern England climate
e. Southampton for coastal and southern England climate

The dwelling typologies are shown in Table 1. The dwelling designs modelled are as supplied by Crest Nicholson for houses and Studio Partington for the apartments.

The dwellings typologies consist of a mix of flats and houses and are defined based on dwelling size/ number of bedrooms, whether single/ dual aspect, ventilation strategy, heating system (individual/communal) and construction type, which are then overlaid with dwelling location. The individual/ communal heating system variable is intended to capture the impact of heat losses from communal heat distribution pipework on overheating risk in flats. Flat typologies in inner London location were assumed to only have communal heating in line with GLA (Greater London Authority) policy. For the relatively lower density sub-urban London Heathrow location, both individual and communal heating options have been modelled.

Houses were modelled with traditional masonry construction. Flat typologies were modelled with two construction types: high rise construction with steel frame and

[8] Unpublished CIBSE report dated 10/08/2016

rainscreen cladding, and mid-rise construction with concrete frame and lightweight block infill.

The flat typologies were assumed to be mechanically or naturally ventilated depending on location to enable compliance with Part L 2013.

Table 1: Modelled dwelling typologies

Type	Dwelling form	Size*	Aspects	Ventilation strategy	Heating system	Construction type	Location (Weather file)
1.	Apartment	1b2p (1 bed, 2 people)	Single	Nat. Vent	Individual	Mid-rise High-rise	Nottingham Leeds
1b.				MEV	Individual		LHR Southampton
1c.				MEV	Communal		LWC
2.	Apartment	2b4p	Single	Nat. Vent	Individual	Mid-rise High-rise	Nottingham Leeds
2b.				MEV	Individual		LHR Southampton
3.	Apartment	2b4p	Single	Nat. Vent	Communal	Mid-rise High-rise	Nottingham Leeds
3b.				MEV	Communal		LHR Southampton
3c.				MEV	Communal		LWC
4.	Apartment	2b4p	Dual	Nat. Vent	Individual	Mid-rise High-rise	Nottingham Leeds
4b.				MEV	Individual		LWC LHR Southampton
5.	Apartment	2b4p	Dual	Nat. Vent	Communal	Mid-rise High-rise	Nottingham Leeds
5b.				MEV	Communal		LHR Southampton
6.	Terraced house	2b4p	Dual	Nat. Vent	Individual	Masonry	All
7.	Semi-detached	3b5p	Triple	Nat. Vent	Individual	Masonry	All
8.	Detached	4b7p	Quadruple	Nat. Vent	Individual	Masonry	All

*No. of bedrooms and occupancy

3.2.2 Fabric and system specification

The modelled thermal specifications are summarised in Table 2. More detailed assumptions are tabulated in Appendix B .

For houses, the fabric U-values are based on the default fabric specifications to deliver against the minimum fabric energy efficiency target required under Part L

2013 as outlined in the National House Building Council (NHBC) Guide (2014)[9], assuming some attention to thermal bridging details. The specifications in the NHBC guide were developed as part of a wider industry engagement, and therefore are expected to be a reasonable representation of current approaches to Part L compliance. The NHBC guide does not make a distinction between specifications for mid and high-rise apartment blocks. Guidelines on the difference in specification between high and mid-rise blocks of apartments were provided by Studio Partington.

Table 2: Modelled fabric and system specification for overheating assessment

Elements	Fabric & System Specification	
	Apartments (mid-floor)	Houses
Floor area	46m² Type 1 61m2 Type 2 and 3 72m² Type 4 and 5	70m² Type 6 115m² Type 7 139m² Type 8
External Wall U-value	0.21 W/m².K	0.18 W/m².K
Ground / Exposed Floor U-value	-	0.13
Roof U-value	-	0.13
Party wall between houses	Fully filled and sealed	Fully filled and sealed or solid
Solid door U-value	1.2	1.2
Window U-value	1.3	1.3
Roof light U-value	-	1.4
Window/Roof-light g-value	0.63	0.63
Percentage of window that is frame	25%	35%
% glazed area relative to floor area	22% Type 1 28% Type 2 and 3 47% Type 4 and 5	16% Type 6 (Terrace) 14% Type 7 (Semi-detached) 16% Type 8 (Detached)
Glazing/ window type; % openable	Side hung; 90% Sliding; 90%	Side hung; 90% Top hung; 75%
Thermal Bridging Y-value (W/m².K) (avg.)	0.10	0.04
Thermal mass parameter (TMP)	Low	Low
Ventilation strategy	Natural Vent / MEV	Natural Ventilation
Design Air Permeability (m³/hm² at 50Pa)	6 (Nat Vent)/3 (Mech. Vent)	6
Heat Transfer Coefficient (W/K)	Type 1, Nat Vent – 42.9 Type 1, MEV – 39.7 Type 2 & 3, Nat Vent – 58.6 Type 2 & 3, MEV – 55.1 Type 4 & 5, Nat Vent – 92.6	Type 6 – 68.7 Type 7 – 118.6 Type 8 – 149.7

[9] NHBC Foundation, Part L 2013 – where to start: An introduction for house builders and designers – masonry construction, 2014

Elements	Fabric & System Specification		
	Apartments (mid-floor)		Houses
	Type 4 & 5, MEV – 88.1		
Space heating	Combi gas boiler	Communal	Regular gas boiler
Hot water cylinder	-		200 litres, 80mm spray foam
Lighting	100% Low Energy Lighting		100% Low Energy Lighting

3.2.3 Internal gains and occupancy schedule

The core modelling runs are based on the following parameters:

– **Occupancy, lighting and equipment gains:** These are assumed in line with TM59 guidelines. TM59 requires that bedrooms are modelled as being occupied 24 hrs a day, with relatively lower occupancy levels during the day compared to night. Living rooms and kitchens are assumed to be occupied between 9am in the morning to 10pm in the night. Equipment and lighting gains vary with occupancy and time of the day. Refer to Appendix B for more details.

  Where dwelling designs include a study, no occupancy has been assumed in this space, though allowance has been made for equipment gains equivalent to those for bedrooms.

  Maximum occupancy in a dwelling has been limited to the design occupancy.

– **Orientation and solar gains:** Living rooms in all dwelling types are assumed to face south. The impact of dwelling orientation on overheating risk is assessed further as part of the sensitivity analysis.

  No external shading or internal blinds/ curtains have been assumed as these are to be examined in Phase 2. Where architectural drawings include any overhang, such as balconies in case of flats, these have been included.

– **Heat gains in communal corridors:** Lighting gains have not been applied to communal corridors assuming good controls with movement sensors. No active summer-time ventilation has been assumed. For typologies with communal heating, heat gains from heat distribution pipework have been included. Refer to Appendix B for more details.

3.2.4 Ventilation strategy and window openings

– **Air Infiltration:** Air infiltration rates have been assumed as continuous. These have been calculated based on CIBSE Guide A empirical values for normally exposed sites (Table 4.24) based on the air permeability rates as set out in Table 2. For specific values for different dwelling typologies, refer to Appendix B . All unheated loft spaces in the houses have an assumed infiltration rate of 1.0 air change per hour (ach).

– **Whole house ventilation rate for dwellings with MEV:** Ventilation rates are in line with Building Regulations Part F minimum requirements.

– **Purge ventilation:** Purge ventilation is assumed to be through openable windows (as per dwelling design) for both naturally ventilated dwellings and those with MEV.

– **Window and door openings:** Windows, patio and balcony doors are modelled to start to open in occupied rooms when indoor operative temperature exceeds 22°C and are fully open when temperature exceeds 26°C. Similarly, window and door openings are modelled to start closing as internal temperature drop below 26°C and are fully closed when internal temperature drops below 22°C. The air changes achieved through openable windows are based on the openable area that windows can achieve as per architectural drawings and assuming no further restrictions apply (refer Table 2). Additional window and door opening profiles were modelled as part of the sensitivity analysis (refer Section 4.2), and further scenarios will be modelled in Phase 2 of the project.

  Internal doors are assumed to be open all the time, with the exception of bedroom doors which are assumed to be closed 22:00 – 9:00. Bedrooms doors are modelled with undercut in line with Part F requirements, equivalent to 1% of the door area during the night hours when shut. The external entrance door is assumed to be shut all the time.

3.2.5 Weather data

The overheating risk has been assessed for the five locations using 2020s Design Summer Year (DSY) weather file based on UKCP09 high carbon emissions scenario with 50% probability (DSY1 2020s – High emissions scenario - 50th percentile), in line with CIBSE TM59 guidance. This future weather file is representative of the time period 2011-2040.

Equivalent weather data for 2050 and 2080 as well as the two alternative design summer year weather files for the 2020s that simulate different profiles for hot spells (DSY2 and DSY3 have been used for the sensitivity analysis.

Figure 1 shows the average external temperature in the summer months for the five locations modelled for the core analysis. Figure 2 shows the variation in maximum external temperatures and wind speeds at the five locations for a week in July. These indicate that London Heathrow has the highest external temperatures of the locations modelled though these are only marginally higher than the London Weather Centre. The latter has more elevated night time temperatures in comparison, potentially due to the urban heat island effect. Nottingham sees the lowest drop in summertime temperatures of the locations modelled.

Figure 1: Average daily external dry-bulb air temperature (DSY1, 2020s)

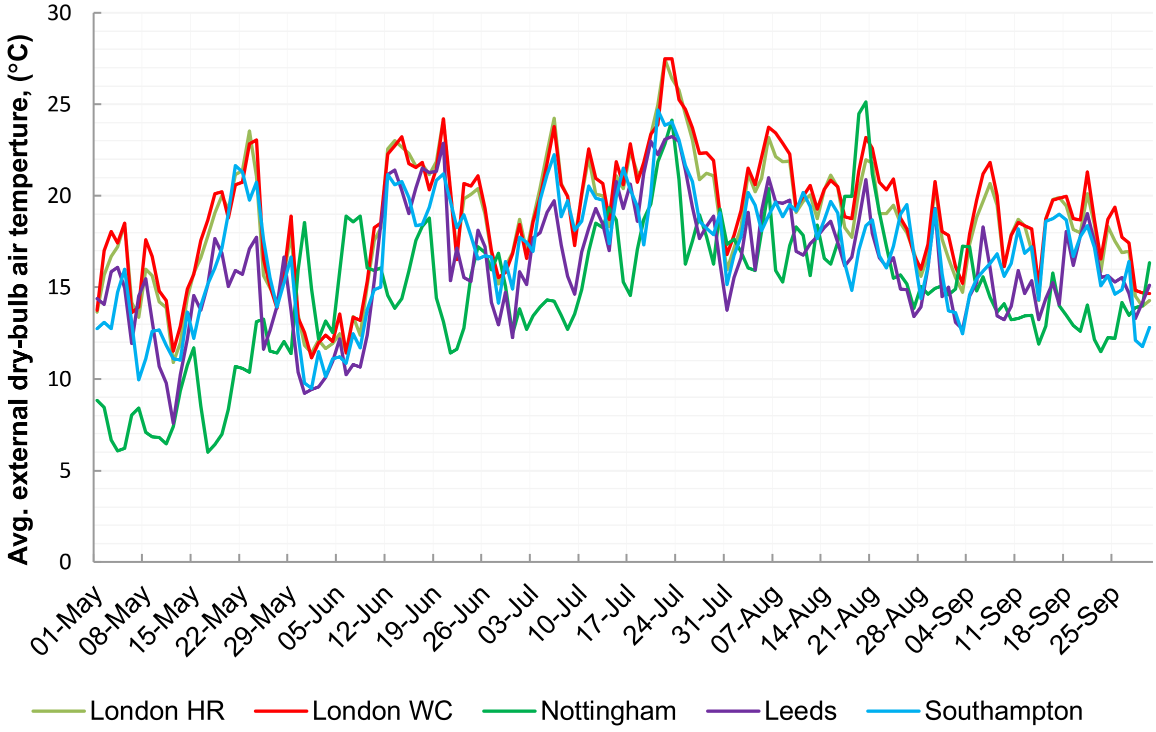
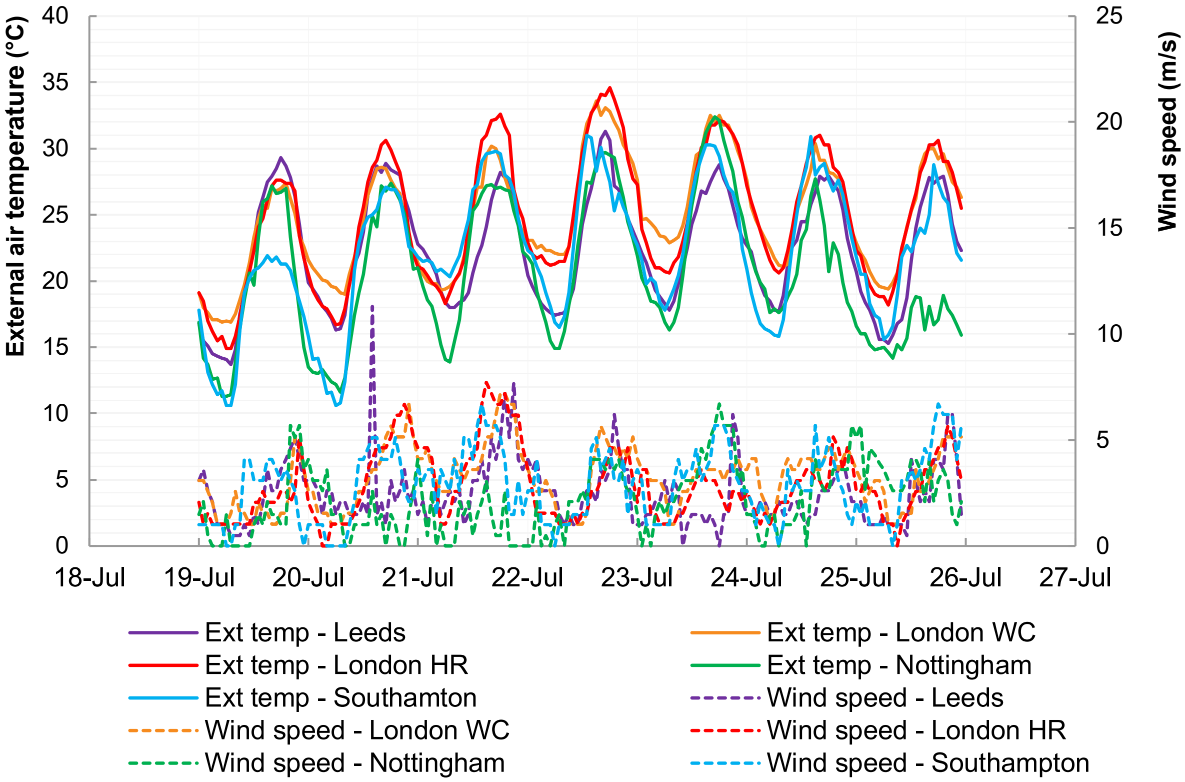


Figure 2: Hourly external air temperature and wind speed (DSY1, 2020s)



When comparing the different weather files and overheating results, it is worth noting that the design summer years (DSYs) for each location have been selected by CIBSE based on a representative summer between 1984 and 2013. This means that the base year from which the DSYs are derived is not the same across the five locations tested and they exhibit different weather profiles e.g. elevated temperatures may occur during different days during the summer months.

In addition, the selection of the DSYs is based on external temperature data (refer CIBSE TM49 for methodology), which does not take into account other variables such as solar radiation and wind speed or direction. An example of this is the difference in wind speeds between the locations for London, where the design summer years for London Weather Centre have noticeably higher wind speeds than those for Heathrow. This can have an impact, for example, on the ventilation rates modelled.

4. Modelling results

4.1 Modelling results by location and dwelling typology

This section discusses the results from the dynamic thermal simulation modelling. Figure 3 to Figure 12 show how the house and flat typologies perform against TM59 compliance criteria A and B for the five locations modelled.

- TM59 Criterion A applies to living rooms, kitchens and bedrooms. It requires that the operative temperature does not exceed the threshold comfort temperature by 1 K or more for more than 3% of occupied hours from 1 May to 30 September. In the modelling, the living rooms and kitchens are assumed to be occupied between 9am in the morning to 10pm in the night whilst the bedrooms are assumed to be occupied for 24 hours
- TM59 Criterion B applies to bedrooms and requires that the operative temperature between 10 pm and 7 am shall not exceed 26 °C for more than 1% of annual hours.

Note that the notation of “1p” and “2p” for bedrooms reflects whether they are single or double occupancy respectively. The dotted red line shows the TM59 compliance thresholds.

Table 3 provides an overview of the results. The key findings are summarised below.

- **All dwelling typologies (including both houses and flats) in all five locations fail to comply with the TM59 overheating criteria,** failing criterion A and for certain locations also criterion B.
    - For Nottingham, Leeds and Southampton locations, all houses and flats fail criterion A. For the houses it is only the living rooms that fail this criterion due to relatively higher internal and solar gains during the daytime, which in turn is a function of the occupancy levels assumed as per TM59 guidelines and the larger glazed areas in living rooms relative to bedrooms respectively. For flats, both bedrooms and living rooms fail criterion A. A key reason for greater failure in flats than houses is the larger percentage glazing in flats relative to the floor area, thereby increasing solar gains. While flats have more openable window area relative to the houses, the increase in solar gains outweighs any benefit from additional ventilation during the day. .

      All typologies in these three locations are compliant with criterion B. This is principally influenced by the occupancy and window opening assumptions which effectively results in bedroom windows, where openable, fully open at 26 °C, which is the TM59 threshold temperature. This helps cool down the bedroom below the threshold, taking advantage of the lower temperatures in the evening and overnight. The percentage of hours exceeding 26°C in bedrooms at night is far lower in flats than for houses. This is attributable to the larger percentage of openable window areas in flats, and in turn the higher ventilation rates, that cool down the internal space in the late evening and overnight.

- For the two London locations, both bedrooms and living rooms in all dwelling typologies fail criterion A. Bedrooms in houses fail criterion B as well though bedrooms in flats comply. As discussed above, bedrooms in flats have more effective window openable area relative to houses, and therefore achieve higher ventilation rates.

- **There is significant variation in results by location** when comparing the number of hours dwellings in these locations tend to overheat. London Heathrow is the worst performing, with the house typologies exceeding the compliance threshold by more than three times, while Nottingham performs relatively better than the other locations tested with the house typologies failing only marginally. This reflects the variation in weather data as shown in Figure 1 and Figure 2.
- **There is no significant difference in results for the two different flat construction types**, i.e. mid-rise concrete frame with lightweight block infill, and high-rise steel frame with rainscreen cladding. This is because in both construction types the thermal mass is assumed to be decoupled from the internal space.

Table 3: Summary of modelling results - Compliance with TM59 overheating criteria

Location	Dwelling type	TM59 Criterion A Living rooms	TM59 Criterion A Bedrooms	Criterion B
Nottingham	Houses	✗	✓	✓
	Flats	✗	✗	✓
London Heathrow	Houses	✗	✗	✗
	Flats	✗	✗	✓
London Weather Centre	Houses	✗	✗	✗
	Flats	✗	✗	✓
Leeds	Houses	✗	✓	✓
	Flats	✗	✗	✓
Southampton	Houses	✗	✓	✓
	Flats	✗	✗	✓

Figure 3: Nottingham – Modelling results for house typologies

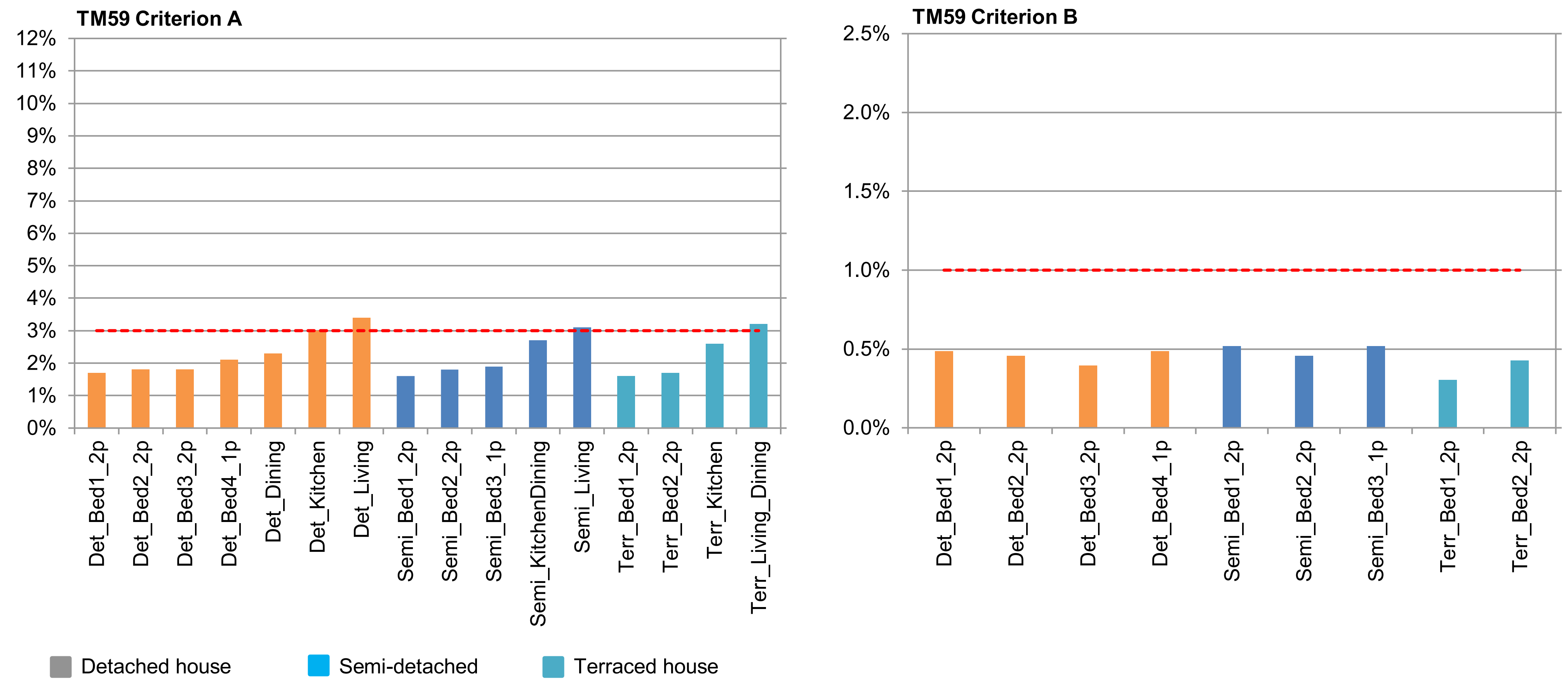


Figure 4: Nottingham – Modelling results for flat typologies

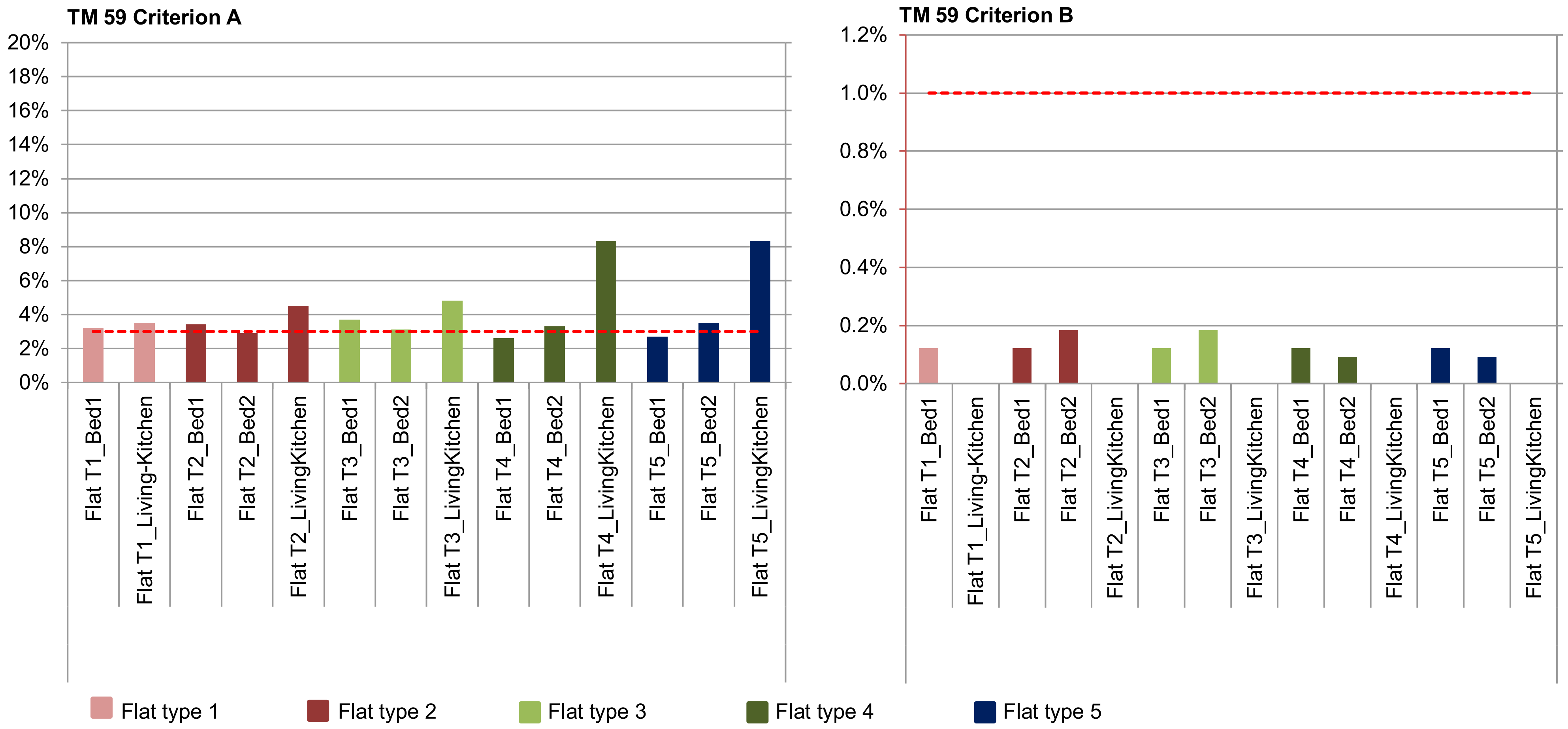


Figure 5: London Heathrow – Modelling results for house typologies

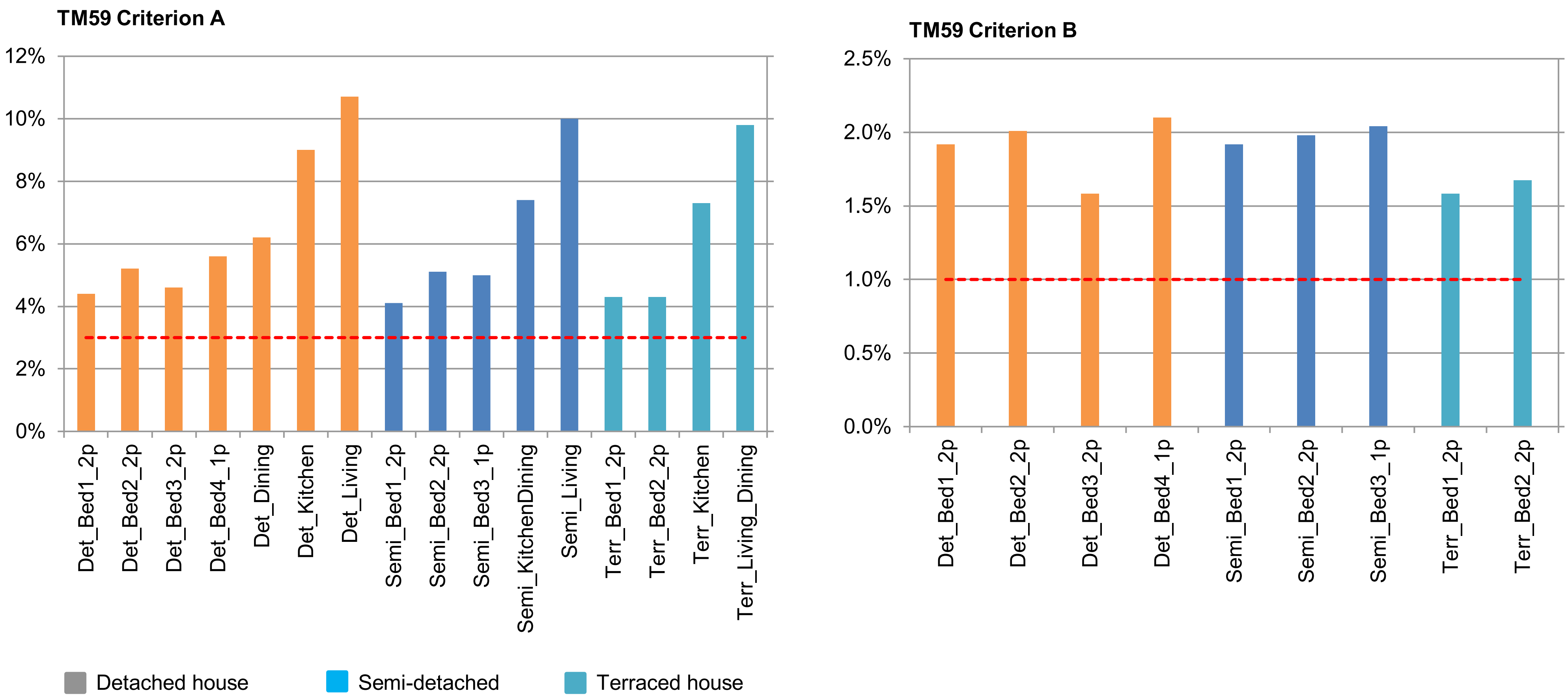


Figure 6: London Heathrow – Modelling results for flat typologies

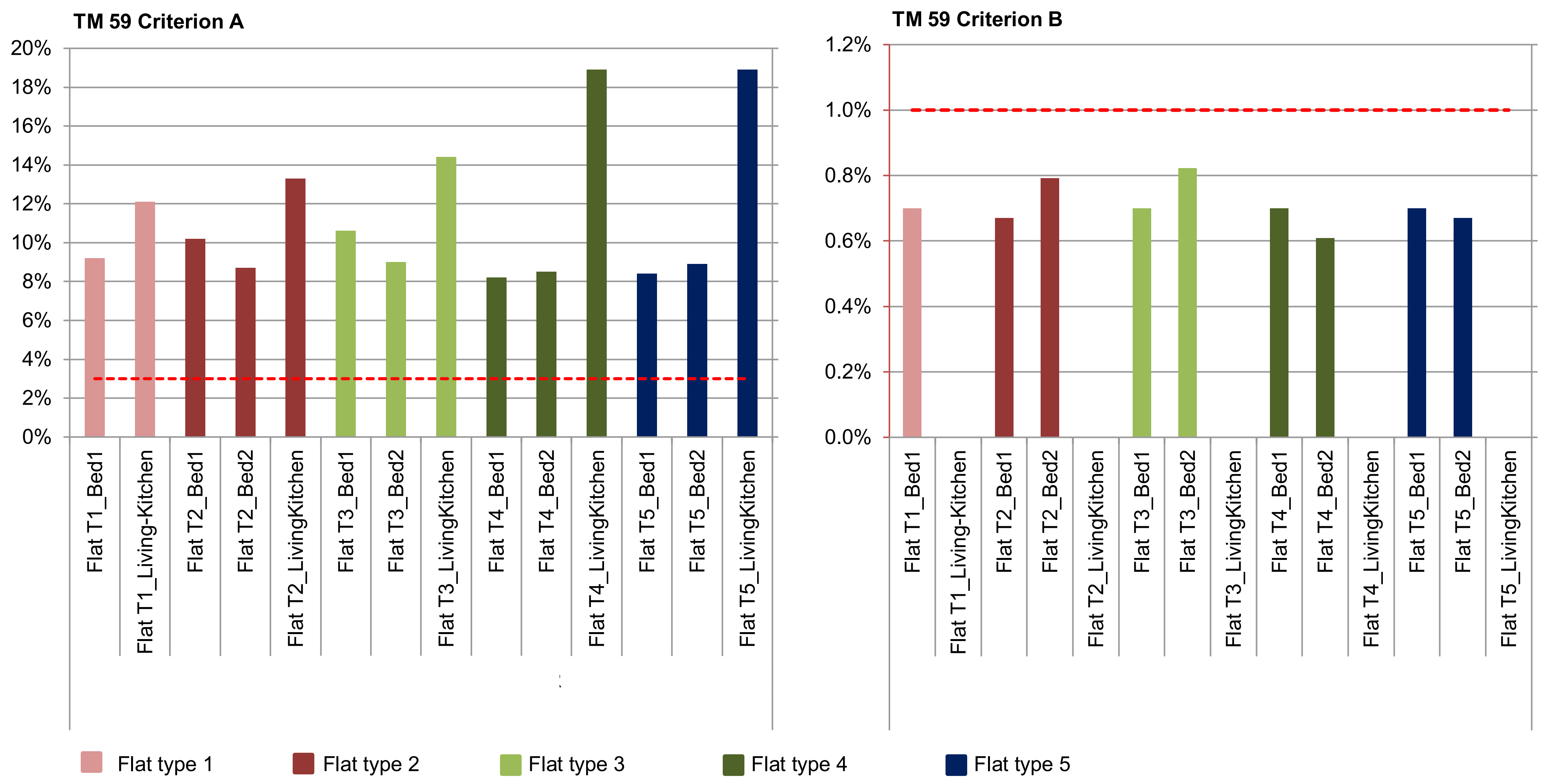


Figure 7: London Weather Centre – Modelling results for house typologies

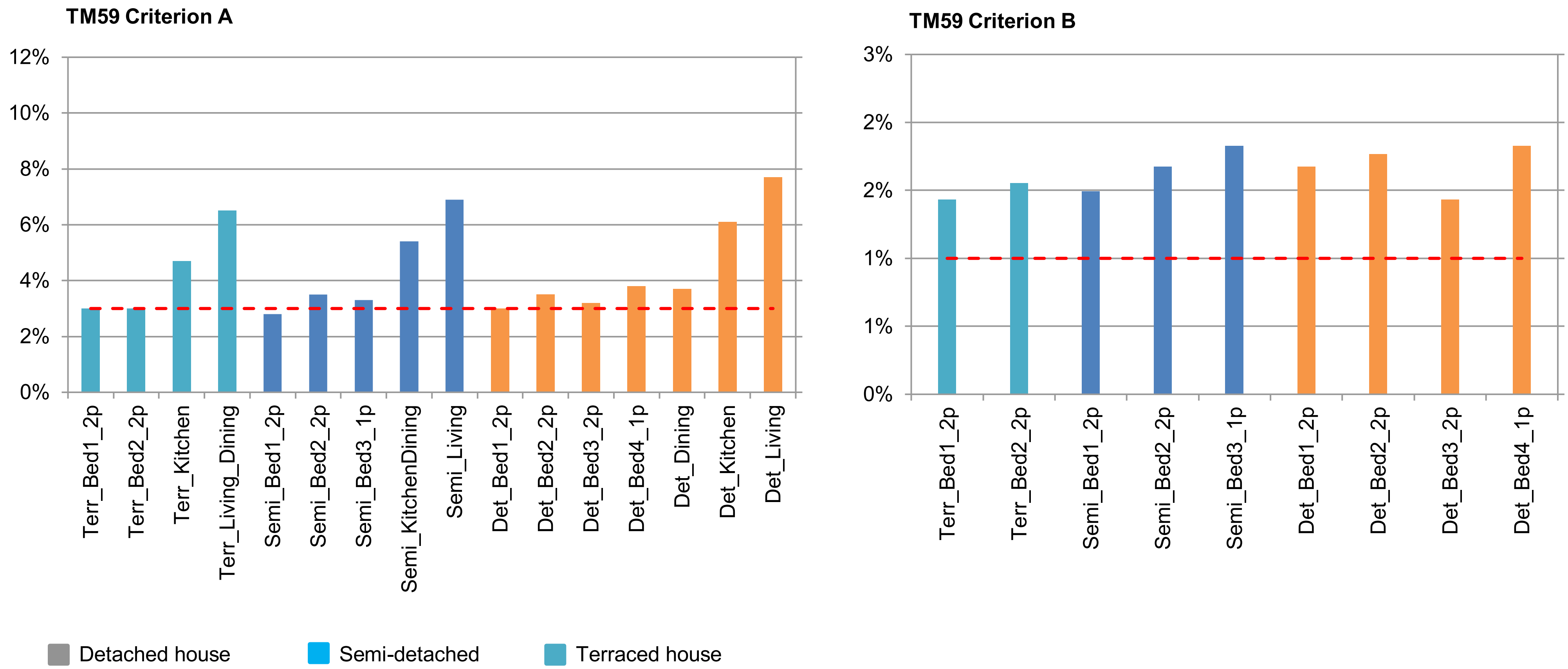


Figure 8: London Weather Centre – Modelling results for flat typologies

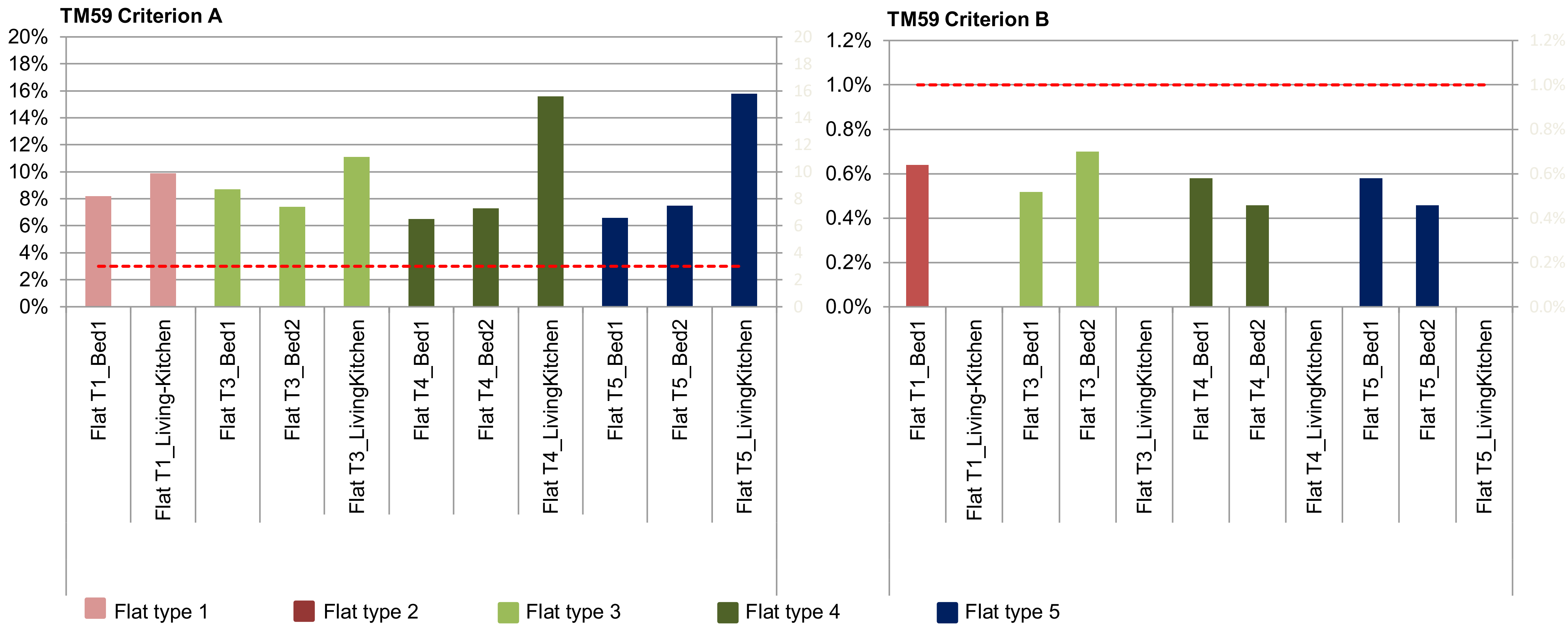


Figure 9: Leeds – Modelling results for house typologies

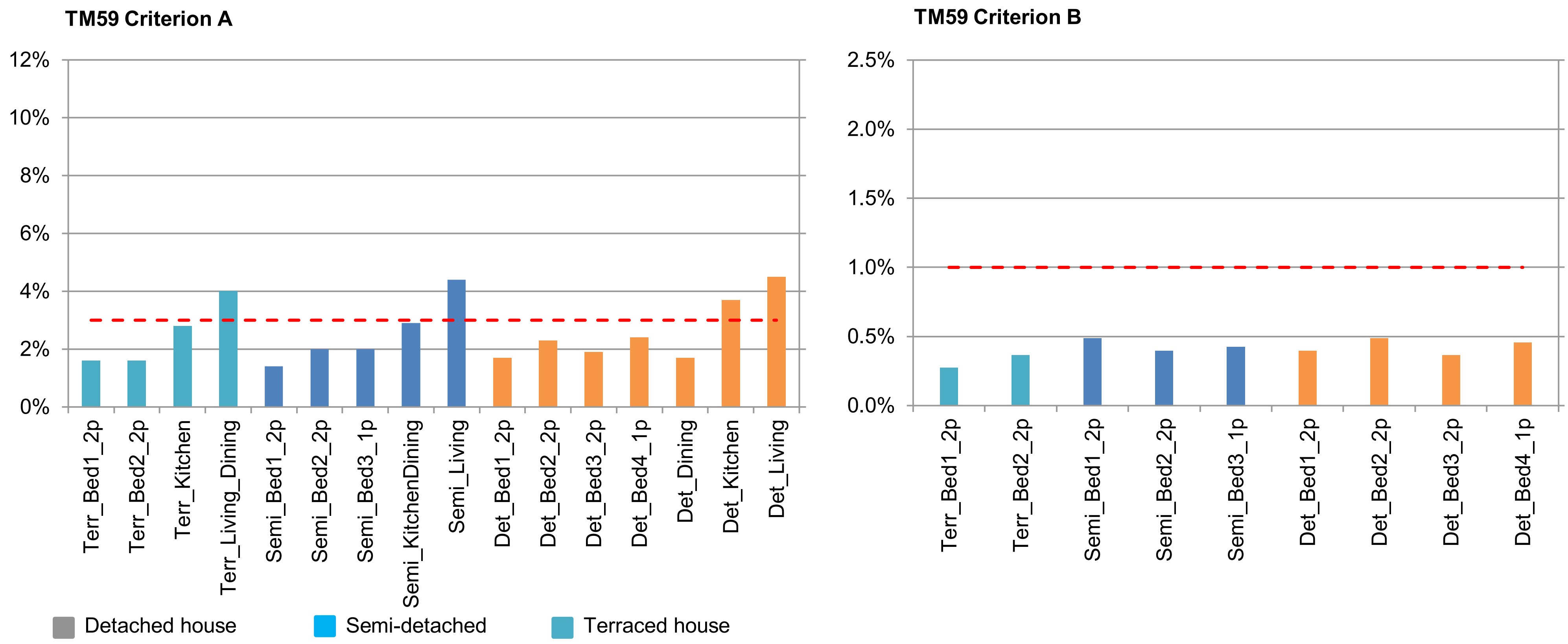


Figure 10: Leeds – Modelling results for flat typologies

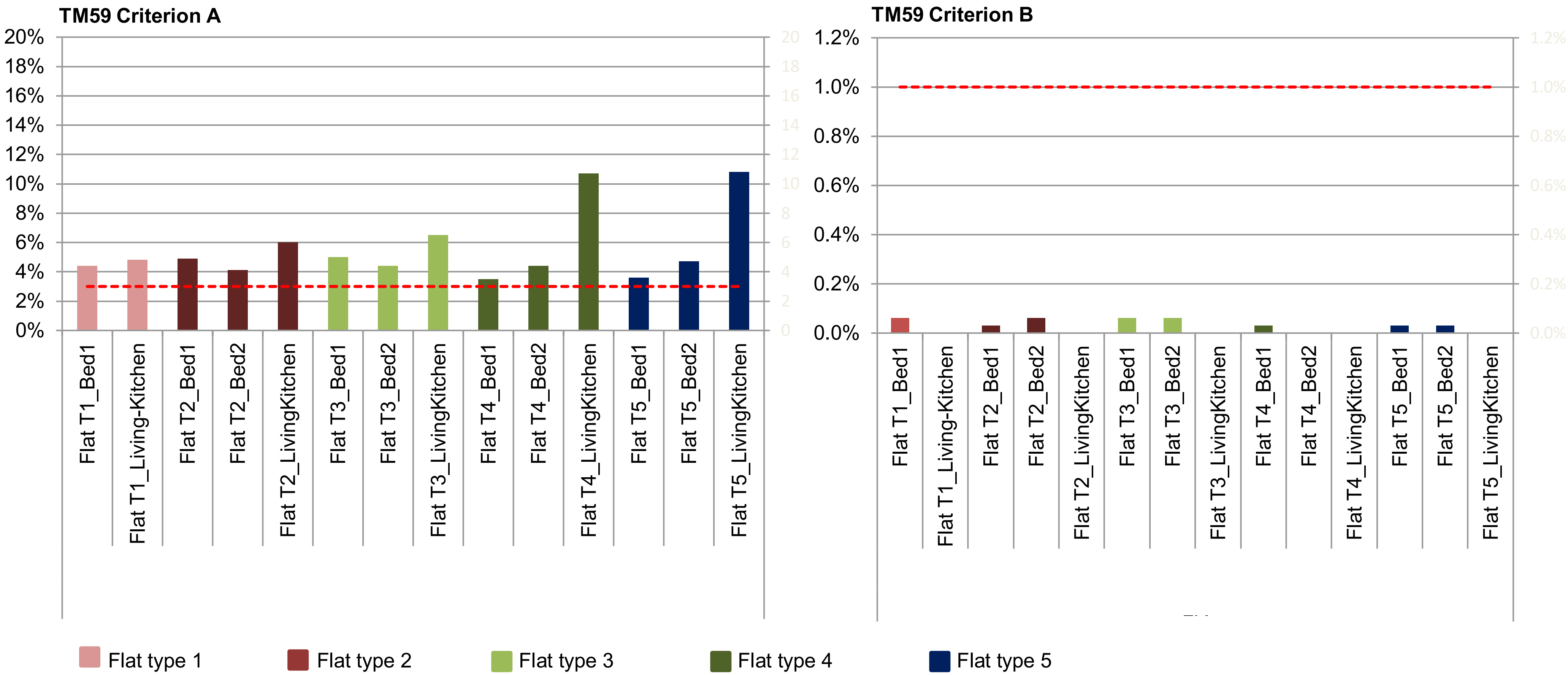


Figure 11: Southampton – Modelling results for house typologies

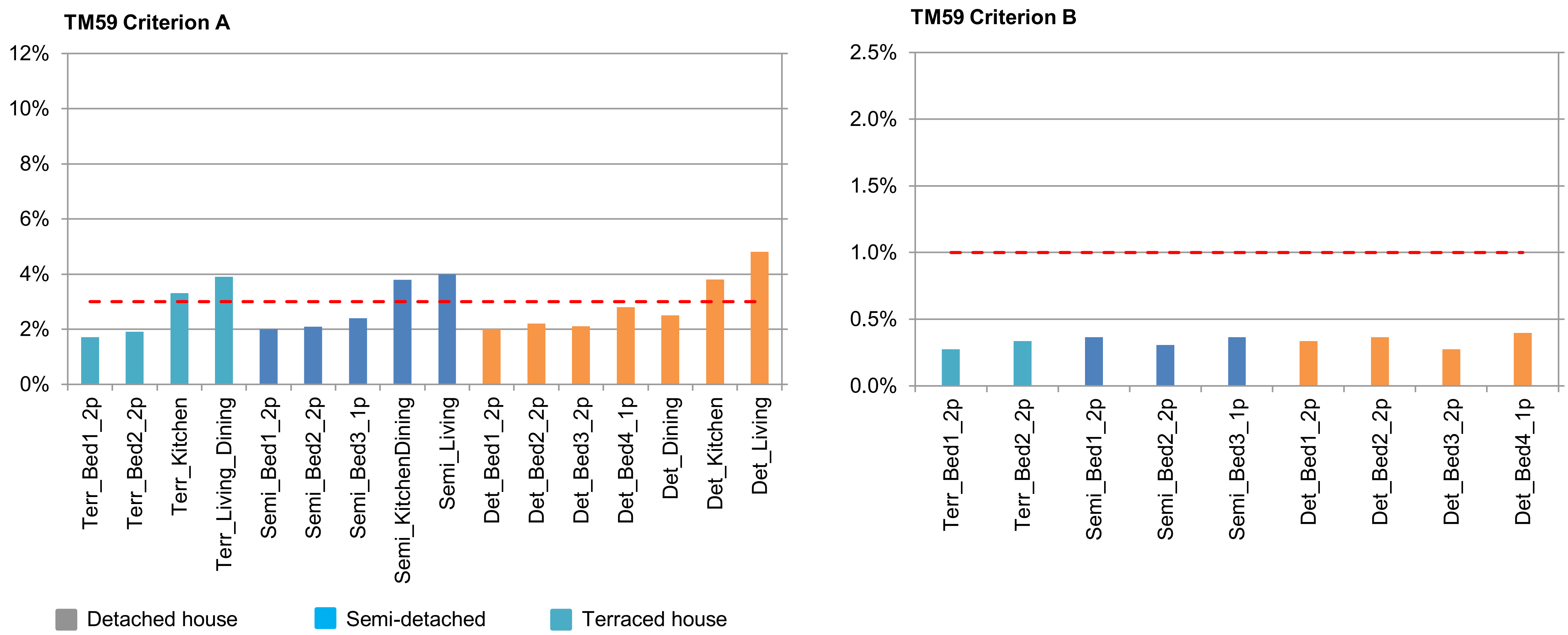
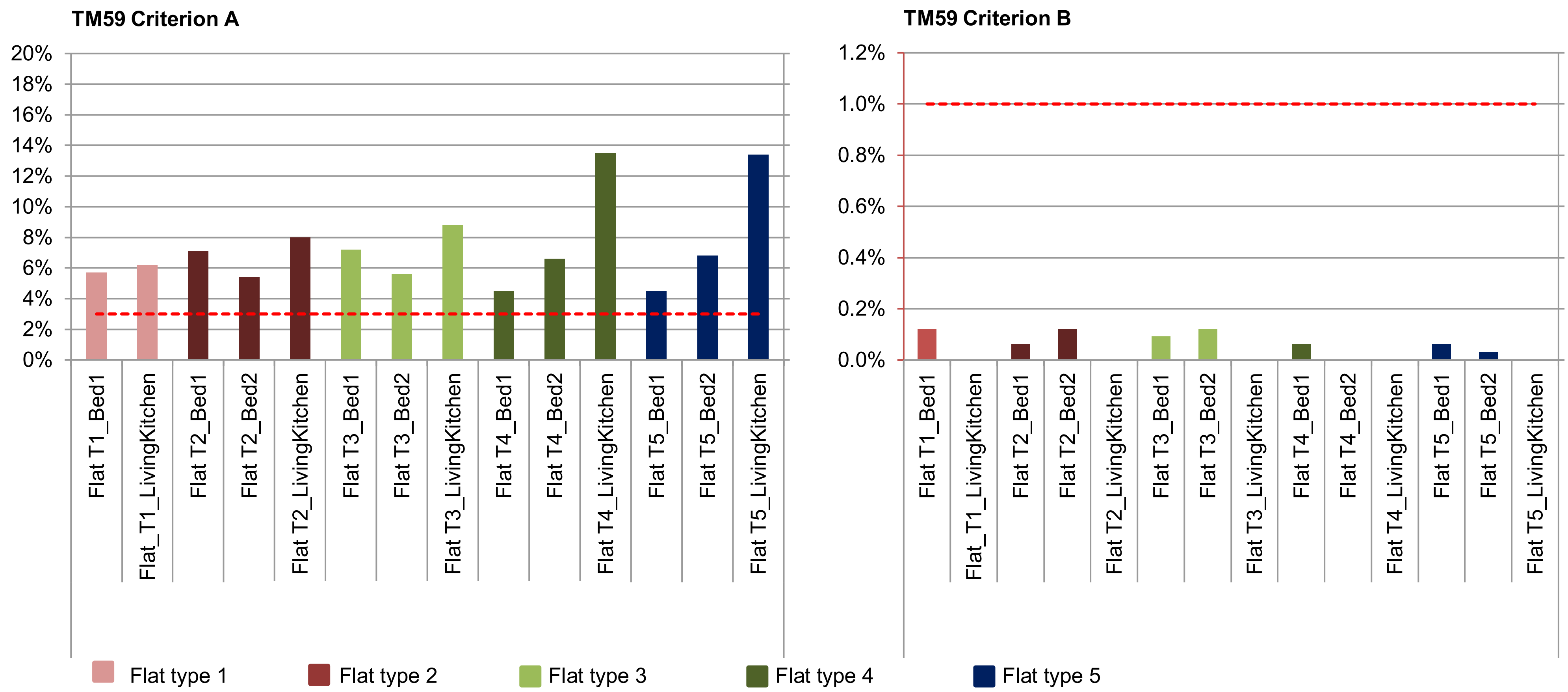


Figure 12: Southampton – Modelling results for flat typologies



4.2 Sensitivity analysis

Sensitivity analysis was carried out on the detached house and a 2-bed single aspect flat (Type 2) located in Nottingham to understand the impact of key variables and assumptions on overheating risk. The results from the sensitivity analysis are presented in Figure 13 and Figure 14: Sensitivity analysis for a 2-bed Type 2 flat in Nottingham

.

Core scenario: The first bar in red on each graph shows the results from the core scenario as presented in section 4.1. The variation in overheating hours is assessed for both TM59 criteria A and B relative to this core scenario. While the TM59 criterion A applies to all occupied rooms, the results are shown for the living room for the sake of simplicity. Other rooms exhibit similar trends.

Weather data: The next five results (in grey) shows the impact of different weather data, specifically

- Current weather data
- Projected 2050s and 2080s DSY1 high emission scenarios
- Projected 2020s design summer year weather data with more severe assumptions around summer heat waves (DSY2 and DSY3)

As shown, the results vary significantly depending on the weather data chosen. The number of hours exceeding the required threshold temperatures increases progressively with future weather data. For criterion A, the impact of using alternative design summer year data on day time exceedance in living rooms is even more stark, with DSY3 results worse than in the 2080s.

The key differences in the three design summer years are worth noting. DSY1 is the mildest out of the three available and is representative of a moderately warm summer, DSY2 has a short intense warm period, and DSY3 has a long less intense warm period[10]. Depending on the location, DSY1 has a return period, which is a measure of its frequency, ranging between 6 to 8 years, while DSY2 has a return period ranging from anywhere between 10 to 38 years, and DSY3 has a return period of between 11 to 50 years[11].

Orientation: The next three results (in black) show the impact of room orientation on overheating risk. Note that the core modelling scenarios have living rooms facing south. In case of criterion A, living rooms facing west see an increase in the number of hours exceeding threshold temperatures, while those facing east and north see a drop due to lower solar gains.

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[10] CIBSE Weather Files 2016 release: Technical briefing and testing. Accessed August 2017

[11] CIBSE Weather Files 2016 release: Technical briefing and testing, Table 9. Figures rounded off. Precise figures vary by location.

Orientation has minimal impact on criterion B results as it applies for night-time hours only and assumptions around window opening regime helps ensure good ventilation and a drop in internal operative temperatures by late evening whatever the orientation.

Ground floor and top floor flats: For the flat typologies (Figure 14: Sensitivity analysis for a 2-bed Type 2 flat in Nottingham

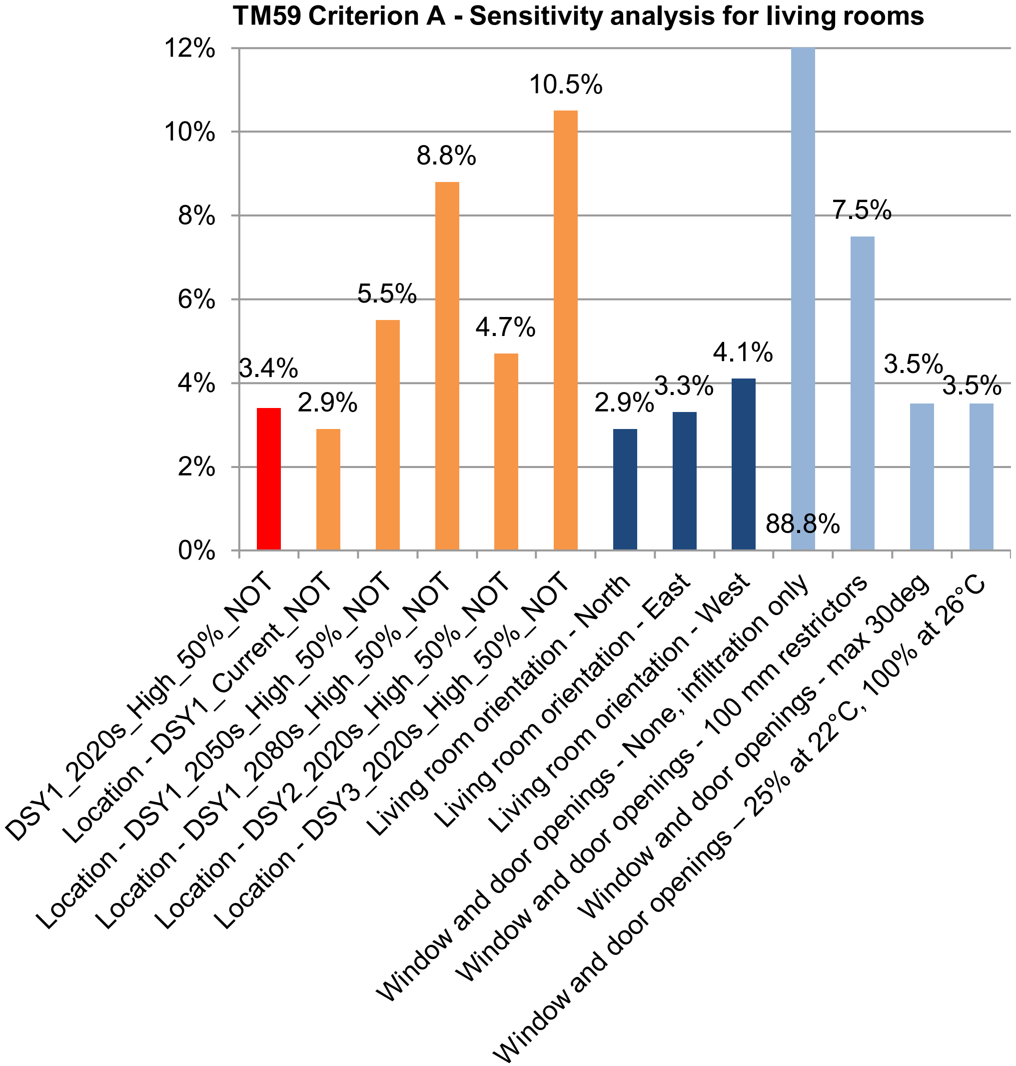
), flat location within the block impacts on overheating results with ground floor flats performing worse relative to mid-floor flats, and top floor performing marginally better. This is largely attributed to higher wind speeds and ventilation rates for flats located on the upper floors.

In reality, obstructions and overshading by adjoining buildings in an urban setting as well as any concerns around noise and security will affect the results. Ground floor flats tend to be overshaded relative to top floor flats, but may also have greater restrictions around window opening due to security concerns. Similarly, window restrictors on high rise flats will limit ventilation options thereby intensifying overheating risk.

Window opening regime: The final set of three results shows alternative window (and external door) opening behaviours. This variable is as significant as the weather data. The core modelling assumption is that for occupied rooms, windows start opening when internal operative temperature exceeds 22°C and are fully open when it exceeds 26°C. In particular, if windows are kept closed or have restrictors installed, it significantly increases the risk of overheating due to reduced ventilation. The impact of occupant behaviour to control the risk of overheating will be examined further in Phase 2.

A number of other variables were tested, such as fabric infiltration rates, ventilation rates in roof void (in case of houses), and furniture thermal mass factor. These variables were, however, not found to affect the results significantly.

Figure 13: Sensitivity analysis for a detached house in Nottingham



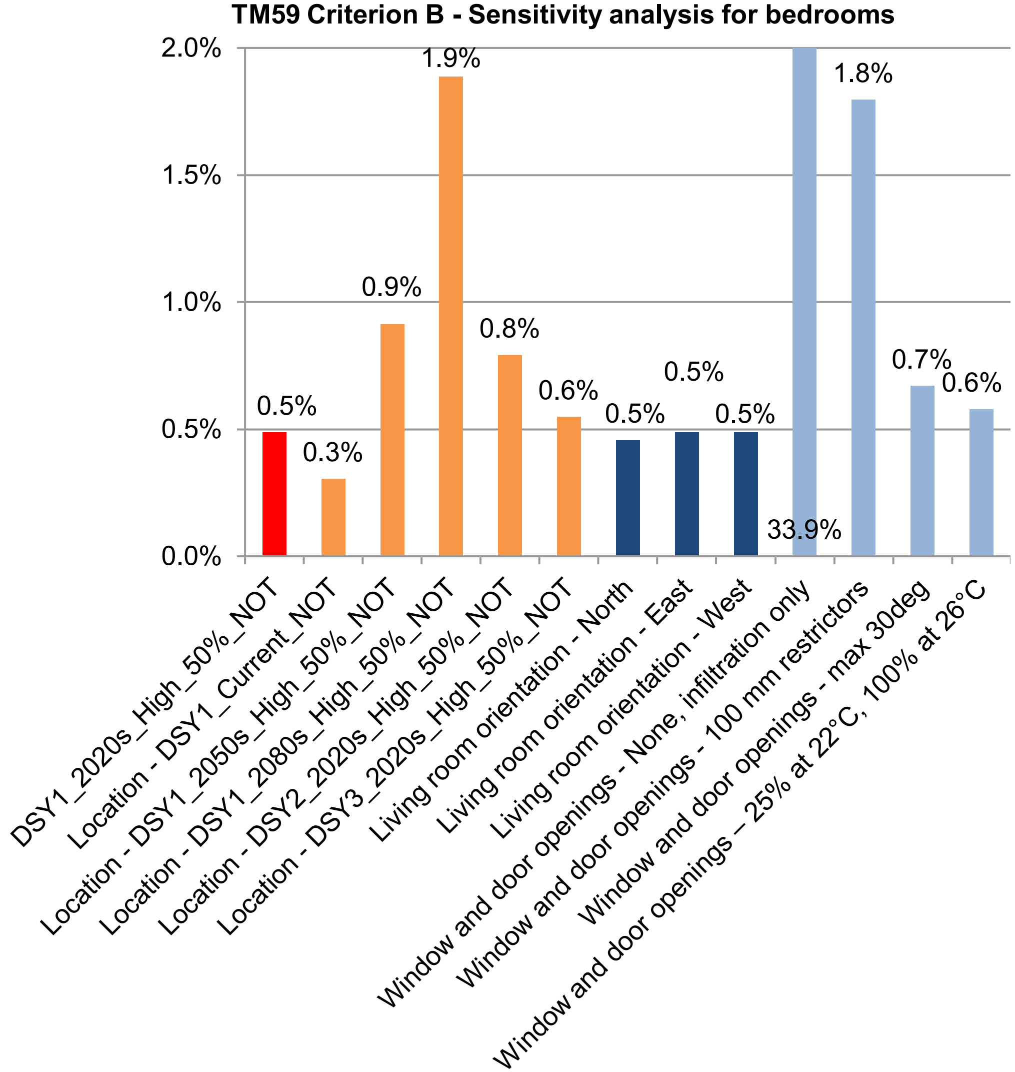
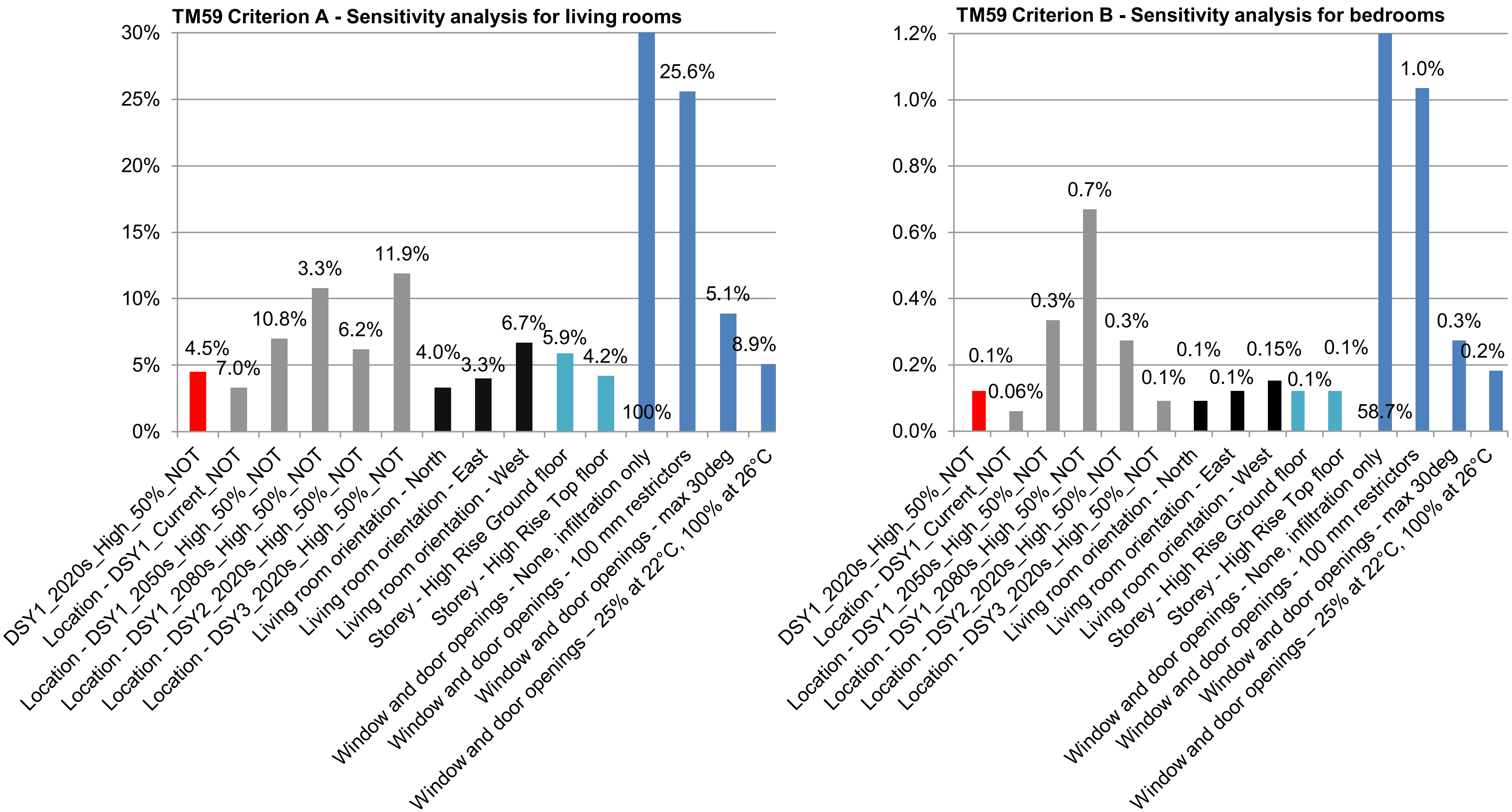


Figure 14: Sensitivity analysis for a 2-bed Type 2 flat in Nottingham



4.3 Modelling software comparisons

An assessment of the overheating risk for a sample of apartments was carried out by CIBSE using three dynamic thermal simulation software – IES-VE, EnergyPlus and TAS-EDSL[12]. The purpose of the exercise was to understand the differences in results across the three software packages and, as part of the development of the TM59, help inform standard assumptions for the assessments. The sample consisted of a mix of 1-bed and 2-bed properties with both single and dual aspects.

Two scenarios were tested as part of the exercise. The key difference between the two scenarios was the window solar transmittance or g-value. Building fabric assumptions, occupancy and internal gains for both the scenarios are shown in Figure 15 below.

Figure 15: Modelling software comparison - Input variables for the scenarios

Building Fabric for Sample Apartments		
Parameter	**Base Case**	**Case 1: Reduced g-value 0.33**
External wall U-values (W/m².K)	0.18	0.18
Floor U-value (W/m².K)	n/a	n/a
Roof U-value (W/m².K)	0.13	0.13
Window U-value (W/m².K)	1.4	1.4
Party walls	fully filled and sealed	fully filled and sealed
Percentage of window façade	As per drawings	As per drawings
Window g-value	0.50	0.33
Light transmittance	~70%	~70%
Percentage of window that is frame	8%	8%
U-values of party walls with sheltered areas (W/m².K)	fully filled and sealed	fully filled and sealed
Blinds and shades	None	none
Thermal Bridging (W/m².K)	Default (y=0.15)*	Default (y=0.15)*
Ventilation (ach)	openable windows & MVHR	openable windows & MVHR
% of openable windows	30%	30%
Design Air Permeability (m³/hm² (@50Pa))	5	5

Occupancy & Equipment Internal Conditions for Residential Units				
Zone Area	**Lighting (W/m²)**	**Occupancy peak (Sensible) (W)**	**Equipment Peak (Sensible) (W)**	**Equipment Standby (W)**
Bedroom double (2P)	2	150	80	10
Bedrooms Single (1P)	2	75	80	10
Living rooms (2 people)	2	75	400	65
Living rooms (3 people)	2	150	400	65

12 Unpublished CIBSE report dated 10/08/2016

Figure 16: Modelling software comparison - Overheating results for base case scenario

Zone Name	Occupied Summer Hours	Max. Exceedable Hours (3%)	Tas	IES	E+
1_1B2P_D_N	3672	110	1.9%	1.0%	1.1%
1_1B2P_K_N	1989	59	3.8%	1.7%	1.2%
2_1B2P_D_NE	3672	110	1.5%	0.9%	1.0%
2_1B2P_K_NE	1989	59	3.0%	1.8%	1.1%
3_1B2P_D_SE	3672	110	1.5%	1.1%	1.0%
3_1B2P_K_SE	1989	59	4.4%	2.2%	1.4%
4_1B2P_D_S	3672	110	7.3%	2.7%	5.0%
4_1B2P_K_S	1989	59	14.1%	3.9%	5.1%
5_2B3P_D_S	3672	110	3.0%	1.9%	2.0%
5_2B3P_S_S	3672	110	3.0%	2.0%	1.9%
5_2B3P_K_SW	1989	59	7.4%	4.0%	3.7%
6_2B3P_D_W	3672	110	9.9%	4.4%	7.4%
6_2B3P_S_W	3672	110	10.1%	4.6%	9.1%
6_2B3P_K_W	1989	59	15.7%	7.0%	9.3%
7_2B3P_D_N	3672	110	1.3%	0.9%	0.6%
7_2B3P_S_N	3672	110	1.4%	1.0%	0.6%
7_2B3P_K_NW	1989	59	5.6%	3.2%	2.8%

Source: CIBSE

Figure 17: Modelling software comparison - Overheating results for low g-value scenario

Zone Name	Occupied Summer Hours	Max. Exceedable Hours (3%)	Tas	IES	E+
1_1B2P_D_N	3672	110	1.1%	0.7%	0.5%
1_1B2P_K_N	1989	59	1.9%	1.2%	0.6%
2_1B2P_D_NE	3672	110	1.0%	0.7%	0.6%
2_1B2P_K_NE	1989	59	1.7%	1.4%	0.6%
3_1B2P_D_SE	3672	110	0.9%	0.7%	0.8%
3_1B2P_K_SE	1989	59	2.3%	1.5%	0.6%
4_1B2P_D_S	3672	110	2.4%	1.4%	2.8%
4_1B2P_K_S	1989	59	4.4%	1.7%	3.0%
5_2B3P_D_S	3672	110	1.4%	1.0%	2.2%
5_2B3P_S_S	3672	110	1.4%	1.1%	1.0%
5_2B3P_K_SW	1989	59	3.4%	1.9%	1.1%
6_2B3P_D_W	3672	110	5.2%	2.3%	4.5%
6_2B3P_S_W	3672	110	5.3%	2.5%	5.9%
6_2B3P_K_W	1989	59	7.6%	3.6%	5.6%
7_2B3P_D_N	3672	110	0.8%	0.8%	1.0%
7_2B3P_S_N	3672	110	0.8%	0.9%	1.5%
7_2B3P_K_NW	1989	59	2.3%	1.6%	0.5%

Source: CIBSE

The results for the two scenarios are summarised in Figure 16 and Figure 17. These indicate that while the overheating results for each of the software follow a logical trend when looking at the sample of apartments (e.g. west orientations performing worse than say north facing apartments), there are significant differences across the three software programmes. In general, the comparison suggests that IES-VE results predict the least risk of overheating with TAS predicting much higher overheating hours in comparison. Based on the sample and variables tested, the difference in results could potentially be much as three times.

Following this comparative exercise, CIBSE incorporated additional guidance in TM59 in relation to equipment gains, air speed, and approach to modelling blinds and reduced g-values to ensure consistency in modelling inputs across the three software. While ensuring consistency of inputs helps to reduce some variations, it is acknowledged that the differences in results are largely attributable to fundamental differences in the software, which (apart from EnergyPlus) are not open source and therefore not open to scrutiny and/or detailed comparison.

4.4 Conclusions on modelling results

The results of the dynamic thermal simulation modelling indicate a significant risk of overheating for the eight dwelling typologies modelled in all five locations, when tested against CIBSE TM59 criteria using 2020's high emissions scenario weather dataset.

While dwellings in all locations tested exceed the TM59 compliance threshold, the results indicate a greater risk of overheating in southern England locations. The results show that certain flat typologies in locations in southern England exceed the allowable percentage of hours above the compliance threshold by more than 6 times.

The sensitivity analysis additionally substantiates the following conclusions.

– The choice of weather file affects the degree of overheating. Accounting for more severe summer weather events and/or projections further in the future increases the scale of overheating and in turn the mitigation measures required.
– Key design and construction parameters that affect overheating risk include window areas (total glazed area and openable area) and building orientation.
– Occupant behaviour and, in particular, window opening regime, is a key variable that impacts overheating risk.

IES-VE software has been used for the modelling overheating risk for this study. Modelling software comparison indicates that the absolute results can vary depending on software package. The comparison, however, suggests that IES-VE results predict the lowest overheating risk relative to the other two widely used models. While the differences in results are largely attributable to fundamental differences in the software, the comparison indicates that new built homes would show a high risk of overheating across all typologies and all urban locations when tested using any of the three software packages.

Weather data is a key factor that affects overheating risk and therefore the conclusions from this study. The 2020s high emissions Design Summer Year (DSY) weather file used for the core modelling is representative of the time period 2011 - 2040. The current DSY data is based on the period 1984 to 2013 depending on location. The “current weather data” could effectively be as much as 20 years old, while the “projected 2020 weather data” is potentially weather that is already occurring. So in that respect the choice of weather file provides a reasonably optimistic approach in predicting the overheating risk in new built dwellings over their lifetime. It is also worth noting that the projected design summer year data for 2020s is only available for the high emission scenario primarily because the underlying UKCP09 (UK Climate Projections 2009) only show a small difference between the low/medium/high scenarios.

The window area and occupant behaviour with regard to window openings are other key variables affecting overheating risk. The core modelling assumes that windows in occupied rooms start opening when internal operative temperature exceeds 22°C and are fully open when it exceeds 26°C, allowing for both late evening and night time ventilation subject to temperatures exceeding the 22°C threshold. This may arguably be reflecting occupant behaviour that is quite conducive to limiting overheating risk. Where occupants choose not to open windows, open windows only after they feel discomfort or where there are other contextual issues limiting ventilation options (e.g. window restrictors, noise and air quality issues), the risk of overheating would increase dramatically as shown by the sensitivity analysis.

The current occupancy profile is based on TM59 assumptions. All occupants are present in the dwelling at all times to effectively ‘stress test’ the building. This results in relatively high levels of internal heat gains and occupants present in the dwelling when solar gains are greatest. It also results in a high level of window opening; windows being open to provide ventilation at all times of the day where the temperature is elevated above 22°C and an occupant present in the room. It is proposed in the Phase 2 cost benefit analysis to consider alternative scenarios to take account of different occupancy and behaviour patterns.

It is important to recognise that good house design will be seeking to address a range of potentially competing factors, including maintaining good daylight levels, achieving high fabric efficiency standards (often now specified or measured using FEES) and reducing the impact of external noise. This will need to be considered when assessing mitigation measures in stage 2.

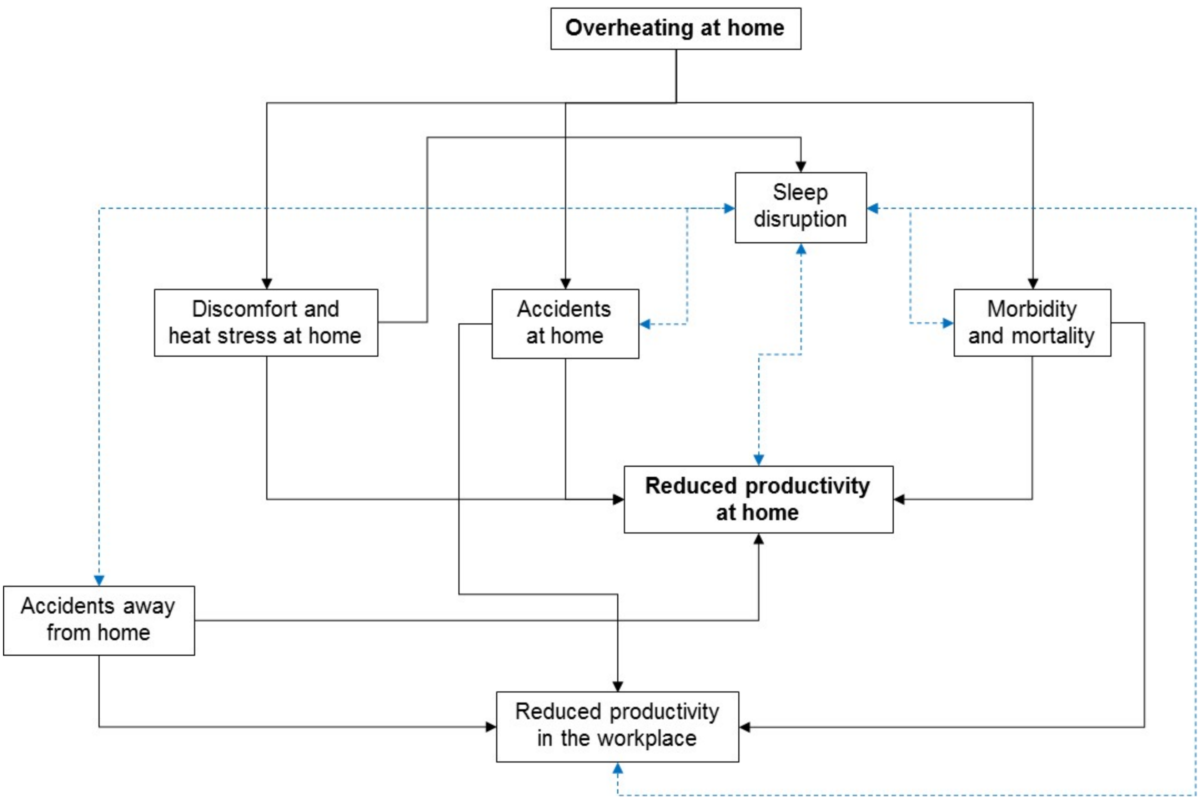
5. Health, productivity and energy impacts of overheating

5.1 Overheating, home-worker productivity and sleep disruption

Existing literature and research looking at the effects of overheating on the productivity of home workers has been reviewed. The prime focus is to understand the direct impact of overheating on people working at home to inform the cost-benefit analysis in Phase 2 of the research. However, the overall picture is more complex and it is important therefore to put this direct effect in context.

Figure 18 summarises some plausible pathways by which overheating at home could have an economic impact. The direct impact of overheating is represented here as the effect of discomfort and heat stress. Overheating can also increase the risk of accidents at home, ill-health and death, while also disrupting sleep. These are important impacts in their own right and – in addition – injury, illness and sleep disruption can affect productivity at home (and in the workplace), with sleep disruption also potentially increasing the risk of accidents away from home. Injury, illness and worries about productivity could, in turn affect sleep quality. In this complex web, sleep disruption appears to play a key role and its effects are therefore picked out as dashed lines in Figure 18.

Figure 18: Plausible pathways for effects of overheating in homes



5.1.1 Direct effects on home-worker productivity

There is a lack of research providing evidence directly on the effect of overheating on home-worker productivity. Conclusions therefore rely on two other streams of evidence, coming mainly from laboratory-based studies:

(a) the impact of moderately elevated temperatures, causing discomfort, on work performance;

(b) heat stress and its effects on ability to do work.

These two issues are discussed below, followed by consideration of how householders' behaviour might mitigate effects of overheating.

Discomfort

Elevated temperatures can affect work performance, and therefore productivity, but the evidence comes from workplaces and laboratory-based studies rather than residential premises. A negative effect of elevated temperatures on performance is well established (e.g. Jensen *et al* 2009, Seppänen *et al* 2006, Wargocki & Seppänen 2006). Jensen *et al* (2009) summarise the effect on the mental performance of office workers in the following equation.

$$RP = -0.0069tsv^2 - 0.0123tsv + 0.9945$$

Where RP = Relative productivity and tsv = Thermal sensation vote.

Since tsv varies with current and recent outdoor temperature, as calculated using the adaptive model (Nicol *et al* 2012), RP should also vary. Furthermore, there is evidence that tsv changes less rapidly with indoor temperature in homes than it does in offices (Oseland 1995). The subjects in this study reported *warmer* thermal sensation at home than in offices or climate chambers, under identical conditions of environment, activity level and clothing. However, this was a winter study and application to hot summer conditions is therefore uncertain.

While workplace studies provide quantitative estimates of the impact of temperature, there will be issues with applying them to the home as a workplace. Even in the workplace, self-rated productivity is related not only to temperature but also to workers' ability to control it (Raw *et al* 1993). In the home, people tend to achieve thermal comfort over a range of temperatures because they can vary not only the temperature but also their activity and clothing. For example, Oseland & Raw (1991) found almost no variation in thermal sensation across a wide temperature range (approximately 18-23°C). This is not because temperature variation has no effect but rather because individuals aim to achieve a temperature that is comfortable for them, given their chosen clothing and activities

Some factors could reduce the impact of overheating for home-workers. Workers at home generally having greater flexibility to:

- choose a cooler location within the home, at a workplace or elsewhere outside the home (e.g. outdoors or in a library);
- decide when to work, for example in the early morning or late evening;

- carry out tasks that are mentally or physically less demanding during warmer periods;
- use lighter clothing;
- adjust shading and air movement to suit a specific work location

Other factors could increase the impact of overheating, such as having to take time to manage the indoor environment or being distracted in ways that would be less likely or less acceptable in a managed workplace. On balance, any estimate of effects based on workplace studies should probably be seen as a maximum effect. Also, the nature of the effect may be different, causing a shift in time and space of work and not simply an effect on performance at a point in time.

Heat stress

The Health and Safety Executive (HSE) adopts the simple definition that "Heat stress occurs when the body's means of controlling its internal temperature starts to fail".[13] The HSE states that heat stress entails core body temperature rising and additional strain from dehydration and increasing heart rate. While noting that susceptibility to heat stress varies between individuals, HSE describes how heat stress can have effects relevant to both mental and physical work, including inability to concentrate, muscle cramps, exhaustion and fainting. The seriousness of effects increases the longer someone remains in the same conditions, with death being a possible outcome.

Extensive studies have produced models of the conditions in which heat stress occurs, taking into account temperature, humidity, air movement, clothing and level of physical activity (e.g. Liljegren *et al* 2008, Lemke & Kjellstrom 2012). Online tools are also available to use such models.[14]

A report by the Zero Carbon Hub (2015) notes an example of the limiting temperatures (based on Wet-Bulb Globe Temperature, WBGT) at which increased periods of rest are needed to avoid core body temperatures exceeding dangerous limits: a study investigating workplace heat exposure and productivity in Central America suggested that continuous light work is possible for an average person at a WBGT of around 31°C, i.e. air temperature of around 29°C at 50% relative humidity (Kjellstrom *et al* 2009). However, this example, along with the majority of evidence, is based on healthy adults. As the review suggests, for certain vulnerable groups, lower temperature limits would apply. However, the more vulnerable groups are also less likely to be working at home.

Heat stress is, in one sense, a simpler issue than comfort because it is defined physiologically rather than by subjective response. However, in reality, people at home have greater flexibility to avoid heat stress than people in the workplace, as noted above in relation to discomfort. They may have less work pressure than people in the workplace, but also less protection. They may well either cease work

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[13] http://www.hse.gov.uk/temperature/heatstress/

[14] For example, https://fswqap.worksafe.qld.gov.au/etools/etool/heat-stress-basic-calculator-test/ or http://www.climatechip.org/heat-stress-index-calculation

before they reach limits defined by heat stress or push themselves beyond a safe level. Nevertheless, heat stress models would be usable in Phase 2 of the project to evaluate the impact of overheating on productivity and also health. A basic application would be to establish the periods of work that can be sustained before rest is required.

Household behaviour

From the above discussion, it is clear that any evaluation of effects of overheating on home-worker productivity needs to take into account what people actually do to respond to elevated temperatures. Evidence is lacking in relation to working at home but there is evidence on what households more generally do to respond to summer overheating.

Clery *et al* (2014) report findings based on a quantitative representative survey of 2,313 British households. Only 9% of respondents said that it would not get too warm on a typical summer day, the remainder needing to take some action to avoid overheating. The action taken was often successful in avoiding overheating; nevertheless there remained 27% who did not always keep cool enough on a typical summer day. The range of methods used to avoid overheating was highly diverse and varied with household and dwelling characteristics. Notably, older people were less likely to report overheating or needing to take specific actions to avoid it. In contrast, there was little variation with whether someone is usually at home during the day. This does not mean that occupancy is irrelevant – this finding probably arises from a combination of someone being at home during the day making adaptation easier but also making exposure to the warmest conditions more probable.

Some of the reported methods of avoiding overheating seek to adapt the indoor environment, either controlling heat gain (by reducing heating or creating shade) or removing heat (e.g. using natural ventilation through windows or doors, or mechanical ventilation or cooling systems). Natural ventilation is the dominant method while mechanical cooling and external shading are rare. But a majority of households also use other methods, adapting themselves rather than the environment: reducing personal insulation (using light clothing or bedding), cooling the body from the inside (e.g. with a cold drink) or from the outside (e.g. with a fan or shower), or a change of location (within the home or by leaving the home).

More than half of households used additional strategies when their usual methods of keeping cool in summer were not enough, with actions similar in type to those used more routinely. Besides when the weather is particularly hot, the main driver for households to change what they do to keep cool was when someone at home was unwell, especially if there were children in the household.

Most households opened their windows to keep cool on a typical summer day (79% during the day, 53% at night). In addition, 40% opened external doors and 13% opened doors to shared indoor spaces (e.g. landings). Opening windows varied with temperature but also due to other reasons than keeping cool, e.g. for fresh air, to let out smoke or smells or to avoid condensation. Perhaps most importantly for the current project, 38% opened windows to help them sleep better. Over half of households sometimes report barriers to opening windows, mainly related to security, noise and other reasons to do with conditions outdoors such as smoke, odours, wind or rain. Roys *et al* (1990) found that the reasons given for closing windows varied with region: cold and draughts were more important in Scotland while a “preservation” factor (related to security, energy conservation and windy conditions) was more important in London (other parts of England were intermediate). This was a winter study but such variations could also occur in summer.

Given the many building, climatic and personal variables affecting domestic window-opening, it is not surprising that there has been limited success in predictive modelling (e.g. Sorensen 2011, Valentina *et al* 2010). However, Schweiker *et al* (2012) found that models developed in non-domestic buildings could reliably predict window usage in a residential context in Switzerland, although not in Japan. A key difference was that, in Japan, homes were more likely to have air conditioning.

Van den Wymelenberg (2012) concludes that there is “no comprehensive consensus about the way people operate blinds or the motivating factors that influence their decisions”. Certainly there is less evidence about use of blinds than use of windows. Nevertheless, Clery *et al* (2014) report that 25% of British households use internal shading to keep cool on a typical summer day and 4% use external shading.

Use of shading is also subject to barriers (in addition to the general absence of external shading). In a study of the first new London dwelling certified to the Passive House standard, occupants were found to use window blinds more frequently than predicted in winter (for privacy) and less frequently than predicted in summer (to enjoy the view out of the window). This resulted in higher energy use for space heating than expected in winter and higher indoor temperatures than predicted in summer. Despite this, occupants indicated an unwillingness to change their use of blinds and windows (Ridley *et al* 2013).

From all this evidence it is clear that people can be highly adaptable but there are limits on what they can achieve, with limitations arising either from building physics or behavioural barriers. In particular, opening windows and using shading (especially external shading) are key passive means to mitigate overheating (e.g. Mavrogianni *et al* 2014, Porritt *et al* 2012). Mavrogianni *et al* also specifically found that the temperature in bedrooms at night can be reduced by (a) window-opening to limit temperatures gains during the day (where the dwelling is occupied during the day or where there is an option for secure window-opening) or (b) a combination of solar shading during the day and ventilation at night. However, the use of windows and shading is limited by barriers as noted above. Therefore, improving the outdoor environment – noise, pollution and crime risk – has a key role in behavioural means of improving the indoor environment.

This all assumes the absence of air conditioning. Where air conditioning is installed, the evidence (from the USA) is that it becomes the default means of keeping cool (Lee & Shaman 2017) and people appear to become more dependent on AC than they need to be:

- air conditioning was the preferred cooling strategy, and for 30% of respondents was the only strategy;
- fewer than a quarter of respondents ever opened windows to alleviate heat in their bedrooms;

- in general, people utilised strategies that modify the environment more than the individual person (e.g. wearing less clothing or having cold drinks);
- among the two-thirds of those who reported thermostatic control, the mean set point was 20.6°C;
- around a quarter of users kept their air conditioning on almost all day and all night for the entire summer

A small-scale study in the UK by Pathan *et al* (2008) provides the following evidence on typical cooling patterns and occupant satisfaction.

- Users reported better quality of sleep with cooling in bedrooms, no adverse health issues or noise disturbance and no purchases prompted by health issues.[15]
- Users stated that they would switch on the air conditioning when feeling hot, which measurements implied meant approximately 24-25°C, with switch-on temperatures only 1°C lower at night than during the day.[16] But thermostats were set at 18-25.5°C, with users setting a low temperature mistakenly hoping to achieve a more rapid temperature drop.
- Actual average night-time temperatures were significantly lower in bedrooms (20.3°C) than living rooms (24.6°C) and lower than the temperatures usually maintained in living rooms during the winter.
- On average, air conditioning was used for five hours during the day and throughout the night in bedrooms. The rooms usually cooled were living rooms, bedrooms, kitchen/dining and conservatories.

5.1.2 Sleep disruption

As depicted in Figure 18, sleep disruption is likely to be a critical factor in estimating the adverse impact of overheating (and hence the benefit of mitigating overheating). The issues to be addressed can be divided between (a) the impact of overheating on sleep disruption and (b) the consequent impact of sleep disruption. The second set of issues is discussed first.

The impact of sleep disruption

Sleep disruption has multiple and complex effects on performance, safety, health and quality of life. The brief review by the Zero Carbon Hub (2015) notes the occurrence of tiredness and falling asleep; reduced concentration and alertness; memory blanks; irritability and frustration; and general cognitive performance

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[15] Improved quality of sleep may arise because people sleep better in cooler conditions (or at least when the room is not overheated) or because the windows can be closed to keep out noise, or both. The evidence is not clear on this but it has implications for the effects of opening windows at night, which could make it cooler but noisier.

[16] This is consistent with a small-scale US study (Kempton *et al* 1992) in which most users relied on manual switching rather than thermostats, possible because of inconvenient and complicated controls that did not reflect users' needs.

decrement after only 24 hours of sleep deprivation. Epidemiological studies suggest that it may be the lack of night-time relief from daytime heat that is particularly deleterious (e.g. Kilbourne 1997, McGeehin & Mirabelli 2001).

The Zero Carbon Hub notes other effects of sleep disruption as increased risk of: accidents; poor mental and physical health including cardiovascular disease and reduced ability to maintain a healthy immune system; poor quality of life; low productivity at work; and death. Lan & Lian (2016) expand on some adverse effects of poor sleep quality, citing: impairment of cognitive performance in older adults (Miyata *et al* 2013); impacts on brain function related to reward processing, risk-taking, and cognition in adolescents (Telzer *et al* 2013); and increased risk of obesity, type 2 diabetes and cardiovascular disease (Miller & Cappuccio 2013, Nagai *et al* 2010).

So the effects are not limited to what happens at home. Poor sleep is a significant predictor of road traffic accidents and contributes to decreased job performance and productivity (Philip *et al* 2014, Rosekind *et al* 2010). These effects are not trivial. For example, Colten & Altevogt (2006) report that almost 20% of all serious car crash injuries in the USA general population are associated with driver sleepiness, independent of alcohol effects. The health consequences of sleep loss are sufficient to impact all-cause mortality (Alvarez & Ayas 2004, Strand *et al* 2015).

Even considering only the effects on productivity of home-workers, Figure 18 indicates the complex effect pathways that would need to be taken into account in order to achieve an overall evaluation of impact. Furthermore, it would be wrong to ignore the effects of sleep disruption on risk of injury, illness and death. Other possible impacts include negative impacts on domestic and other relationships, assaults and poor purchase/investment decisions. These effects will all vary between population groups and depend on the duration of periods of overheating – within and between sleep periods. This would require a massive literature review and econometric exercise, and would still lack good evidence in many areas. To undertake such an exercise is beyond the capacity of this project and certainly beyond the scope of this review.

Fortunately, others have sought to estimate the overall impact of sleep disruption. Depending on the final scope of Phase 2, these are three examples of analyses that could be applied.

– Hafner *et al* (2016) review causes of sleep loss though this is very focused on working life affecting sleep. The review does not mention the thermal environment in the bedroom or even noise. The authors, however, offer an estimate of the economic impact of sleep loss as a whole, covering workplace productivity but not explicitly productivity at home. This gap in the analysis can be ignored if work is assumed to be simply transferred from workplace to home. Economic modelling of data from five OECD countries found that individuals who sleep fewer than six hours a night on average have a 13 per cent higher mortality risk than people who sleep at least seven hours. At a national level, up to 3 per cent of GDP is lost due to lack of sleep.

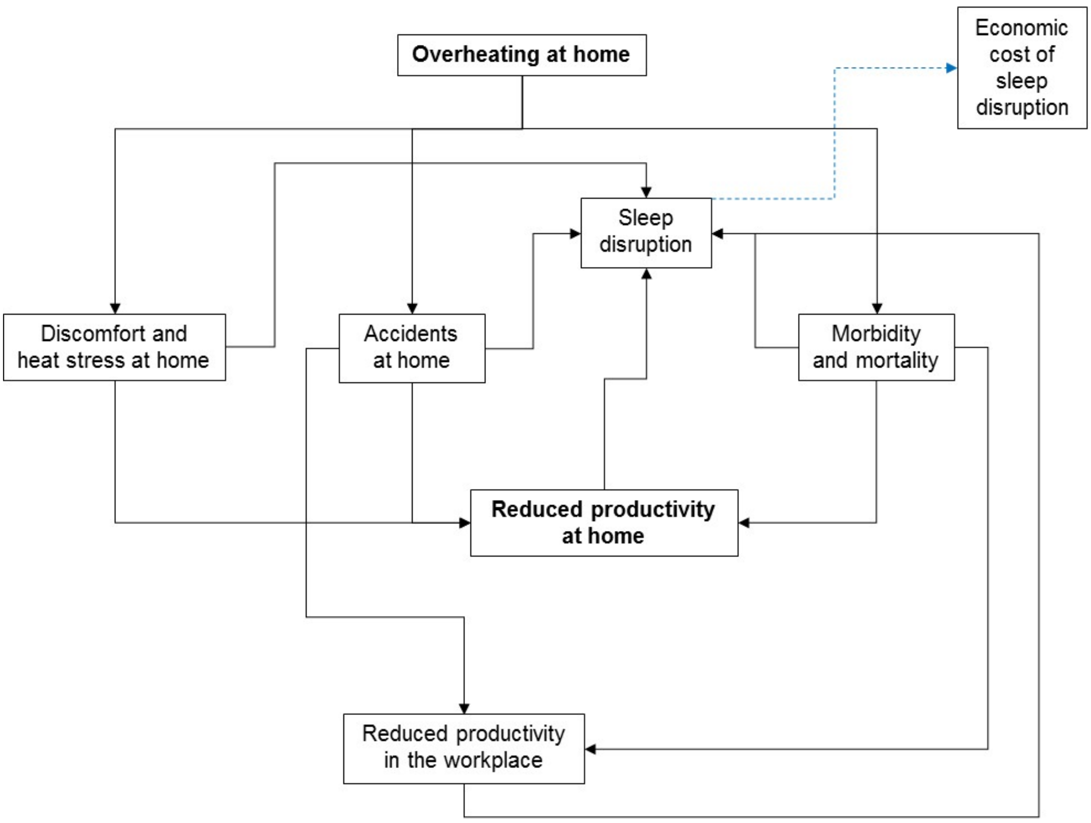
– Colten & Altevogt (2006) review the effects of sleep disruption and the impact of sleep intervention programmes including those aimed at reducing the incidence of Sudden Infant Death Syndrome, which is related to high room temperature.

They estimate a cost of sleep loss and sleep disorders in the range of “hundreds of billions of dollars a year”, taking into account direct medical costs, productivity and increased likelihood of accidents.

– Rosekind *et al* (2010) assess the impact of sleep disturbances on work performance/productivity, based on a survey of employees of four US corporations. Compared with at-risk and good-sleep groups, insomnia and insufficient sleep syndrome groups had significantly worse productivity, performance, and safety outcomes. The insomnia group had the highest rate of sleep medication use. The other groups were more likely to use non-medication treatments. Fatigue-related productivity losses were estimated to cost $1,967 per employee annually.

The analysis in these papers is undoubtedly imperfect in fully quantifying the economic impacts of sleep disruption. In order to take advantage of the existing analysis, it would need to be supplemented by estimates of the effect of overheating on sleep disruption. This would also need to take account of the fact that sleep disruption due to overheating does not generally extend to long periods. Hence the complexity of Figure 18 could be reduced to that in Figure 19 below.

Figure 19: Plausible pathways for effects of overheating at home - First simplification



The impact of overheating on sleep

The prime consideration here is the direct effect of sleeping conditions being too warm. This is shown in Figure 19 as the effect of discomfort and heat stress although it might be considered that comfort (being a subjective entity) has no meaning during sleep. If overheating also causes (directly or indirectly) accidents or ill-health, this could also affect sleep. Loss of productivity could also lead to excessive work hours or worries that then have an indirect effect on sleep (Hafner *et al* 2016).

Experimental human studies under laboratory conditions show that overly warm environments increase wakefulness and disturbance, and reduce sleep time (Bach *et al* 2002, Haskell *et al* 1981, Horne 1992, Lan *et al* 2014, Schmidt-Kessen & Kendel 1973). Colten & Altevogt (2006) summarise how body temperature regulation is related to the sleep cycle: (a) at night sleep onset and maintenance are promoted by a gradual decline in body temperature and heat production, and an increase in heat loss and (b) a gradual increase in body temperature, heat production and conservation several hours before waking, eventually promoting waking. Lan *et al* (2014) cite related evidence that:

(a) heat is redistributed from the body core to the shell at the onset of sleep and sleep is associated with greatly elevated skin blood flow, thus increasing heat loss;

(b) during sleep, thermoregulatory function is reduced and re-activating it disrupts sleep;

(c) rapid eye-movement (REM) sleep is more sensitive to air temperature than other sleep stages.

The implication is that the thermal environment needs to make it possible for body temperature to fall (by a small amount). So there is a clear mechanism by which elevated room temperature could disrupt sleep. Okamoto-Mizuno K & Mizuno K (2013) go further and state that “The thermal environment is one of the most important factors that can affect human sleep”, an assertion that is further supported in some detail by Lan & Lian (2016). Overall, the evidence is that overheating could reasonably be estimated to reduce good sleep from 8 to 6 or 7 hours, making a good connection with the economic analysis by Hafner *et al* (2016).

This evidence then raises the question of how warm is too warm; there is very little research in the UK that addresses this question. CIBSE Guide A (2015) advises that bedroom temperatures should not exceed 26°C and this has since been adopted as the threshold temperature in CIBSE TM 59 (2017). However, the criterion value of 26°C is based on a small sample (21 volunteers from among the researcher’s colleagues) in a pilot study conducted in 1975 using mechanical thermographs.[17] At 26°C the volunteers were still using a sheet covering and (presumably) nightclothes. Subject to cultural or personal barriers, further adaptation should be possible: Okamoto-Mizuno & Mizuno (2013) note that the effects on sleep stages vary with the

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[17] Described in Humphreys *et al* (2015).

use of bedding and/or clothing. In semi-nude subjects, sleep stages are more affected by cold exposure than heat exposure. Humid heat exposure further increases thermal load during sleep and affects sleep stages and thermoregulation.

The range of temperatures suitable for sleep is evidenced by the findings of Lan *et al* (2014) in a laboratory study of 18 healthy Chinese students who wore short-sleeved sleepwear and were covered with a thin blanket. Sleep quality declined at 30°C whereas 26°C was identified as the neutral temperature for “comfort” during sleep (subjects actually reported feeling on the cool side of neutral at this temperature). This contrasts sharply with the CIBSE criterion of a 26°C maximum. Physiological measurements supported subjective reports: the duration of sleep onset latency was longer and the duration of slow wave sleep was lower at 30°C. Unfortunately, Lan *et al* compared only three temperatures: 23, 26 and 30 °C. This means that it cannot be said with certainty that 26°C was the best temperature, only that the temperature should be much closer to 26°C than 30°C.

In any case, it is not clear how the specific temperatures employed in this study would translate to people in England or to different population groups or to alternative conditions of clothing, bedding or air movement. In fact, Lan & Lian (2016) emphasise that the neutral point differs between genders and varies widely across studies (20-29°C) although 29°C applies mainly for subjects sleeping nude and without covering. They also show that gentle air movement can have a significant effect of improving sleep quality under warm conditions. However, if an appropriate neutral temperature can be established, it should be possible to estimate the effects of deviation from the neutral temperature and the appropriate levels of clothing and bedding for any given temperature.

A key finding of Lan *et al* (2014) is perhaps that the temperature for thermal comfort was higher in sleep compared with that in waking state. Subjects felt thermally comfortable at 23°C before sleep but reported this temperature to be uncomfortably cool for sleep; 26°C was assessed to be slightly cool for sleep but slightly warm before sleep. This indicates that thermal requirements differ between sleeping and awake people and it is not sufficient simply to adjust for different metabolic rate. Together with the winter study of Pan *et al* (2012) neutral temperatures are estimated to be around 3°C higher during sleep (Lan & Lian 2016). It is also obvious that, while asleep, people cannot adapt by means such as turning on a fan, or putting on or taking off clothing or bedding (although they can do this before sleeping or if they awake during their sleep period).

5.1.3 Conclusion

There is a significant challenge in assigning an economic cost to overheating (or an economic benefit from avoiding overheating). Overheating can have direct effects on health, safety, comfort and productivity (during exposure and for a period afterwards). It can also disrupt sleep (itself an adverse effect) with consequential effects on health, safety, comfort and productivity.

This review has shown how some simplification is possible, taking advantage of existing analysis of the economic impact of sleep disruption (incorporating any effect on productivity at home). Furthermore, although the evidence is not perfect, it should be possible to estimate the direct impact of elevated temperatures on sleep disruption. Similarly, the direct effect of overheating on productivity of home-workers can be estimated. In each case, some sensitivity analysis will be helpful.

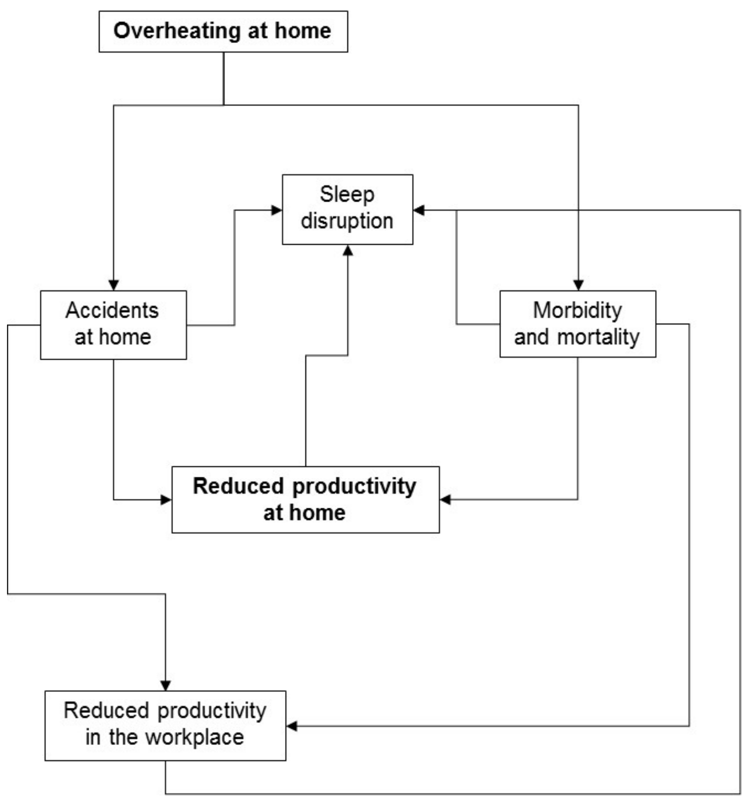
Further simplification is possible as suggested in Figure 20.

- the non-sleep effects of overheating on accidents, morbidity and mortality;
- the effects of injury and illness on productivity and sleep;
- the effects of reduced productivity on sleep.

These effects are outside the scope of the current work programme. It is possible that impact evaluation would be decisive without incorporating these factors, of by assigning small effects to them.

Overall, impact evaluation should be possible, based on current evidence and reasonable assumptions.

Figure 20: Plausible pathways for effects of overheating at home - Second simplification



5.2 Uptake of air-conditioning

It is helpful for the purposes of Phase 2 to predict the uptake of air conditioning if the Government did not undertake any measures. This would inform the counterfactual baseline against which to assess the cost and benefits of any intervention.

Current penetration of air-conditioning in the UK housing stock is very low, with less than 3% of the dwellings resorting to active cooling, including fixed and portable units (Hulme et al. 2013). The question is how a warming climate and an increase in internal temperatures will increase uptake of air-conditioning in new built homes.

Existing literature has been reviewed to gain insight into future trends for uptake of air-conditioning in the UK residential sector, including any relevant evidence from other countries. The Federation of Environmental Trade Associations (FETA), and via them individual suppliers and manufacturers of air conditioning, were contacted to supplement the literature review; however, they were not able to provide any additional data on projected residential air-conditioning demand in the UK or uptake rates in other countries.

The literature review identified very limited information on the likely uptake of residential air conditioning in the UK.

– Peacock et al (2010) adopted a relationship developed in the US between cooling demand (cooling degree days) and the uptake of residential air conditioning and applied it to weather data for London and Edinburgh in 2030. They found no demand for air conditioning in Edinburgh and estimated that 18% of homes in London would install air conditioning systems by 2030. The paper does highlight limitations in directly applying the US data to the UK including cultural and behavioural differences and the social acceptance for residential air conditioning.

– Projections for energy demand from air-conditioning by National Grid also indicate significant variations in uptake rates depending on affordability, economic context and wider policy drivers.18,19 Under the 'slow progression' (business as usual activities prevail) and 'no progression' (economic conditions limit society's ability to transition to a low carbon world) scenarios the energy demand for air-conditioning does not change significantly by the 2050s as shown in

– Figure 21. Under the 'consumer power' scenario (market-driven world, with limited government intervention), there is additional money available to buy equipment to respond to a warmer climate, less attention is paid to energy efficiency and electricity retail prices are moderate. National grid predicts over 5 million units installed by 2040 under this scenario. This suggests roughly a threefold increase relative to today, with around 15% of the homes having air-conditioning compared to around 3% today20. The 'gone green' scenario (policy interventions target long term environmental goals) sees air-conditioning demand run contrary to the general trend of reduced energy demand with almost 4 million units installed by 2040, which translates to a penetration rate of around 12%. Under both the 'consumer power' and 'gone green' scenarios National Grid predicts a dramatic rise in air-conditioning post 2040.

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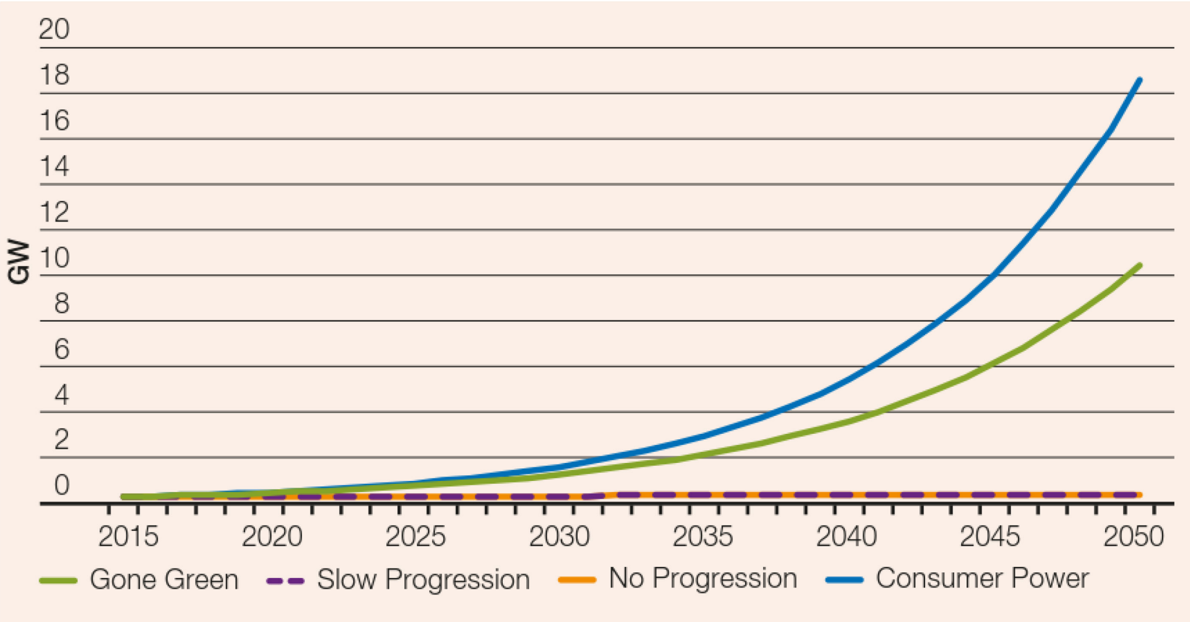
[18] National Grid, Future Energy Scenarios, July 2016
[19] http://fes.nationalgrid.com/insights/residential-air-conditioners/
[20] 15% penetration rate calculated based on 5 million units and a projected figure of 32.8million homes by 2040. This assumes that one unit is installed per home, rather than multiple units.

It is unclear how the National Grid has developed its projections. Whilst these projections have been made in the context of anticipated future external temperatures, the projections do not appear to be directly related to thermal discomfort / overheating risk in homes. The scenarios presented however do emphasise the complexities around predicting future trends given the range of triggers and external drivers.

Figure 21: Predicted energy demand for air-conditioning out to 2050[21]



Source: National Grid, Future Energy Scenarios, July 2016
Note: Trends allow for efficiency gains from equipment over that time period.

The literature review does highlight a number of factors that are likely to influence uptake rates, including among others the penetration of air-conditioning in non-domestic buildings, extreme weather events, household income and affluence, and architectural trends (for instance, a shift away from vernacular building practices).

– Studies indicate that uptake patterns are strongly influenced by occupant expectation on summer comfort, and positive feedback/ experience of occupants in air-conditioned office, retail and leisure spaces (Hitchin and Pout, 2000). Research from the US suggests that when 20% of the office space in a city has air-conditioning then this starts to become the expectation of occupants and may be viewed as a tipping point (Walker et al 2014).

– A study on uptake of air-conditioning in Mexico points to a strong link between climate, household income, and uptake of air-conditioning in the domestic sector. The study found that in cool areas below the Mexican average the uptake of air-conditioning was low across all income levels but in warmer areas the uptake had

[21] Note that the projections are based on the number of homes in Great Britain increasing to 32.8 million by 2040 compared to 27.7 million today, an 18% increase.

a strong positive correlation with income level (Davis and Gertler, 2015). Anecdotal evidence in the UK also suggests a growing market expectation for cooling to be specified in urban apartments priced at the higher end of the market (Young, 2014).

– Extreme weather events can also act as a significant trigger that may boost uptake. For instance, homes in Athens tended to have only one of the rooms fitted with air-conditioning units. After the extreme hot summer in 2007, it became the norm to install air-conditioning units in every room (Gething and Puckett, 2013).

– The shift away from vernacular architecture and changing cultural norms can trigger an increase in use of air-conditioning as has been the case with a number of developing countries (Walker et al 2014). Vernacular typically tends to be more climate responsive and any deviations/ architectural trends that do not respond to climatic considerations may trigger an increased use of active cooling technologies. By inference though, pro-actively incorporating climate responsive design features in new built homes may therefore delay and/or reduce uptake of air-conditioning.

Overall, whilst the expected trend is for a potentially significant uptake of air conditioning if there is no Government intervention, there appears limited evidence upon which to base a quantitative prediction of actual update rates. The currently proposed approach would be to apply the methodology taken by Peacock et al (2010), but updated with the most recent CIBSE future climate data and applied across different locations in England, as a central estimate. Given the uncertainty in these projections, it is proposed that lower and higher projections of uptake are also evaluated as sensitivities to analyse the impact of potential variation from the central estimate e.g. +/- 50% of the central estimate. It is recommended that this approach is discussed with the Research Group and refined as necessary at the commencement of Phase 2.

6. Addressing overheating risks – Existing housing and lessons learnt from other countries

6.1 Existing housing in England

A review of published research and data relating to overheating risk in existing housing in England has been carried out. A number of studies have measured overheating risk in different dwelling typologies and attempted to identify patterns or trends. In most instances, these studies offer broadly similar hypotheses on the inherent characteristics that are less likely to result in certain typologies overheating. It is worth noting that these studies use different temperature thresholds for assessing overheating. The comparative results between different dwelling typologies should however still offer useful insights.

A national study of summertime temperatures in English dwellings was undertaken (Beizaee et al. 2013). The study recorded living room and bedroom temperatures in 207 homes across England during the summer of 2007, and supplemented these with household interviews. The results indicate that detached dwellings and those built before 1919 were significantly cooler than those of other type and age. In contrast, flats and modern homes built after 1990 were significantly warmer. There was a general trend towards higher mean and maximum internal temperatures in the living room and bedroom as house age decreased (i.e. for newer homes). The hypothesis offered by the authors is that modern homes are better insulated than older homes, and flats have a reduced external wall area to volume ratio relative to detached houses (both limit the removal from the building of internal and solar heat gains). Top floor flats were particularly warmer compared to flats on other floors. Additionally, wall construction (its U-value and inherent thermal mass) was found to be an influencing parameter, with cavity walls homes being warmer than those with solid stone construction. The study was based on a threshold temperature of 28°C in living rooms and 26°C in bedrooms to assess overheating risk. These findings are based on a single, relatively cool, summer period and no attempt has been made to extrapolate the findings to warmer summers or changing climate over the next few decades.

Further analysis of this national study was undertaken for measurements taken from 22nd July to 31st August 2007 (Firth and Wright. 2008). It concluded that purpose-built flats and end terraces have the highest average summer temperatures and therefore have the highest overheating risk. When looking at age bands, post 1990 dwellings have the highest average and maximum temperatures, and are most likely to overheat. The authors hypothesize that high levels of insulation and air-tightness were the influencing factors. In contrast, the higher thermal mass for pre 1919 dwellings meant that these were the least likely to overheat.

The trends are corroborated by measurements of internal summertime temperatures in 268 homes in Leicester (Lomas and Kane. 2013). These indicated that flats and homes with insulated cavity walls tend to be significantly warmer than other house types, while detached houses and solid wall homes tend to be significantly cooler. The findings align with simulation results indicating that exposed thermal mass offers a certain degree of protection against elevated temperatures. The results are also consistent with the expectation that better insulated homes will be warmer. The study findings however contradict the conclusions from other studies on the overheating risk in modern (post 1980) homes. It found that bedrooms in modern homes were significantly cooler than those in older houses, suggesting that the increased likelihood of loft insulation, reducing heat gains from the loft space to the bedrooms, may be an influencing factor. The relatively lower thermal mass in modern homes may also be a contributing factor; high thermal mass tends to be unhelpful during the night as heat stored during the day is gradually released into the internal space.

A number of other studies have also concluded that newly built or retrofitted highly energy efficient dwellings, particularly those built to PassivHaus standards may be at risk of overheating (Morgan et al. 2015, Sameni et al. 2015).

Pathan et al. (2017) monitored overheating in 122 London dwellings. The study monitored dry bulb and relative humidity in the main living and sleeping area during the summers of 2009 and 2010, and assessed overheating risk using the ASHRAE Standard 55 adaptive thermal comfort method. It concluded that the problem of overheating in London is widespread and not limited to flats or newly built flats. However, dwellings built post 1996 tend to have significantly higher temperatures above the ASHRAE threshold and for longer compared to older properties.

Analysis of the data collated as part of the 2011 'Energy Follow-Up Survey (EUFS) suggests that a combination of dwelling and household characteristics determine whether occupants will find it difficult to keep at least one room in the dwelling comfortable in summer (Hulme et al. 2013). The dwelling characteristics include dwelling form (with bungalows being the least likely to report overheating issues), dwelling age (with occupants in pre-1919 dwelling least likely to report overheating problems relative to those in post-1990 dwellings), urban/ rural location, region (with dwellings in London most likely to report overheating problems) and SAP rating which is good proxy for how insulated a dwelling is (with dwellings with SAP rating >70 more likely to report problems). Household characteristics include tenure, families with children and household size, with social housing tenants, those with children and larger households more likely to report problems. Monitored data confirms the survey findings, with occupants reporting problems with overheating showing higher mean room temperatures during summer months and on the hottest day of the year.

In addition to the physical characteristics of the dwellings, studies assessing the impact of occupant behaviour found this to be a strong influencing factor (Morgan et al. 2015, Sameni et al. 2015).

Overall, the studies indicate that typically dwellings that have a lower risk of overheating tend to have one or more of the following characteristics – higher thermal mass, poorer thermal insulation and higher leakage rates. The studies reviewed concluded that built form is also a key factor; flats have the highest risk of overheating, and detached dwellings sit at the other end of this spectrum. The studies suggest a statistically weak correlation between age and overheating risk. In most instances dwellings built before 1919 were the least likely to overheat while dwellings built post 1990 were the most likely. The studies reviewed did not in particular look at attributes such as solar gains, purpose-provided ventilation rates, orientation, shading or the impact of internal layouts on overheating risk.

6.2 Lessons from other European countries

The project team engaged with three international experts to better understand the risk of overheating, the differences in design and construction, and the mitigation strategies that are typically incorporated in the residential sector in other EU countries. Telephone interviews were held with experts from France, Germany and Greece: Alois Thiebaut (Project Manager, Thermal regulation of new buildings at the French Ministry of Ecological and Solidarity Transition), Professor Anton Mass (University of Kassel) and Professor Mat Santamouris (University of Athens and University of New South Wales).

The discussions highlighted that overheating risk is also a concern in other European countries, and not just for southern climates. However, these is no single approach to how overheating is defined as well as the design and regulatory response.

Regulations relating to assessing thermal comfort and/or overheating risk in new dwellings across these three countries are outlined below.

- In France, the 2012 regulations require the internal comfort temperature in new, naturally ventilated, buildings to be less than or equal to a reference temperature, which is an absolute temperature threshold that is set depending on region, building construction and certain architectural characteristics. Warmer regions have a higher temperature threshold as do timber buildings, while masonry buildings have a lower threshold. Compliance is demonstrated through hourly simulation for the hottest month of the year using government approved software. The French regulations have mandatory requirements on window shading and the ability to open windows for ventilation, as well as requirements around minimum window surface area, albeit these are not necessarily driven by thermal comfort requirements.
- A new indicator based on the adaptive comfort model is currently being developed for all new buildings in France, both for naturally ventilated buildings and those with active cooling.
- In Germany, regulations stipulate the maximum number of annual overheating degree hours over a reference internal temperature. The country is divided into three summer-regions and the reference value varies for these three regions, ranging from 25°C - 27°C. A simplified method (which has been developed based on dynamic thermal simulation modelling) is used to demonstrate compliance for new dwellings.
- Greece does not currently have regulations for thermal comfort and/or overheating.

Both anecdotal evidence and data from detailed monitoring studies provide some insight into the risk of overheating in new build and existing housing stock in these countries.

- In Germany, occupant feedback from buildings built over the last 10 - 20 years highlighted a number of instances of overheating problems, which led to a revised methodology for assessing overheating risk in new dwellings under the current (2013) regulations.
- The French PREBAT study (Cerema, Dec 2015) analysed monitoring data and data from occupant surveys from new build and retrofit low energy projects to inform the 2012 regulations. The study highlighted that overheating was not just an issue for the Mediterranean hot-dry zone, but the problem was more widespread. The discussions indicated that light-weight timber buildings were seen as most problematic in France, with older/ vernacular buildings with high thermal mass and relatively smaller windows performing well. Depending on region, this older housing stock differs in the construction techniques and materials used, which includes stone, brick and earth construction.
- In Greece, the risk of overheating is particularly worse for low income households due to poor quality of housing with no or minimal insulation, single glazing, lack of adequate ventilation and shading, and often higher than average housing densities that worsen the urban heat island effect. The running cost of air-conditioning is also as much has 3 times higher for such households compared to high income households. Hourly indoor temperature data from 50 low income houses in Athens showed that mean indoor temperatures during the hot season were 4°C above external (Sakka et al, 2012).

Key attributes in terms of building design and construction to mitigate overheating risk include thermal mass coupled with night time ventilation, shading of windows, building orientation, and passive cooling systems (such as ground cooling and evaporative cooling). The PREBAT study observed that low energy buildings have an inherent tendency to retain heat due to the high insulation levels, but this was more than balanced by reduced external heat gains from opaque surfaces. The impact of high levels of insulation on thermal comfort is dependent on the building's potential for night time ventilation. Reducing solar gains through effective window shading and use of thermal mass is also critical to dampen the effect of the heat gains. However, it was noted in discussions with Professor Mat Santamouris that increasing insulation levels over a certain threshold may tend to increase the risk of overheating and in turn the cost of active cooling.

External finishes also have an impact on solar gains through opaque surfaces. For instance, it is typical in south of France and in certain parts of Greece to paint external walls in white, which increases reflectivity and reduces heat gain through the fabric.

The discussions highlighted that there is no single strategy that fits all buildings, and mitigation approaches will need to respond to the locational attributes, construction practices and occupant behavioural aspects. In Germany, for instance, it is very common practice for new buildings to have external shutters for solar shading. Cool roofs feature in Greek vernacular architecture but may be less relevant to modern insulated buildings. The degree of mitigation desired is also a function of cultural and physiological differences in local population (and inherent differences in expectation around comfort temperature) and therefore the mitigation strategies adopted in say southern Europe may not always be directly relevant to northern climates.

Occupant behaviour has been found to be a critical factor affecting overheating risk. The PREBAT study observed that where building occupants were more proactive in the thermal control of their buildings, such as use of solar shading during the daytime and opening windows at night, then this significantly affected summer thermal comfort. The study found instances where some buildings in northern France were more prone to overheating than those in the south, with occupant behaviour cited as being a crucial determinant. Occupants in the Mediterranean region were much more aware of how best to use the building features to mitigate overheating while those in northern France were less so. There were also instances where the internal temperatures varied by around 4°C in the different flats within a block depending on the use of solar protection, opening of windows and internal heat gains. Where, for instance, flats facing north/ north-east did not open windows at night, these were found to be hotter than those that did and faced south. Informing building users on good practice is therefore an important part of managing overheating risk in homes.

7. Options to assist housebuilders in assessing overheating risk

A key activity in Phase 2 of the project is to develop a tool, method or guidance which assists house builders in both assessing the overheating risk in new homes and implementing the most cost effective mitigating measures to address any risks identified. The project team have engaged with house builders in Phase 1 to identify what option(s) would be of most benefit and the conclusion of this are summarised here.

A workshop was held with housebuilders including representatives from the Home Builders Federation (HBF), the Federation of Master Builders (FMB) and a Housing Association. The workshop also included representatives from both CIBSE and NHBC who have each produced guidance on overheating in homes and could be a route for any future guidance. It is important to note that this workshop was held part way through Phase 1 when the results from the modelling were not yet available. Information gained from this workshop is supplemented by feedback from the second Research Group meeting for which the results of the modelling were available.

Currently all builders assess the risk of overheating using SAP Appendix P as required by Part L of the Building Regulations. More detailed software packages, such as dynamic thermal modelling, are used particularly for larger developments and such analysis is commonly required in London by the GLA as part of the planning process. Whilst there is awareness of sources of overheating guidance, the developer‘s participating in the workshop did not particularly use them.

A number of gaps were identified in terms of guidance/tools, which are summarised below.

– There is a lack of a clear definition of the risk of overheating for new homes. Most attendees to the workshop were unaware of the new CIBSE TM59 definition. It was suggested that it may be necessary for the current technical definition used as a basis for modelling the risk of overheating to be presented more simply for the less technical reader.

– There is a need for a robust but relatively simple-to-use overheating assessment tool that accounts for future weather and location. The current version of SAP Appendix P was viewed as too simplistic whereas dynamic thermal modelling was seen to be overly complex and costly. An alternative could be that SAP is simply used as a warning check which requires more detailed modelling (e.g. dynamic thermal modelling) where the risk is identified as high. There was a more general concern around the confidence of thermal models as good predictors of overheating but an understanding that they are the best assessment tools currently available.

– There is a need for simple guidance on mitigation strategies and their cost-effectiveness. It may be possible to produce a decision tree where based on the dwelling type, location and other characteristics, appropriate approaches to mitigation can be recommended. Given the number of potential variables that affect overheating, this may be best focussed on standardised designs for more common situations. The guidance should be very visual and easy to understand.

- More generally it was suggested that it would be useful to have an information hub which references the most current authoritative guidance. This should include up-to-date case studies which demonstrate both good and bad practice.
- It was highlighted that it was important to carefully consider the overheating risk and any necessary mitigation strategies during the planning stage as many key factors are decided at this stage e.g. glazing area, orientation, single vs dual aspect dwellings. It was further emphasised that it would be too expensive to undertake detailed thermal modelling generally prior to planning.
- There was a concern that improved guidance and/or tools on their own would be insufficient. There would need to be a legal requirement for developers to adopt CIBSE TM 59 for example. This also results in a similar playing field for all developers i.e. developers may currently choose not to spend money on more detailed overheating assessments and/or install additional risk mitigation measures if other developers are not doing so. It was noted that DCLG branding of guidance and/or tools may be seen by some as a de facto regulatory requirement.

It is useful to review this in light of the modelling results. Dynamic thermal simulation modelling carried out using the TM59 methodology indicates a high risk of overheating for all dwelling typologies and locations modelled. Hence, within the scope of this project, it is proposed that it is best to focus resources on simple guidance on mitigation strategies and their cost-effectiveness. If possible, the mitigation strategies recommended should reflect to some degree the overheating risk e.g. greater measures may be required for central London where it is projected to be warmer with greater number of hours exceeding the compliance thresholds than for a more northerly location.

8. Conclusions

The results of the dynamic thermal simulation modelling indicate a significant risk of overheating for new homes in general across England without the application of mitigation measures. The new CIBSE TM59 methodology for assessing the risk of overheating in homes has been applied to eight dwelling types representative of new homes, each modelled in five locations across England using IES-VE software, and in each case the dwelling has failed the TM59 overheating compliance criteria.

The analysis shows that the risk of overheating does depend on dwelling location and typology. In particular, it identifies a greater risk of overheating in southern England locations. The compliance criteria are based on an allowable percentage of hours that the dwelling can exceed a threshold value and, for example, the results show that certain flat typologies in locations in southern England exceed the allowable percentage of hours by more than 6 times. Any mitigation strategy needs to account for such variations to be most cost-effective.

The evaluation is based on Category I occupancy, i.e. it assumes that the dwellings may be occupied by vulnerable persons and as a result the compliance criteria is more stringent. However, to at least partly balance this, the criteria do not include allowance for relative humidity which can affect thermal comfort, particularly at elevated temperatures.

The analysis highlights that the overheating assessment is sensitive to the input parameters and assumptions, as well as the choice of modelling software itself. It would be valuable to validate further some of the assumptions (e.g. around occupant behaviour) and the modelled outputs, as well as the overheating criteria themselves. However, the Government needs to consider carefully whether to delay action until the results of such research. Given the Government's ambition for one and a half million new homes to be built by 2022 and without a significant consideration of mitigation strategies now, it may well result in more expensive and energy and carbon intensive retrofit measures later (e.g. occupants subsequently retrofitting air conditioning rather than developers designing in passive measures at the design stage).

It is certainly recommended beneficial to implement Phase 2 of this project now and undertake a cost benefit analysis of alternative mitigation measures. Sensitivity analysis can be undertaken to account for uncertainties in the overheating assessment. Some significant measures are likely to be able to be delivered at relatively low-cost, in particular the risk of overheating is significantly dependant on occupant behaviour such as window opening patterns.

It is proposed that Phase 2 also includes the production of simple guidance for developers on mitigation strategies and their cost-effectiveness. This is based on feedback from developers and others within the project's Research Group within Phase 1. A decision tree could be constructed based on the dwelling type, location and other characteristics, and appropriate approaches to mitigation can be recommended depending on what decision path is followed. Given the number of potential variables that affect overheating, this may be best focussed on standardised designs for more common situations. Whether the Government decides or not to regulate for overheating in new homes, this guidance should be useful to developers who wish to look to mitigate the risk of overheating. DCLG may also wish to consider complementary guidance for occupants to best adjust their behaviour to remain comfortable during summer months.

During Phase 1, additional analysis has been undertaken to prepare for Phase 2. In particular, this has included a review to better understand the implications of overheating on health and productivity. Given this increased knowledge, it is recommended that DCLG and the project team meet prior to the commencement of Phase 2 to review the scope of the cost benefit analysis and refine it as necessary.

Appendix A Pros and cons of alternative modelling methodologies

The pros and cons of the alternative modelling methodologies and tools are outlined in the table below. This is not intended to be an exhaustive list but has been helpful in identifying the appropriate methodology to adopt for this project.

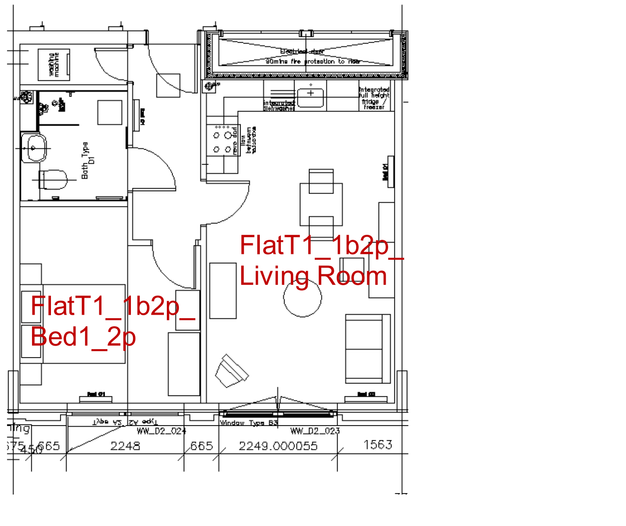
Methods	Pros/ Cons	Functionality
SAP	Pros (+)	- very quick calculation process - takes account of internal gains - takes account of thermal mass - suited to high level sensitivity analysis - industry access to tool and technical support
	Cons (-)	- not dynamic analysis - based on monthly mean temperature - fixed ventilation rates from openings - internal load profiles are fixed - does not take account of humidity and latent gains - not robust in terms of predicting overheating - moisture / humidity analysis not considered
CIBSE Admittance	Pros (+)	- very quick calculation process - user can define hourly internal load profiles - suited to sizing cooling plant - takes account of humidity and latent gains from occupants
	Cons (-)	- not suitable for working with annual hourly weather data - tends to over-predict summer time temperatures
DTM	Pros (+)	- fairly quick calculation process - takes account of internal gains - takes account of thermal mass - takes account of humidity and latent gains from occupants - user can define hourly internal load profiles - suited to detailed sensitivity analysis - able to model bulk air movement using standard wind pressure coefficients

Methods	Pros/ Cons	Functionality
		- industry access to tool and technical support - well suited for working with annual hourly weather data
	Cons (-)	- results may differ depending on software used - do not take account of temperature stratification (i.e. each thermal zone is assumed to be fully mixed) - most DTM packages do not take account of moisture transfer with building fabric
CFD	Pros (+)	- takes account of internal gains - takes account of thermal mass - takes account of humidity and latent gains from occupants - user can define hourly internal load profiles - suited to detailed sensitivity analysis - able to model detailed air movement through window openings due to buoyancy, turbulence and wind pressures - takes account of temperature stratification - takes account of humidity and latent gains from occupants
	Cons (-)	- very time intensive compared to DTM, in particular to run transient analysis over a year - not robust at modelling solar gains - not suited to transient analysis with annual hourly weather data, hence unsuitable for assessing risk of overheating - does not take account of moisture transfer with building fabric - current licence and technical support costs mean these are not widely accessible to industry

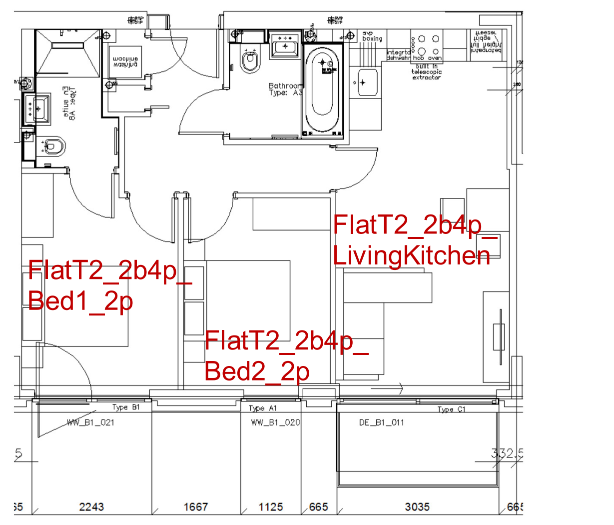
Appendix B Detailed modelling assumptions

B.1 Geometry

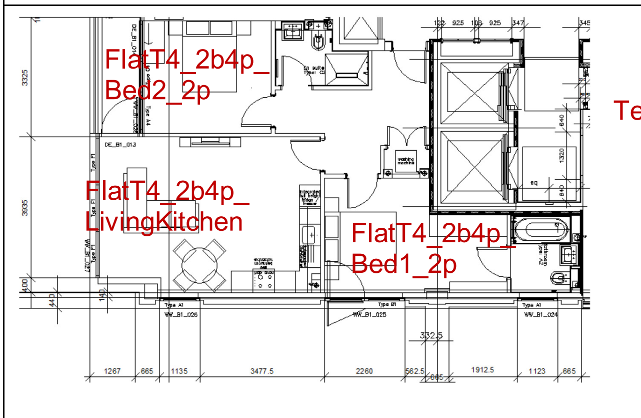
Figure 22: Layouts of dwelling typologies used for the overheating analysis



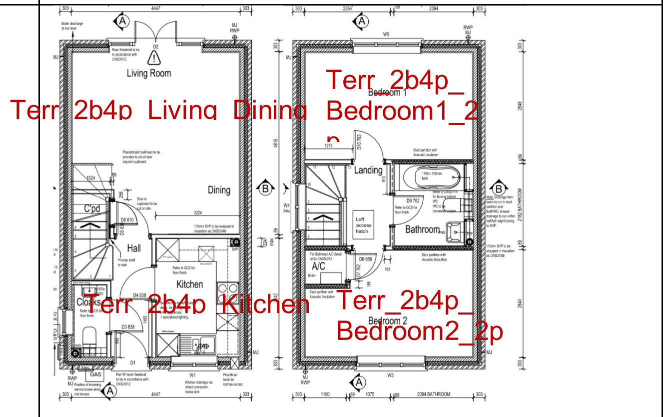
Type 1 – 1b2p apartment single aspect



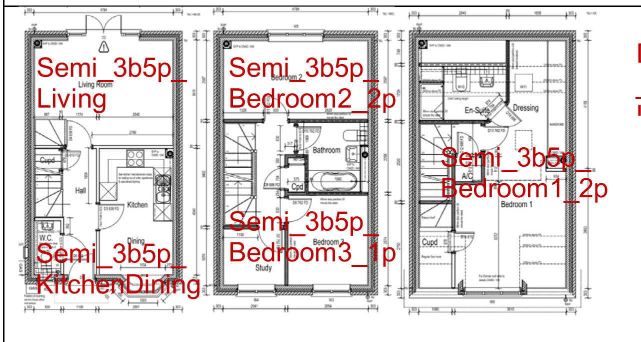
Type 2 & 3 – 2b4p apartment single aspect



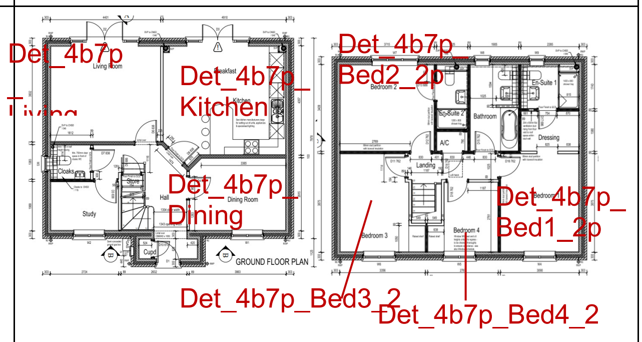
Type 4 & 5 – 2b4p apartment dual aspect



Type 6 – 2b4p terraced house



Type 7 – 3b5p semi-detached house



Type 8 – 4b7p detached house

Figure 23: Dwelling elevations

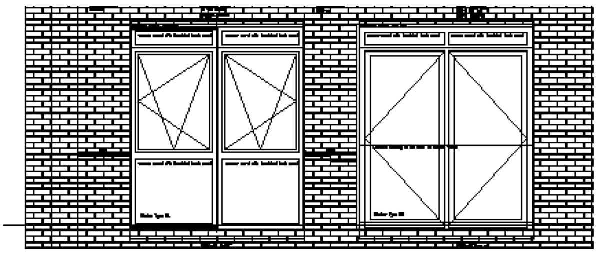
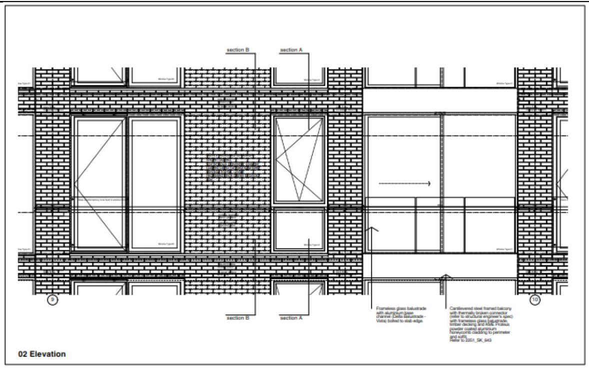
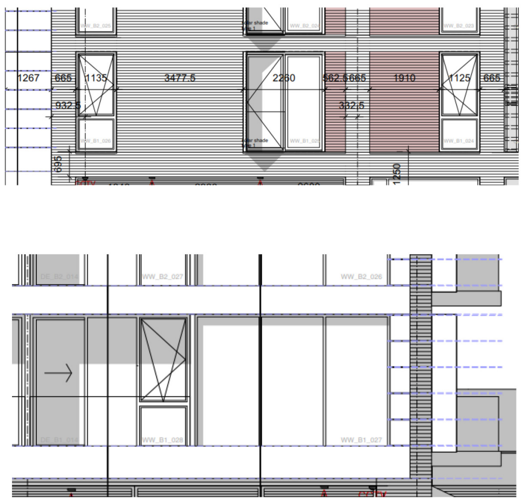
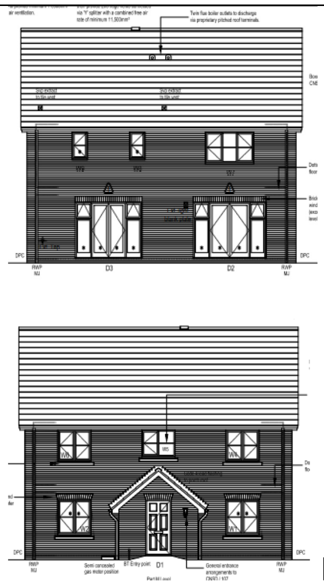
	
Type 1 – 1b2p apartment single aspect	Type 2 & 3 – 2b4p apartment single aspect
 S W	 S N
Type 4 & 5 – 2b4p apartment dual aspect	Type 6 – 2b4p terraced house
 S N	 S N
Type 7 – 3b5p semi-detached house	Type 8 – 4b7p detached house

Table 4: Dwelling dimensions

Dwelling type	Total floor area (m^2)	External wall area* (m^2)	Ground floor area (m^2)	Roof area (m^2)	Window area (m^2)	Glazed doors (m^2)	Openable glazing incl. glazed doors (m^2)	Storey height
Type 1	46.2	19.3	-	-	10.2	0.0	8.1	2.7
Type 2 & 3	61.2	24.5	-	-	10.0	7.0	9.0	2.7
Type 4 & 5	72.1	60.0	-	-	25.2	8.9	19.9	2.7
Type 6	70.3	44.0	35.2	35.2	8.4	2.5	7.8	2.4/2.6 (Gnd/1st)
Type 7	113.8	125.1	38.2	52.7¤	13.7	2.8	9.7	2.4/2.6/2.6 (Gnd/1st/2nd)
Type 8	139.3	172.1	71.0	71.0	16.7	6.0	15.2	2.4/2.6 (Gnd/1st)

* including windows and doors

¤ area of pitched roof

B.2 Occupancy and equipment loads

Table 5: Occupancy, lighting and equipment loads in the apartments

Room types	Max. no. of people	Occupancy (Sensible) W	Lighting W/m²	Equipment W	Occupancy, lighting & Equipment Schedule
Bedrooms - Double	2	150	2	80	In line with CIBSE TM59
Bedrooms - Single	1	75	2	80	In line with CIBSE TM59
Living room/Kitchen – 1bed	1	75	2	450	In line with CIBSE TM59
Living room/Kitchen – 2bed	2	150	2	450	In line with CIBSE TM59
Corridors	-	-	2	-	N/A
Bathroom	-	-	-	-	N/A
Toilet	-	-	-	-	N/A
Store	-	-	-	-	N/A

Table 6: Occupancy, lighting and equipment loads in the houses

Room types	Max. no. of people	Occupancy (Sensible) W	Lighting W/m²	Equipment W	Occupancy, lighting & Equipment Schedule
Bedrooms - Double	2	150	2	80	In line with CIBSE TM59
Bedrooms - Single	1	75	2	80	In line with CIBSE TM59
Living/Dining – 2bed	2	150	2	150	In line with CIBSE TM59
Living room – 3bed	2	150	2	150	In line with CIBSE TM59
Living room – 4bed	3	225	2	150	In line with CIBSE TM59
Kitchen – 2bed	2	150	2	300	In line with CIBSE TM59
Kitchen/Dining – 3bed	2	150	2	300	In line with CIBSE TM59
Kitchen – 4bed house	3	225	2	300	In line with CIBSE TM59
Dining – 4bed	3	225	2	150	In line with CIBSE TM59
Study – 3bed	0	-	2	80	Lighting & Equipment schedule as in bedrooms
Study – 4bed	0	-	2	80	Lighting & Equipment schedule as in bedrooms
Dressing	0	-	2	-	Lighting schedule as in bedrooms
Bathroom	0	-	-	-	N/A
Toilet	0	-	-	-	N/A
Store	0	-	-	-	N/A

Table 7: Heat gains from hot water storage in houses and communal heating in corridors

Room types	Storage required (litre)	Standing loss (W)	Schedule
House – 2 bed	170	50	Continuous
House – 3 bed	210	59	Continuous
House – 4 bed	250	67	Continuous
Communal Corridors with District heating*	n/a	420	Continuous

* Losses from a communal heating system are based on an average 10W/m loss over a 21m long corridor and multiplied by 2 for both flow and return pipes. For pipe sizing, an apartment block is assumed to have more than 5 apartments on each floor.

B.3 Ventilation rates

Infiltration Rates

The air infiltration rates have been calculated from CIBSE Guide A[22] based on the air-permeability rates set out in Table 2.

- Naturally ventilated mid and high-rise apartments: 0.43 ach
- Mechanically ventilated mid and high-rise apartments: 0.25 ach
- Houses: 0.30 ach

All unheated loft spaces in the houses have an assumed infiltration rate of 1.0 ach. Note that no further allowance has been made for background (trickle) ventilation or intermittent extract ventilation in the naturally ventilated houses and apartments.

Mechanical Extract Ventilation in Apartments

The apartment typologies located in the South and South-east, i.e. the weather files for London Weather Centre, London Heathrow and Southampton have MEV (Mechanical extract ventilation), with supply in bedrooms and living rooms and extract from bathrooms and kitchens. The ventilation rates are taken from the Approved Document F, Table 5.1b. The following rates are assumed to be on continuous;

- Apartments – MEV – 1 bed (46m^2): 13.8 l/s
- Apartments – MEV – 2 bed (62m^2): 21 l/s
- Apartments – MEV – 2 bed (72m^2) corner: 21.6 l/s

Note, in Approved Document F a 2-bed dwelling is assumed to have 17 l/s if the second bedroom is occupied by 1 person. As the 2 bed typologies both have double bedrooms an additional 4 l/s per occupant has been added. Also, a minimum rate of 0.3 l/s is required per m^2 area and therefore the ventilation rate for the1- bed and the 2-bed corner apartments have been adjusted to meet this criterion.

Table 8: Airflow rates for MEV system in apartments

	Supply (litres/ sec)				Extract (litres/ sec)		
Room types	Total MEV	Living rooms	Bedroom1	Bedroom2	Kitchens	Bathroom	En-suite
1bed apartment	13.8	6.9	6.9	-	8.5	5.3	-
2bed apartment	21.0	7.0	7.0	7.0	9.4	5.8	5.8
2bed apartment corner	21.6	7.2	7.2	7.2	9.6	6.0	6.0

[22] Refer Table 4.24

Appendix C References for literature review

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