AN INVESTIGATION INTO FUTURE PERFORMANCE AND OVERHEATING RISKS IN PASSIVHAUS DWELLINGS

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ABSTRACT

In response to UK government policy mandating the construction of 'zero carbon' homes by 2016 there have been significant changes in the way dwellings are being designed and built. Recent years have seen a rapid uptake in the adoption of the German Passivhaus standard as a template for ultra-low energy and zero carbon buildings in the UK. Despite genuine motivations to mitigate climate change and fuel poverty there is a lack of research investigating the long-term performance of Passivhaus buildings in a rapidly changing UK climate. This paper sets out to investigate whether Passivhaus dwellings will be able to provide high standards of thermal comfort in the future or whether they are inherently vulnerable to overheating risks. Scenario modelling using probabilistic data derived from the UKCP09 weather generator (WG) in conjunction with dynamic simulation and global sensitivity analysis techniques are used to assess the future performance of a range of typical Passivhaus dwellings relative to an identical Fabric Energy Efficiency Standard (FEES) compliant dwelling over its notional future lifespan. The emphasis of this study is to understand what impact climate change will pose to overheating risks for Passivhaus dwellings relative to the de facto (i.e. FEES) alternative, and which design factors play a dominant role in contributing to this risk. The results show that optimization of a small number of design inputs, including glazing ratios and external shading devices, can play a significant role in mitigating future overheating risks.

Keywords: Overheating; Thermal comfort; Thermal mass; Global Sensitivity Analysis; Enhanced Morris method; Building simulation

1 INTRODUCTION

In response to the UK government's overarching climate change mitigation strategy [1,2] and the recast European Energy Performance in Buildings Directive (EPBD) [3] targets have been set for the implementation of a revised 'zero carbon' dwelling standard in the UK by 2016 [4,5,6]. As a result of these legislative drivers and the voluntary adoption of advanced performance standards, such as the Passivhaus standard, there have been significant changes in the way dwellings are being designed and constructed both in the UK and across Europe.

Over the past decade the evolution of Approved Document L1A (Conservation of fuel and power for new dwellings) of the UK Building Regulations [7] has prioritised incrementally reducing space heating consumption, since this has historically dominated the CO_2 emissions profile of UK dwellings [8]. Attempts to further reduce energy consumption and $CO_{2\,e}$ emissions in Passivhaus, FEES and advanced performance standards have largely focused on reducing thermal transmission losses and making optimal use of passive solar gains [9,10] whilst less attention has been paid to whole-life performance issues such as long-term thermal comfort and occupant wellbeing.

Implementation of these advanced performance standards is taking place against a background of rapid climatic change. Bows and Anderson [11] suggest that a revised interpretation of atmospheric $CO_{2\,e}$ concentration indicates that stabilization much below 650 ppmv by the end of this century is now improbable. Earlier predictions by Meinshausen [12] estimated the mid-range probability of exceeding a 4°C threshold at approximately 40 per cent for 650 ppmv. Bows and Anderson [11, p18] state that "given this analysis has not factored in a range of other issues with likely net positive impacts, adapting for estimated impacts of at least 4°C appears wise." A 4°C, average global temperature, increase by the end of this century is consistent with the Intergovernmental Panel on Climate Change (IPCC) best estimate for the A1FI trajectory, commonly known as the 'High' emission scenario, [13; table 3.1]. Reframing likely emissions in this light suggests that modelling the impacts of the A1FI scenario on the built environment can no longer be regarded as a cautionary approach.

The risk of perverse consequences in the form of exacerbated overheating risks in super insulated Passivhaus dwellings have been highlighted in a number of Northern European [14,15,16,17]), Central European [18,19,20] and Southern European [21,22] reports. Larsen and Jensen [16, p1] conclude that, "the large focus on energy performance has reduced the focus on indoor environment.

This has amongst other problems, resulted in problems with overheated buildings." These finding suggests that there may be an emerging conflict between the implementation of such standards and the policy recommendations set out in Article 4 of the recast EPBD ,which states; "These requirements shall take account of general indoor climate conditions, in order to avoid possible negative effects…"[3, p19].

Despite documented reports of overheating in UK (and neighbouring Republic of Ireland) Passivhaus dwellings [23,24] the subject has received only scant consideration in the scientific literature. However as attention focuses on the development of a national methodology to meet the 2016 'Zero Carbon' target, awareness of the potential for unintended consequences associated with super-insulated airtight dwellings is mounting. In 2010 the Zero Carbon Hub (ZCH) cautioned that, "There is some anxiety that homes we are building today may be at risk of overheating even in the current climate. Given the prospect of significant warming, well within the expected lifetime of homes, this risk will increase with potentially serious consequences." [25, p7]. In a comprehensive review of the evidence of overheating in new UK homes, Dengel and Swainson conclude that there is, "a growing body of evidence that modern energy efficient, i.e. well insulated, airtight dwellings are suffering from overheating, and that in some cases this is resulting in adverse health effects for the occupants of these properties" [26, p19]. In light of these findings, this paper sets out to answer three questions that are central to gaining a better understanding of these issues:

1) Do Passivhaus dwellings, as currently designed in the UK, offer a robust model in the face of future climatic changes?
2) Will Passivhaus dwellings perform better or worse than an equivalent FEES 'Zero Carbon' dwelling faced with identical climatic change scenarios?
3) What are the key design variables influencing the future performance of Passivhaus dwellings?

2 BACKGROUND - AN OVERVIEW OF PASSIVHAUS AND LOW ENERGY BUILDING PERFORMANCE

The Passivhaus standard is generally considered to be a low energy building performance standard; characterised by super insulated, airtight envelopes, the use of mechanical ventilation with heat recovery (MVHR) and optimal use of passive solar gains. However, achieving clearly defined thermal comfort criteria are also central to the concept. The functional definition of a Passivhaus, states that: "A Passive House is a building in which thermal comfort can be guaranteed solely by heating or cooling of the supply air which is required for sufficient indoor air quality – without using additional recirculated air" [27].

A detailed description of the technical requirements for achieving quality approved Passivhaus status are described in the Passive House Planning Package, Version 7 [28]. The adoption of the Passivhaus concept in the UK is a relatively recent occurrence, with the first certified Passivhaus buildings being completed in 2010 [29]; as a result only minimal post occupancy data is available to date. Elsewhere in Europe a number of studies that have reported on overheating risks in Passivhaus dwellings and the key findings are summarised in section 2.1. Climate change and heat waves are likely to have significant implications for the future UK built environment and the main findings are summarised in section. 2.2. Thermal comfort and the impacts of overheating on human health are issues which are central to the assessment of future overheating risks, and the main implications are summarised in section 2.3.

2.1 Overheating risk in Passivhaus buildings

A number of studies have reported specifically on overheating and the summer performance of Passivhaus buildings in a variety of European climatic zones. A finding common to many of these studies is that the occupants of Passivhaus dwellings often report better thermal comfort in winter than in summer [30,31,32,33,34] . Contrary to this finding, there are also a number of reports, based on Post Occupancy Evaluations (POEs) and monitoring carried out by the Passivhaus Institute, indicating high levels of occupant satisfaction under summer conditions [35,36,37,38,39].

Studies documenting overheating in certified Passivhaus buildings located in Northern Europe warrant further investigation since they are of considerable relevance to the UK climatic context. In Skibet, Denmark, Larsen and Jensen [16] carried out data logging of the internal environment of 10 certified Passivhaus dwellings. The Skibet development is located at 55.7 North (a latitude which is slightly south of Glasgow, UK). They recorded data for dry bulb temperature (dbT), relative humidity (RH) and CO_2 levels in multiple locations from 2008 to 2011. The data recorded in this study was then compared to the criteria set out in category B of DS/CEN/CR1752 [40], which specifies an acceptable summertime dry bulb range from 23 to 26°C. The results for the month of July for the 2009 interval show that this criterion was exceeded 40% of the time. In 2010 the same criteria was exceeded 60% of the time, resulting in severe overheating [16]. One factor contributing to the difference in the duration of overheating was attributed to different occupant ventilation patterns and another to different weather patterns experienced over the two summer periods. What is notable is that such a prolonged overheating risk was not predicted by the PHPP model of the certified dwellings, however it was subsequently replicated by a dynamic simulation programme (DSP) BSim [41] and also via manual calculation in accordance with SBI instruction 202 [42].

A similar study carried out in Lindås, Sweden showed that mean summer temperatures of 25.2°C were recorded in a group of 20 terraced apartments built to the Passivhaus standard [43] (Ruud and Lundin, 2004). Significant variability was recorded in the internal temperatures between apartments with some recording acceptable conditions and others reaching internal temperatures of up to 30°C in summer. Further Post Occupancy surveys carried out in the Oxtorget, Glumslöv and Frillesås districts of Sweden also reported thermal discomfort due to overheating. In the worst case, 56% of the Passivhaus residents in the Glumslöv district reported their indoor temperature as too warm during the summer period [44].

By examining the performance of Passivhaus dwellings in climatic zones that are already warmer than the present day UK climate, it might be possible to infer the likely impacts of future climatic change. However, few studies have investigated the performance of dwellings built to a full Northern European Passivhaus specification in a Southern European context (primarily, because they are seldom built to the same specification). As part of the Passive-On project, Schnieders [21] set out to determine the optimal performance characteristics of a cost efficient model of a Passivhaus dwelling located in Marseille. In this study Schnieders used a DSP model (Dynbil) to simulate the performance of an end-terrace Passivhaus, based upon a design previously used in the Hannover-Kronsberg development [46]. Four variants of the 'First Guess' Passivhaus were modelled to assess performance differences between the use of a well-insulated fabric U values ($\leq$0.15 W/m^{2}K) with a less well insulated alternative U values (circa 0.25 W/m^{2}K). The buildings were modelled with both double (U value 1.19 W/m^{2}K, g value 0.64) and triple glazing (U value 0.71 W/m^{2}K, g value 0.5) options, with and without heat recovery ventilation (μ_{HR} =0.75) using a typical weather year [47] for Marseille. The maximum temperature in this weather year is 34°C with a summer monthly average of around 25°C [21]. The findings of this study are interesting because they show that over the year the dwelling with the lowest annual heating demand resulted from the *least* insulated fabric in conjunction with double-glazing and no heat recovery system. In term of overheating mitigation all dwellings were modelled with night purge ventilation and automated external blinds. Despite these interventions the goal of not exceeding the overheating threshold, defined by the PHI as 25°C for 10% of the year [28] was not be met in any of the prototypes. Furthermore, without active cooling, maximum temperatures

exceeding 27°C were recorded in bedrooms. However when cooling was applied to maintain the supply air temperature below 25°C, the well-insulated triple glazed variant with Heat Recovery ventilation recorded a slightly lower cooling demand than the other variants [21].

In a larger study Schnieders [22] used different thermal specifications, and cooling strategies to examine the feasibility of the Passivhaus concept in twelve different reference locations across Southern Germany, Italy, Southern France and the Iberian Peninsula. Schnieders concludes that the Passivhaus concept is able to provide a comfortable indoor climate, in accordance with EN/ISO 7730 [48] in all twelve locations exclusively by pre-conditioning (i.e. active cooling of) the supply airflow. Schnieders points out that (in summer) solar control; via external shading, reduction of solar load through opaque elements and minimising internal heat loads are decisive characteristics in maintaining thermal comfort. Night purge ventilation and to a lesser extent ground coupling were considered critical factors in removing heat from the building, with supply air cooling providing the remaining cooling and dehumidification requirement. Carrilho da Graça et al [49] came to similar conclusions in a comparative study of two Net Zero Energy Home (NZEH) prototypes in a Southern European context (Lisbon). Comparing a conventional highly glazed NZEH (using internal shading) with an almost identical moderately glazed Passivhaus (using external shading) Carrilho da Graça et al (2012) found that the highly glazed house had substantially higher overheating risks, with living room temperatures exceeding 28°C for more than 46% of the summer season. In contrast, the externally shaded Passivhaus rarely exceeded this threshold.

In addition to the heating and cooling demands being lower than for conventional dwellings Schnieders [22] found that the peak heating and cooling loads where also less pronounced and internal temperature fluctuations were lower regardless of whether active cooling was applied. From a design perspective, Schnieders cautioned, "it is important to note that the differences in climates and the effects of individual building parameters are so large that a dedicated energy balance must be set up for every Passive House. The use of standard values for different buildings is not appropriate" [22, p279]. These findings highlight the parametric sensitivity of Passivhaus and ultra-low energy buildings, reinforcing the need to study these issues in context.

Evidence suggests that the overheating risks in Passivhaus dwellings are highly dependent on context, and are strongly influenced by both user behaviour; including ventilation patterns, shading strategies and internal gains [16,33] as well as the building's thermal specification [21,22]. Notably in almost every case external shading was required to maintain summer thermal comfort. Schnieders DSP modelling in a South West European context was predicated upon automated external shutters closing whenever the ambient temperature exceeded 23°C [22, p268]. Relatively little is known about the acceptability of such strategies to domestic occupants. A number of authors [49,50,51,52] have suggested that the operation of blinds is determined primarily by visual comfort requirements and not by indoor temperature; however, all of these studies have assessed non-residential buildings. To date full external shading devices have been seldom used in UK residential buildings. A recent post occupancy evaluation of the Welsh, Larch and Lime, Passivhaus dwellings supports the finding that occupant use of external shading devices is driven by visual and psychological comfort criteria and not temperature regulation [23].

2.2 A changing climate and its impact on buildings

Observed climatic trends for the UK show that, between 1961 and 2006, maximum summer temperatures across the South East had increased by 2°C on average and in Greater London by up to 2.7°C [53]. According to the United Kingdom Climate Projections (UKCP09) even under a Medium emissions scenario by 2080 the summer average temperature (at the 50th percentile) is estimated at 5.4ºC higher than the 1961–1990 baseline (2.2 to 9.5ºC, 10th - 90th percentile) in parts of southern England. Summer mean cloud cover is predicted to decrease over this period by up to –18% (–33 to –2%, 10th - 90th percentile) in parts of southern UK, resulting in an extra +16 Wm^{-2} (–2 to +37 Wm^{-2}, 10th - 90th percentile) flux in downward shortwave radiation [54].

Along with the overall warming trend and higher irradiation levels suggested by these probabilistic estimates, the frequency of extreme weather events including heat waves is also predicted to increase. According to the UK Office of National Statistics during a ten-day period in August 2003 more than 2000 excess mortalities occurred in England and Wales as a result of a heat wave [55]. Persons over 75 years of age, in London, were the most severely affected group during this period with an excess mortality rate 59% higher than reference levels [56]. Although the term 'heat wave' does not have a generally accepted definition in the UK, one study proposed a working definition as 'a continuous set of days when the average temperature was above 20°C' [58]. Hajet et al [58] proposed a more precise definition based on the three-day rolling average value (at the 97th percentile value) exceeding 21.5°C. Whilst the UK Health Protection Agency have defined a heat wave as a period when daily mean temperatures on the current day, and at least the previous two days are above the 98th percentile of the whole year temperature distribution [59]. According to this definition, a present day heat-wave in London would correspond to daily mean temperatures of 22.6°C or higher occurring for three of more days.

During the 2003 heat wave, maximum daily Central England Temperature (CET) exceeded the baseline (1971 – 2000) reference values by 8°C. In London a daily maximum of 37.9°C was recorded with overnight lows as high as 26-27°C in some areas [56]. In a monitored study carried out during this heat wave Wright et al [57] compared internal temperatures in four blocks of London flats and one semi-detached dwelling. They found that average internal temperatures were above 27°C in every room in all of the dwellings throughout the weeklong monitoring period. In one block of flats, the mean internal temperature was recorded as 29.9°C during this period (peaking at 39.2°C).

Although the occurrence of 'heat wave' events is currently infrequent MetOffice predictions suggests that by the 2080's daytime summer temperatures might exceed 42°C in lowland England as often as once a decade, under a 'High' emissions scenario [57]. As a consequence it is likely that previous maximum temperature records will be more frequently exceeded in a changing climate [60]. Met Office analysis [61] indicates that by 2040 the heat wave of 2003 could reflect average summer conditions. By 2060 this same event would represent a cooler than average summer under a Medium-high (A2) emissions scenario (Figure 1).

Figure 1. Temperature anomaly of 2003 heat wave in relation to Medium High emission trend© Crown Copyright, Met Office.

In a future characterised by significantly warmer summer temperatures and an increase in extreme climatic events [54,62] active cooling may become necessary to maintain thermal comfort and even to safeguard life [63]. The use of domestic air conditioning in the UK is estimated to be rising by 8% per year [64], a phenomenon which could result in an additional six million tonnes of CO_2 emissions by 2020 [65]. Unless they are extensively subsidised, the ownership of cooling systems is likely to reflect socioeconomic inequalities. O'Neill et al [66] noted that the prevalence of central air-conditioning amongst black households, in four US cities, was less than half that of white households; resulting in greater vulnerability to heat related mortality. Ownership of an air conditioning system does not guarantee immunity from heat related health affects however, since major power blackouts have historically occurred during periods of high heat stress [63]. In light of these risks the UK Health Protection Agency have suggested that "Passive cooling options (building orientation, shading, thermal insulation, choice of construction materials, etc.) implemented at the design stage of urban developments may be equally effective as active cooling in reducing the health burden of heat and would be environmentally sustainable options" [59, p47].

The precise point at which overheating occurs and active cooling is required is central to the assessment of risk, and yet there is no precise or accepted definition of overheating in the UK [26, p7]. To date much of the building performance literature has been concerned with the contiguous issue of thermal comfort; whilst the thresholds at which overheating contributes to elevated health risks have been largely ignored. How thermal comfort and overheating risks are defined will strongly

influence the outcome of any overheating investigation and these issues are addressed in the Methodology (section 3). The question of whether the Passivhaus concept can delay the onset of overheating and is inherently less vulnerable to heat related risks (in comparison to a conventional dwelling) is highly relevant to adaptation planning, as well as wider mitigation strategies. Faced with a contiguous increase in both economic and social risk factors, including de-rated electricity supply margins [67,68] and an ageing population [69]; this question is likely to become increasingly relevant.

2.3 Thermal comfort and its impact on human health

From the perspective of evaluating thermal comfort in relation to overheating, an overheating metric and comfort range are typically defined. The two most widely adopted thermal comfort models are the Heat Balance model (as found in EN 7730 -2006 [48]) developed by Per Ole Fanger [70] and the Adaptive model (as found in ASHRAE 55-2004 [71] and EN 15251-2007 [72]) and presented in the work of de Dear et al [73], Nicol et al [74] and Humphreys and Nicol [75]. Berglund [76] provides an overview of some of the main mathematical models used for predicting thermal comfort.

From a practical perspective Nicol et al [77, p355] acknowledge that where the adaptive criteria 'is determined by both the building category and the mean external dry bulb temperature for a number of previous days, then the measurement and ultimate determination of overheating becomes more complex.' Many building performance studies have used consistent indices of thermal comfort in preference to running means [22, 78, 79, 80] although many of these authors also acknowledge that there is likely to be a difference between current and future thermal comfort thresholds. In the UK, CIBSE Guide A [81] states that (in warm summer conditions) 25°C is an acceptable operative temperature (OT) in the living area of dwellings and 23°C is acceptable for bedrooms. CIBSE Guide A defines 'overheating' as occurring when the OT exceeds 28°C for more than 1% of the annual occupied hours in the living areas of (free running) dwellings or when the bedroom OT exceeds 26°C for more than 1% of the annual occupied hours (unless ceiling fans are available). This assessment is based on a warmer than average summer, using a DSY dataset. It should be noted that CIBSE TM 36 recommends a slightly lower limit (of 25°C) should be regarded as the upper limit of acceptability for the temperature of sleeping areas [82], citing evidence from Thomas et al [83].

CIBSE Guide A [81] also offers an adaptive method of assessing the acceptable OT using an exponentially weighted running mean of the daily mean ambient air temperature (T_{rm}) at a rate of 0.33K per K. The upper and lower comfort bounds are 4K apart and the prediction is valid in the T_{rm} range of 8°C to 25°C. EN 15251 [72] uses a very similar approach to the CIBSE method (although the standard is applicable for T_{rm} up to 30°C) and defines two categories of thermal comfort. Cat 1 is applicable for spaces inhabited by very sensitive and fragile persons, including the sick, very young and elderly and uses a 4K upper and lower comfort range (identical to the CIBSE method). Whilst Cat 2 is applicable to normal levels of expectation and is considered appropriate for new buildings and renovations, spanning a 6K comfort range.

In terms of the upper limit of acceptable internal temperature the CIBSE living area thresholds tend to be higher than those given in EN ISO 7730 [47] where Category A allows a maximum temperature of 25.5°C, whilst category B allows 26°C (at a relative humidity of 60%). These comfort categories are further defined in relation to maximum fluctuations in the OT, whereby a Predicted Percentage Dissatisfied (PPD) of <6% is required for Category A and <10% for Category B. The overheating threshold used in the Passive House Planning Package (PHPP) [28] originated from the German DIN 1946-2 [84] upper limit of 25°C. Based on this threshold Rouvel [85] established the criterion for active space cooling as occurring when the 25°C limit was exceeded for more than 10% of the period of annual usage. For a Passivhaus dwelling this is interpreted as being 10% of the year, since continual occupancy is assumed [28]. In the context of energy efficient office buildings, post occupancy research by Voss [52] suggests that the acceptable duration of overheating above 25°C should be reduced to 5% or less. Contrary to Voss's recommendation however the recent DIN 4108-2 [86] incorporated a more adaptive approach, defining a series of three limiting temperatures (25, 26 and 27°C) that cannot be exceeded for more than 10% of the occupied period depending on the

monthly ambient temperature of the region (below 16.5°C, below 18°C and above 18°C respectively). Deutscher [87] argues that this slackening of overheating limits in the German standards is attributable to the fact that the original targets were too difficult to implement in some German regions without necessitating the use of external shading devices.

Irrespective of whether a deterministic or adaptive approach is used, the criteria which currently define 'overheating' in dwellings have largely evolved from occupant studies of thermal comfort; many of which were carried out in offices and commercial buildings. As a result 'overheating' has been defined as occurring at a point, or range, above which occupants experience discomfort. Dengel and Swainson [26] suggest a counterproposal to this approach is needed, stating that by definition the existing approach is not based on occupant health but is grounded in the concept of 'thermal preference'. Dengel and Swainson's view is supported by the World Health Organisation (WHO) guidance for air temperatures in dwellings [88,89] which is aimed at protecting health, particularly that of those vulnerable to extremes of temperature, and not at sensations of satisfaction with the ambient temperature [90]. WHO research, suggests that there is minimal risk to the health of sedentary people, including the elderly, in dwellings where the ambient temperature is between 18°C – 24°C [89]. In support of this approach there is a body of evidence which suggests that the elderly may report feeling comfortable at temperatures which are not, in fact, healthy for them [91,92,93].

In order to evaluate health and safety risks originating from deficiencies in dwellings the UK Government introduced the Housing Health and Safety Rating System (HHSRS) in 2005 [94]. Since the HHSRS replaced The Housing Fitness Standard contained in section 604 of the 1985 Housing Act (as amended by the schedule 9 to the 1989 Local Government and Housing Act) judgements regarding the lack of safety defined under the HHSRS are enforceable under this Act [95]. Accordingly, the health effects of 'excess heat' have a statutory definition in the HHSRS, which states that, "High temperatures can increase cardiovascular strain and trauma, and where the temperatures exceed 25°C, mortality increases and there is an increase in strokes. Dehydration is a problem primarily for the elderly and the very young" [94, p60].

In a mortality assessment of England and Wales, Armstrong et al., [96] established a heat threshold, by statistical model fit, broadly occurring at the 93rd percentile of the all-year daily maximum ambient temperature distribution within any given region. Similar research carried out by the UK Health Agency has shown that the daily mean temperature (rather than maximum temperature) can equally be used at the 93rd percentile as a threshold above which an elevated risk of heat related mortality occurs. In the present day case of London this would correspond to a mean ambient temperature of 19.6°C [59]. Whilst regional ambient temperature thresholds and air pollution levels are widely used for epidemiological predictions [59,97,98,99,100] , the corresponding building OT and Indoor Air Quality (IAQ) risk thresholds are rarely documented.

Research by Bouchama and Knochel [101] established that it is the heat stress experienced across day and night that determines the risk of heat related mortality. An improved understanding of the relationship between OT thresholds and exposure periods in relation to morbidity and mortality data is therefore of critical importance to adaptive building design and heat risk prevention strategies. Basu and Samet [102] proposed that the micro-environmental model, widely used in assessing individual exposure to atmospheric pollutants, [98] could be extended to create a micro-environmental time weighted exposure model for the assessment of heat related exposure. Their initial fieldwork in Baltimore, USA established the validity of this approach; whilst also pointing to the need for larger population studies in multiple geographic regions together with a better understanding of effect modifiers (sex, age, body mass, air conditioning use, and other behavioural adaptations) [103].

To date little work has been carried out in the UK context to establish a robust correlation between OT thresholds and morbidity rates in dwellings, although CIBSE Guide A notes that sleep may be impaired above 24°C [81]. Increased sleep fragmentation has been directly linked to poor health and reduced work place productivity [104] as well as directly impairing the ability to recover from daytime heat stress [105]. Changes in skin temperature of as little as 1°C are known to impair the

quality of sleep, notably in the elderly [106,107]. In light of these findings the OT's of bedrooms should play an important role in the assessment of overheating risk.

Heat exposure alone is not the sole parameter governing heat related mortality. Johnson et al [108] note that excess mortality in England and Wales was significantly higher during the 2003 heat wave than the 1976 heat wave (16% compared to 10%) despite the temperatures being broadly similar; a situation which they postulate may be attributed to an ageing UK population. The fact that the elderly (over 75 years of age) are more vulnerable to heat related mortality has been documented in both the UK [109] and elsewhere [110,111]. Alongside this Rooney et al [109] and Stedman [112] have documented that elevated ground level ozone (O_3), PM_{10} (particulate matter $< 10\mu m$ in diameter) and Nitrogen dioxide (NO_2) played a contributory role in the localised incidence of mortality during the 1995 and 2003 UK heat waves. Despite the relevance of these findings to the urban context a detailed evaluation of these concomitant factors is beyond the scope of this study.

3   METHODOLOGY

The research presented here expands on previously published work by investigating the likely future performance of UK dwellings built to the Passivhaus standard under a series of future probabilistic climatic scenarios [113]. In the first stage of this paper a DSP was used to model a range of individual interventions in order to understand the general evolution of the Passivhaus and FEES dwellings faced with increasingly severe climate change scenarios. In the second stage of the research a Global Sensitivity Analysis (GSA) technique was introduced in order to examine which design factors, within the designers influence, have the most pronounced impact on the building's future performance.

Three different variants of a typical Passivhaus dwelling were modelled in order to account for the influence of thermal mass. An additional control model was used throughout the study in order to show the comparative performance between the Passivhaus concept and a similar dwelling built to comply with the proposed Fabric Energy Efficiency Standard (FEES) [10].

Although extremes of hot weather are likely to become much more common in the future [53, 61], climate models predict that extreme cold weather events are still likely to occur even under 21st century warming scenarios [114]. In accordance with this finding, the impacts on both overheating and heating parameters were evaluated, in order to determine whether design interventions that may have influenced one parameter positively had done so at the expense of another (Figs 4-8,12).

3.1 Simulation setup and parameterization

3.1.1 Dwelling – location and typology

A 5 x 5km grid square centred on Islington (UKCP cell reference 5350185) [115] was chosen as the context for this study, in order to include some of the additional affects induced by the UHI within these Greater London locations (see section 3.3.1 for more information). A two bedroom end of terrace dwelling with a gross internal floor area of $70m^2$ was used as representative format for this study. A dwelling at the western end of the terrace row (Figure 2) was chosen, consistent with similar studies [116, 22] based on the logic that this unit is most exposed to the influence of solar irradiation during the afternoon when the sun is in the western hemisphere and ambient temperatures peak.

Dwelling typology has been shown to have a significant effect on both heating demand and overheating risks. In comparison to detached dwellings, compact dwelling formats (with reduced external surface areas) are likely to have lower transmission heat losses in winter but conversely may be prone to greater summer overheating risks as a result of reduced external heat exchange surfaces and fewer ventilation openings. Research investigating future overheating in the UK Housing stock by Gupta and Gregg [117] demonstrated that purpose built flats and mid-terraced houses were at significantly greater risk of overheating in future climatic scenarios than semi-detached or detached dwellings. Porritt et al [118] also showed that dwelling orientation plays a decisive role in

determining the magnitude of overheating risks, with end of terrace dwellings having less risk of overheating than mid-terrace dwellings when facing West but conversely greater risk of overheating for North, South and East orientations.

In this study the dwellings were orientated to face south, as this is consistent with optimal Passivhaus design in the Northern hemisphere, since it allows the greatest utilisation of passive solar gains during the winter heating season [28]. The dwellings were assumed to be positioned on a horizontal plane without topographical shading (Figure 2). Whilst this arrangement is considered to be optimal from a passive solar design perspective, it is acknowledged that a large number of site specific constraints (including shading obstructions, density requirements and access issues) are likely to have a significant influence on the performance of dwellings built in an urban context. For these reasons the findings of this study should be viewed as a comparative analysis of a series of theoretical future scenarios rather than a context specific deterministic study.

3.1.2 Simulation software
The IES-ve (2012) v6.4 Apache software was used for the dynamic simulations in this study. Apache was developed in the early 1990's and is a widely used DSP both in the UK and internationally. Apache has an extensive validation history which was documented using the CIBSE Applications Manual AM 11 (1998) Appendix B protocol [119] by McLean in 2006 [120] . The software performed well in independent Building Energy Simulation Test (BESTEST) [121] benchmarking assessment carried out by the BRE [120] and has been subject to extensive Empirical testing by Lomas et al (1994) [122] and Gough and Rees (2004) [123]. Apache uses a discretization scheme known as 'hopscotch' whereby explicit and implicit time stepping is applied to alternate nodes in the construction; this approach is thought to provide both accurate and efficient computation (Struck, 2012) [124].

Figure 2.Floor plans and IES model view showing end terrace dwelling (South elevation)

3.1.3 Dwelling specification – thermal characteristics, glazing ratios, ventilation
Whilst a number of previous studies have addressed the role of thermal mass in relation to overheating risks in UK dwellings [125,126,127,128,129,130,131,132], none of these studies has investigated the influence of thermal mass in the context of Passivhaus dwellings. In order to evaluate the role thermal mass might play in Passivhaus dwellings in a future UK climatic context three different construction types (light, medium and heavyweight) were selected as representative of a range of UK Passivhaus constructions (table 1). In order to provide a control study, for comparative analysis, a naturally ventilated FEES compliant dwelling was modelled in a traditional heavyweight construction format (table 1), in accordance with the FEES specification [10]. The effects of linear thermal bridging were incorporated into the FEES DSP model by adding a y value adjustment factor of 0.05 W/(m^{2}K) to the opaque U values [10].

Internal volumes, glazing ratios, external emissivity and solar absorptance coefficients remained consistent between all four dwelling models. In addition to the above criteria, the Passivhaus dwellings were modelled using a common ground floor construction (pre-insulated raft slab) as well as identical: fabric U-values, glazed U-values, g-values, infiltration and ventilation rates (table 1). All Passivhaus dwellings were assumed to be 'thermally bridge free' in keeping with the criteria set out in the Passive House Planning Package [28, p109].

Table 1. Principal performance characteristics of 4 dwelling types (3 complying with the Passivhaus standard and 1 modelled according to the FEES Standard)

According to CIBSE Guide B in the UK a CO_2 level of 800 -1000 ppm (equating to a fresh air ventilation rate of approximately 8 ls^{-1} per person) is widely used as an indication that the ventilation rate in a building is adequate [133, p15]. CO_2 is often used as a proxy indicator of Indoor Air Quality

(IAQ) in general [134] and concentrations above 5000 ppm CO_2, for more than 8 h, are considered to represent the upper limit of acceptability in the UK [133].

In both the FEES and Passivhaus dwellings, CO_2 concentrations were used as a proxy indicator of IAQ, with the goal of maintaining an upper threshold ≤1000 ppm above ambient levels. Supply air ventilation in the Passivhaus dwellings was provided via Mechanical Ventilation with Heat Recovery (MVHR) and a summer heat exchanger bypass system was modelled whenever the outside temperature exceeded 20°C. In contrast the FEES control dwelling utilised natural cross ventilation via ramped window opening profiles to maintain the 'supply air quality' (table 2). In order to control overheating risks an identical purge ventilation strategy was used in both the FEES and Passivhaus dwellings in accordance with the 'purge ventilation' profile strategy (table 2). Maximum window opening angles were limited to 10 degrees in all dwellings in keeping with the use of window restrictors. Such devices are a standard safety feature in new build social housing in the UK in accordance with guidance from the Royal Society for the Prevention of Accidents (RoSPA) [135].

Table 2.Ventilation profiles according to dwelling type

In order to model the ventilation profile of the FEES and Passivhaus dwellings in accordance with the above guidance two independent window opening profiles were used. In the FEES model, the first ventilation profile was defined by CO_2 concentration and the second by the requirement to 'purge' excess heat. In the Passivhaus model IAQ is maintained by mechanical ventilation via the MVHR unit and additional 'purge' ventilation is modelled as a cooling strategy using the same (restricted) window opening profile as for the FEES model (table 2).

3.2 Internal gains and occupancy patterns

The occupancy patterns and internal gains profiles used were common amongst all four dwellings

3.2.1 Internal gains
The Passive House Planning Package [28] uses a default assumption of 2.1 W/m^2 with respect to the effective residential internal heat gains (IHG's). This figure is then rounded upwards to 2.6 W/m^2 (as a safety margin) in the PHPP model for the purpose of assessing summer overheating risk. The derivation of these figures is based upon assessments carried out in German Passivhaus dwellings using a default occupant density of 35m^2 per person and actual appliance schedules [136]. The 'effective' IHG figures used in PHPP account for both the internal heat gains (including occupants) as well as the internal heat losses (e.g. cold water entering cisterns, evaporation) [28]. A detailed breakdown of this calculation procedure can be found in Schneiders [22, p75].

For the purpose of this study the standard residential IHG figures of 2.1 W/m^2 used in PHPP (2012) was adjusted using the PHPP 'Internal Gains' worksheet in order to reflect the higher UK social housing occupant densities (and smaller TFA) used in this study. Using this approach the appliance and services IHG's based on 3 occupants (but excluding the occupant gains) are: 180 W (total) – 132W (occupant gains) = 48W (appliance and services gains). Scaling this to the 70m^2 treated floor area the resulting (appliance and services) specific internal gains are 0.69 W/m^2. Using occupant gains from CIBSE Guide A [81] based on three occupants (assuming two adults and a mature child) the total internal sensible heat gains are: 48W + (3*70W) = 258W. Adjusting this to the 70m^2 treated floor area the total specific internal gains are 3.69 W/m^2 (when the dwelling is fully occupied).

In order to assess the sensitivity of the key outputs relative to the internal gains assumptions, in the second part of this study, the influence of low and high IHG figures were assessed. Based on the assumption that the figures currently specified in the PHPP software [28] are likely to reflect the use of very energy efficient appliances and moderate electricity consumption profiles the above figure was taken as a the basis for the 'low IHG' profile. Assuming that IHG's could be elevated by a factor of up to 3, in some households [137, 22] the 'high IHG' appliance and services gains were estimated

as 3 x 48W, thus the specific (appliance and services gains) would be 144W/ 70m^2 = 2.06 W/m^2. Using occupant gains from CIBSE Guide A [81] based on three occupants (assuming two adults and a mature child) the total internal sensible heat gains are: 144W + (3*70W) = 354W. Scaling this to the 70m^2 treated floor area the total 'high' (non-occupant related) internal gains are 5.05 W/m^2 (when the dwelling is fully occupied).

3.2.2 Occupant density and patterns
In order to create a realistic occupancy profiles for the purpose of this study occupant numbers were modelled as a whole number. A larger than average household size based on 3 occupants was chosen in order to err on the side of higher occupant density and internal gains. Occupancy schedules were created to reflect UK household survey statistics [138]. Occupant gains were then assigned to the IES model based on sub-hourly activity data recorded in the UK Time Use Survey [139] with occupant gains data according to activity from CIBSE Guide A [81]. The weekly occupancy profiles were assigned to the model based on sub-hourly activity profiles created for the 3 occupants. Weekly profiles were created for a 'working adult', a non- working 'houseparent' and a 'student'. Maximum occupancy was assumed at weekends in order to test the influence of higher than average internal heat gains during these periods.

3.3 Future climate data and scenarios

3.3.1 Future climate data and the urban context
The UKCP09 grid [115] location 5350185, centred on London Islington, has been selected as the reference location for this study. London's urban context is known to create a pronounced micro climate: with one of the consequences being that temperatures are at times significantly higher than surrounding rural areas. Research by Graves et al [140] demonstrated that the nocturnal ambient temperature peak for Westminster, London, have occasionally exceeded 7K during the summer months. The temperature difference between an urban area and its rural surroundings is commonly referred to as the urban heat island (UHI) effect, and is typically most pronounced at night [141]. This localised phenomenon results primarily from the heat generated by human energy production (HEP) being retained in an area of high thermal mass – much of which also has a relatively low albedo, or surface reflectivity [140,142].

One of the main challenges for overheating risk prevention in urban dwellings occurs as a result of the magnitude and the timing of the peak intensity of the UHI, which in inner London locations can occur between 11pm and 8am [142, 143]. The resultant dampening of the diurnal temperature range has implications for the cooling of naturally ventilated buildings, as it compromises the effectiveness of strategies using night-time 'purge' ventilation to cool thermal mass. For this reason it is important that any synthesised or predictive weather data used in an urban modelling context accurately reflects the localised influence of the urban micro climate.

Some caution is necessary with respect to the future climatic changes predicted by the UKCP09 scenarios in dense urban areas, since an explicit representation of urban areas was not included in the HadRM3 model [141]. In a large urban conurbation such as Greater London the effects of the existing UHI are captured in the UKCP Weather Generator (WG) model by virtue of the fact that a number of the climate stations used for the interpolation process are situated within the UHI [144]. At the 25 km^2 resolution of the HadRM3 model the largest urban areas can be seen to exert some influence on the local simulated climate [145]. It follows therefore, that if the UHI effect does not change significantly in the future, it is reasonable to add the UKCP09 climate change projections to the observed baseline (5km^2) urban climate in order to generate future urban climatic predictions at this scale [144]. Conversely if future changes occur in the amount of energy dissipated in cities (e.g. cooling systems become widespread), or if the density of a city changes then these factors could alter the current UHI effect, and projecting future climates in cities will then require additional techniques to be deployed [141].

In relation to the temporal evolution of the UHI, comparative temperature measurements taken at an inner city location (St. James Park) and a suburban site in Surrey suggest that London's nocturnal UHI has intensified by approximately 0.5°C on since the 1960s [143], partly as a consequence of increased HEP, denser urbanisation, and the changing frequency of weather patterns. Since the 5km^2 baseline data is based on measured data collated over the 1961-1990 period it is likely that only a relatively small component of these evolutionary changes are missing from the UKCP09 projections [6]. The main limitation of the UKCP09 WG projections is that the current model does not fully incorporate all of the highly localised effects of the UHI, significant discrepancies may therefore be anticipated when attempting to predict the performance of buildings at a higher resolution than the current 5km^2 grid allows [140,141].

Generating an improved understanding of the future evolution of localised UHI's is a complex and important area for building simulation, where significant further research is needed. For more information on the implications of the London UHI for micro-regional assessments of building performance, please refer to McLeod et al [113] Kershaw et al [141] Graves et al [140], Watkins et al [146] and Wilby [143].

3.3.2 Assessing risk - emissions scenarios and probability

In order to represent both a mean weather year and a warmer than average (one in ten) year both the 50th and 90th percentile Test Reference Year (TRY) datasets were used to assess future climate change impacts. An alternative procedure, to assess warmer than average future weather years, would be to use Design Summer Years (DSYs) - which are also available from the PROMETHEUS database [147,148]. DSY years are intended to represent the third warmest summer (April–September period) in a twenty year period [149], however the statistical basis under pining their selection is considered to be unreliable. Coley et al [148] remark that some of the current DSY's, generated from observed data, are in fact cooler than the TRY datasets for some UK cities.

The WG is capable of generating probabilistic weather files for each future decade from 2020 to 2080 sampled from any percentile of the Probability Density Function (PDF). Whilst the underlying Met Office grid data for the period 1961- 1990 is used to create a control dataset, reflecting the historical 1970's baseline [150]. In studying the temporal evolution of climate change the UKCP09 data leaves a large gap (50 years) between the historic control period (1970's) and the near future (2020's). In order to fill this gap and to model current day climatic conditions the CIBSE London 2005 TRY and DSY climate files were used in this study.

3.4 Performance criteria –thermal comfort and overheating thresholds

In this study the frequency of living area operative temperatures >25°C (OT_{25}) was assessed in keeping with the Passivhaus assessment criterion [28], WHO guidance [89] and the HHSRS assessment criteria [94]. In addition a higher threshold was used to assess the frequency of living area operative temperatures >28°C (OT_{28}) in accordance with CIBSE Guide A [80] and CIBSE TM36 [81]. The absolute maximum internal operative temperature (OT_{max}) was also recorded (as an indicator of heat related mortality risk) for comparative purposes [58,103,151,152,153]. Since the impacts of warmer operative temperatures in bedrooms requires special consideration, the frequency of bedroom operative temperatures >26°C ($BedOT_{26}$) during occupied hours (11pm-7am) was assessed in relation to the CIBSE Guide A threshold [81] and the Predicted Percentage Dissatisfied (PPD) EN ISO 7730 [47]. Bedroom overheating risks are considered to be particularly important in relation to performance criteria in an urban context due to the timing of the peak intensity of the UHI (as discussed in section 3.3.1).

3.5   Sensitivity Analysis

For reasons of computational economy, most building simulation studies are based on a limited number of deterministic scenarios. As a result, in some cases, the dependence of performance

outcomes upon key input parameters and their possible interactions may remain unknown. Sensitivity Analysis techniques enable designers to understand which input factors have the most important influence on outputs, and the use of Sensitivity Analysis has been extensively documented in relation to building simulation [124,154,155,156].

3.5.1 Elementary effects method

Morris [157] developed an efficient screening method for determining which input factors have important direct and indirect effects on an output. Morris' method, also known as the Elementary Effects (EE) method, is considered to be a Global Sensitivity Analysis (GSA) technique because it samples the entire space over which the input factors may vary. The method uses an individually randomised one- factor at- a-time (OAT) sampling method, to assess which parameters are: i) non-influential or negligible ii) linearly influential iii) non-linearly influential (or influential by interaction with other parameters) [158,159]. The Latin hypercube (LH) sampling technique [160] is often used to create the starting points for the OAT sampling. LH divides each factor into r stratified intervals of equal probability, which are then sampled OAT.

Morris' method has undergone further enhancement by Campolongo et al., [161] and has been validated against qualitative variance based methods (such as the method of Sobol') by a number of researchers [158,162,163,164]. One of the main advantages of the Morris method is the low sample size required to evaluate the effect of each factor. The number of model executions required is $r(k+1)$, where k is the number of factors and r is a predetermined number of sampling intervals. In comparison the widely used Sobol' method requires in the order of $500(k + 2)$ evaluations) [158]. As a result the enhanced Morris method is well suited to studies which have either a large number of input factors or require expensive computation.

Mathematically the building simulation model can be represented as the function $y(x)$ where y is the output variable of interest and x is a row vector composed of real input variables with k input coordinates ($x_1, x_2, x_3, ... x_k$). Each input variable is defined within a given interval ($x_{min} – x_{max}$) and the input variables are then scaled into dimensionless variables in the interval [0, 1], such that $x'_i = (x_i – x_{min}/x_{max} – x_{min})$. The region of interest (Ω) is defined by the domain of the vector x which can be visualised as a k dimensional unit hypercube (H^k) which is composed of p discrete grid levels.

A number of different sampling strategies have been proposed in order to optimize the scanning of the input space (see for example [156, 158, 165]).The sampling strategy results in the construction of r different random simulation trajectories in Ω, where each trajectory corresponds to ($k+1$) model executions and each sampling point differs from the proceeding point by a single, randomly permutated, coordinate. Thus for a given trajectory r each input parameter (k) changes only once in accordance with a pre-defined step size Δ_i. The relationship between the number of grid levels (p) in the hypercube and the step size between coordinates (Δ) is critical to ensuring an equal probability of sampling at every level of the input space. For this reason Morris [157] recommended that p be an even number, and that $\Delta_i = p/[2(p_i – 1)]$ in order that each sampling point x_i has an equal probability of taking on values from $\{0, 1/(p – 1), 2/(p – 2),..., 1\}$.

If $x^{(l)}$ and $x^{(l+1)}$ are two sampling points in the nth trajectory which differ only in their ith component then the elementary effect (EE_i^n) of the nth trajectory associated with input factor i is:

$$EE_i^n\left(x^{(l)}\right) = \frac{[y\left(x^{(l+1)}\right) - y\left(x^{(l)}\right)]}{\Delta_i}$$

[1]

Where the ith component of $x^{(l)}$ is increased by Δ_i (Eq.1), and conversely:

$$EE_i^n\left(x^{(l+1)}\right) = \frac{\left[y\left(x^{(l)}\right) - y\left(x^{(l+1)}\right)\right]}{\Delta_i}$$

[2]

Where the ith component of $x^{(l)}$ is decreased by Δ_i (Eq.2)

The function $y(x)$ is re-evaluated at every point in the trajectory by running the simulation model, thereby allowing a coefficient of output variation (or EE) to be computed for each input factor i, for $i =1,\dots, k$. Once the EEs for each input factor have been determined, sensitivity statistics can be computed relative to the output distributions: The mean μ provides an indication of the overall importance of an input factor, whilst σ (an estimate of the standard deviation) indicates the magnitude of the higher order effects of a factor (i.e. those which are non-linear and/or result from interactions with other factors).

$$\mu_i = \frac{1}{r} \sum_{n=1}^{r} EE_i^n$$

[3]

$$\sigma_i = \sqrt{\frac{1}{(r-1)} \sum_{n=1}^{r} (EE_i^n - \mu_i)^2}$$

[4]

Since EEs with a negative sign can occur where input variables have a non-monotonic response on the output (or are involved in interaction effects) Campolongo et al [158] proposed the use of the mean of the absolute EE μ_i^* (Eq.5) as a more reliable indicator of the overall influence of the factor on the output.

$$\mu_i^* = \frac{1}{r} \sum_{n=1}^{r} |EE_i^n|$$

[5]

Campolongo et al. [158] demonstrated that μ^* is a good proxy of the total sensitivity index (S_T). According to Saltelli et al [165] the use μ^* also solves the problem of type II errors (failure to identify a factor which has considerable influence on the model). In order to evaluate the respective influence of these sensitivity measures Morris [157] recommended using a graphical representation of σ vs. μ , this approach also helps in the identification of type II errors since factors with EEs of different signs tend to have a low value of μ but a considerably higher value of σ [165].

The purpose of this analysis is to investigate the sensitivity of key design inputs upon the performance of the Passivhaus dwellings in a future climatic context. A 2050, 90th percentile year is assessed under a High emissions scenario, for the Islington (5350185) grid cell, in order to reflect a warmer than average mid-century urban climatic context. It is assumed in this assessment that supply and extract ventilation is provided by a whole house MVHR system operating in summer bypass mode (Table 2). In order to test a 'worst case scenario' it is assumed that natural cross ventilation through openable windows cannot be used to cool the dwellings during the summer months due to factors associated with the urban context (such as noise, air pollution and crime).

In this study a limited number ($k =5$) of influential building parameters were selected in order to assess their influence upon a range of critical performance characteristics (section 3.4). The

parameters evaluated were chosen to reflect factors which might typically be within the designers influence in this particular context. In practice a larger or smaller set of input parameters may be selected depending on computational resources (e.g. whether the sensitivity analysis can be fully automated) and whether the influence of other parameters (e.g. orientation, solar absorptance coefficients etc.) are considered to be of interest. The range through which the designer is realistically capable of influencing these values (on any given project) defines the minimum and maximum (lower and upper bounds) of the parameters. In practice the bounds of the range are almost always context dependent and are likely to be constrained by a number of issues including: site layout, building regulations, planning policies, structural considerations, cost implications, Passivhaus criteria, the contractor's expertise etc.

For the purpose of this case study the following input distributions are described, either as discrete values or as uniform (min/max) ranges:

1. Thermal mass (Discrete distribution; based on, lightweight (LW), mediumweight (MW) and heavyweight (HW) mass options - see table 1).
2. Glazing percentage on south side (Uniform distribution; based on percentage of south facing façade area)
3. External shading device transmission factor (Uniform distribution; based on external shutters shading ratio)
4. Airtightness (Uniform distribution; based on normalised n_{50} value in accordance with EN832, assuming a moderate screening, screening coefficient e=0.07)
5. Internal gains (Discrete distribution; based on the non-occupant related effective internal gains component), see section 3.2.1

Parameter	Distribution type	min - max (or discrete values)
1. Thermal mass	Discrete	light, med, high
2. Glazing ratio on south facade	Uniform	10 - 60%
3. External shading transmission factor on south facade	Uniform	0 – 100%
4. Airtightness (ach^{-1})	Uniform	0.0042 – 0.042
5. Internal gains (excl. occupant gains)	Discrete	0.69 W/m^2 (low) 2.06 W/m^2 (high)

Table 3. Sensitivity analysis parameters

It should be noted that some authors [155,166,167] argue that internal gains should not be included as inputs in a sensitivity analysis since they are *a priori* scenario dependent, and therefore cannot be regarded in the same manner as other design related parameters. However since the non-occupant component of the effective IHG's are partially influenced by the appliance and building services specification, this component of the IHG's has been included as an input parameter. In order to evaluate the 'relative' significance of the non-occupant related internal gains, two levels of internal gains (low and high) have been included as discrete distributions in the sensitivity analysis (the derivation of these gains is explained in further detail in section 3.2.1). A flow diagram of the overall simulation and sensitivity analysis process is shown in Figure 3.
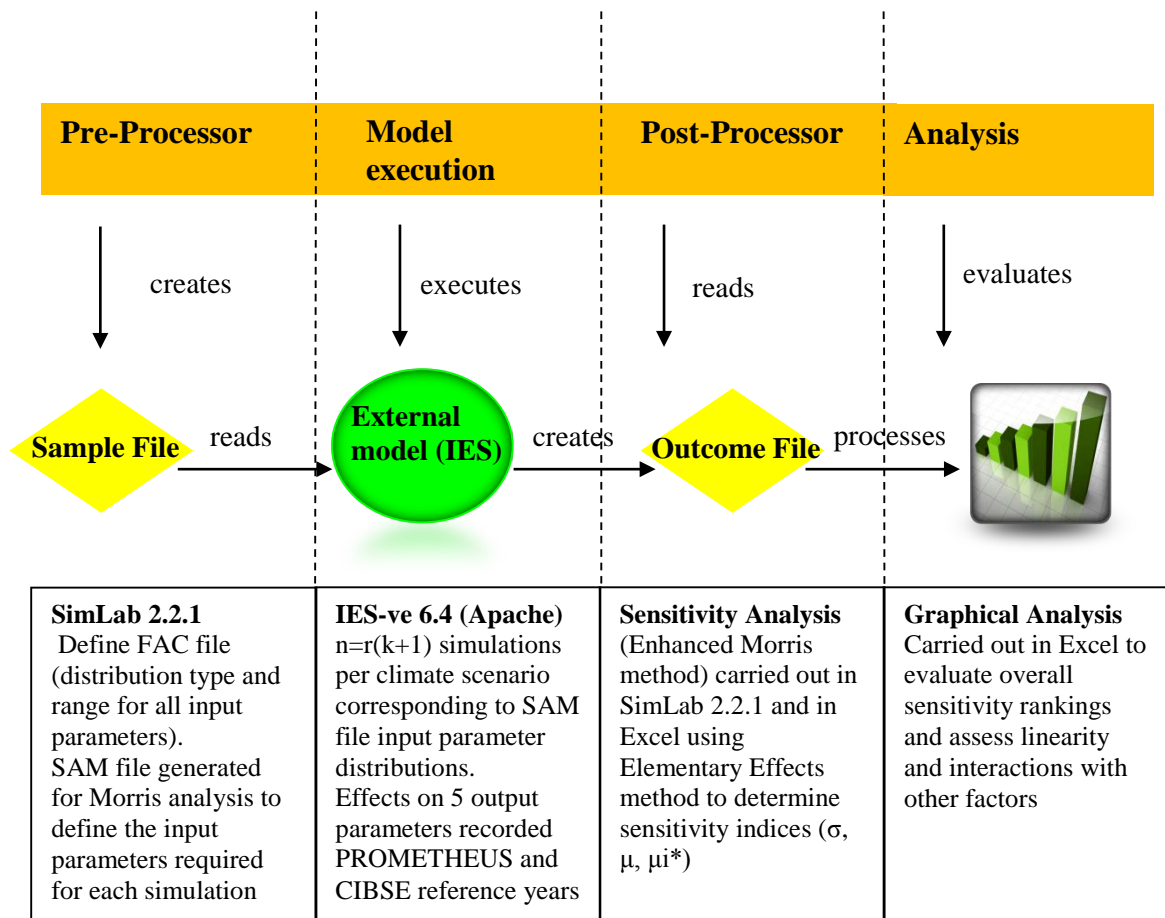
Pre-Processor	Model execution	Post-Processor	Analysis
SimLab 2.2.1 Define FAC file (distribution type and range for all input parameters). SAM file generated for Morris analysis to define the input parameters required for each simulation	**IES-ve 6.4 (Apache)** n=r(k+1) simulations per climate scenario corresponding to SAM file input parameter distributions. Effects on 5 output parameters recorded PROMETHEUS and CIBSE reference years	**Sensitivity Analysis** (Enhanced Morris method) carried out in SimLab 2.2.1 and in Excel using Elementary Effects method to determine sensitivity indices (σ, μ, μi*)	**Graphical Analysis** Carried out in Excel to evaluate overall sensitivity rankings and assess linearity and interactions with other factors

Figure 3. Simulation and analysis procedure

4   RESULTS AND DISCUSSION

Dynamic thermal simulations were first carried out for a series of base case scenarios in order to establish the overall trend in key performance characteristics between the four dwelling models from the historic (1961-1990) reference period through to 2080, under a High (A1FI) emissions scenario. The purpose of the base case assessment was to establish the comparative performance and temporal trends exhibited by the four dwellings types over a notional 100 year time period.

The deterministic assessments carried out for the base case scenario were followed by a sensitivity analysis of the three Passivhaus dwellings for a range of individual interventions (listed in table 3). The sensitivity analysis was carried out under a 2050 High (A1FI) emissions 90th percentile TRY scenario, in order to establish which design factors would most significantly influence the key performance outputs of the Passivhaus dwellings, at their mid-life stage (under a warmer than average probabilistic scenario).

4.1 Base case – transitional assessment of 4 dwellings under a High emission scenario (1970 -2080) The base case assessments were carried out for the four dwellings with specifications given in Table 1. The purpose of the assessments was firstly to establish whether the models were complying with the designated baseline energy performance standards (FEES and Passivhaus respectively). The base

case also provides a comparative indication of the evolution of key performance criteria with respect to time. In order to establish a comparative estimate of performance between a dwelling built to the FEES standard [10] and dwellings designed to the Passivhaus standard [28] identical forms, internal volumes, glazing ratios and purge ventilations strategies (Table 2) were used in all dwellings.
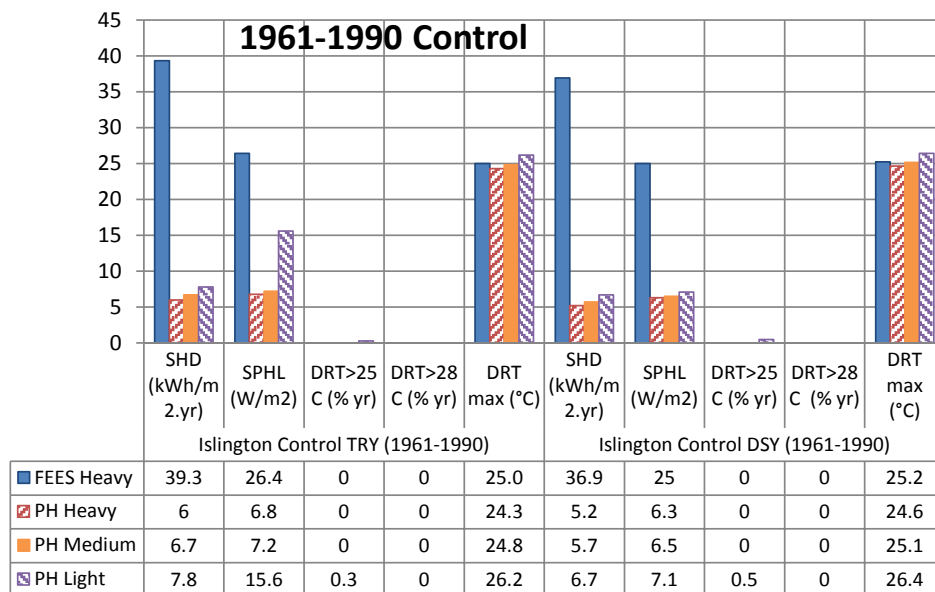
1961-1990 Control

	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
	Islington Control TRY (1961-1990)					Islington Control DSY (1961-1990)				
FEES Heavy	39.3	26.4	0	0	25.0	36.9	25	0	0	25.2
PH Heavy	6	6.8	0	0	24.3	5.2	6.3	0	0	24.6
PH Medium	6.7	7.2	0	0	24.8	5.7	6.5	0	0	25.1
PH Light	7.8	15.6	0.3	0	26.2	6.7	7.1	0.5	0	26.4

Figure 4. Key outputs 4 dwellings (Islington, 5350185), TRY and DSY control scenario (1961-1990)

2005 - CIBSE London

	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
	CIBSE London 2005 TRY					CIBSE London 2005 DSY				
FEES Heavy	40.2	26.5	0.4	0	26.2	37.3	26.2	1.6	0	27.3
PH Heavy	5	6.7	0.2	0	25.5	4.2	5.9	0.9	0	26.4
PH Medium	5.6	7.9	0.4	0	26.0	5.2	8.6	1.3	0	26.9
PH Light	6.7	7.5	1.1	0	27.7	6.3	16.1	3.2	0	28.5
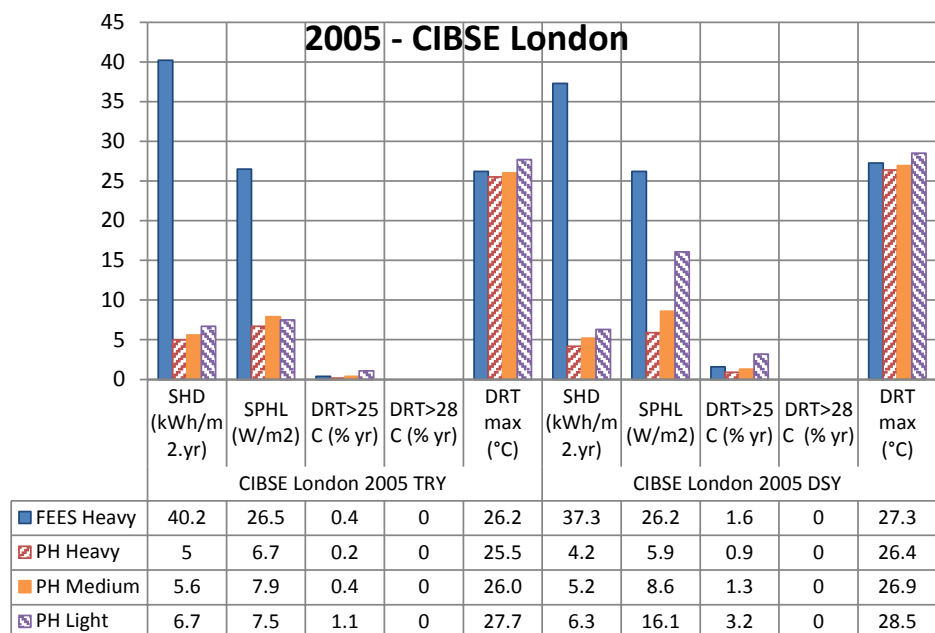
Figure 5. Key outputs 4 dwellings (London Weather Centre), TRY and DSY current day scenario (CIBSE 2005)

2030 High

	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
	Islington 2030 A1F1 (TRY 50th percentile)					Islington 2030 A1F1 (TRY 90th percentile)				
■ FEES Heavy	32	21.5	1	0	26.4	27.2	22.2	3.9	0	27.2
▨ PH Heavy	3.4	6.8	0.5	0	25.7	2.4	7.2	2.4	0	26.3
■ PH Medium	4.2	6.9	0.8	0	26.1	2.9	6.1	3.5	0	26.9
▨ PH Light	5.1	7.6	2.1	0	27.6	3.4	5.8	5.8	0.2	28.6
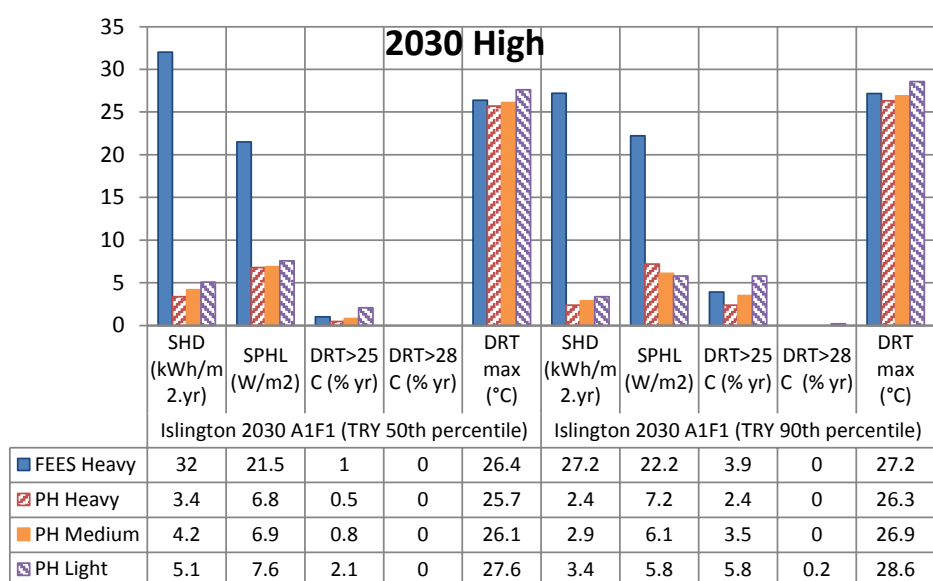
Figure 6. Key outputs 4 dwellings (Islington, 5350185), TRY50th and TRY90th percentile (2030 High)

2050 High

	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
	Islington 2050 A1F1 (TRY 50th percentile)					Islington 2050 A1F1 (TRY 90th percentile)				
■ FEES Heavy	29.9	23.9	2.7	0	27.3	23.1	20.1	8.2	0.5	29.0
▨ PH Heavy	2.9	5.7	1.9	0	26.5	2	5.4	6.6	0	28.0
■ PH Medium	3.5	6	2.4	0	26.8	2.4	5.6	7.6	0.3	28.7
▨ PH Light	4.1	7.2	4.1	0.2	28.4	2.9	6	10	1.2	30.2
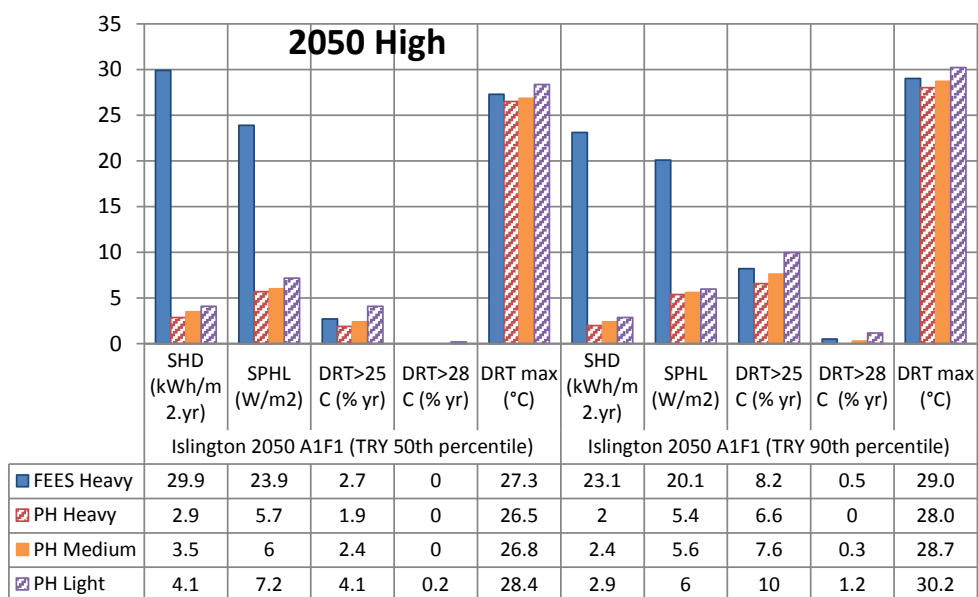
Figure 7. Key outputs 4 dwellings (Islington, 5350185), TRY50th and TRY90th percentile (2050 High)

	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)	SHD (kWh/m2.yr)	SPHL (W/m2)	DRT>25 C (% yr)	DRT>28 C (% yr)	DRT max (°C)
	Islington 2080 A1F1 (TRY 50th percentile)					Islington 2080 A1F1 (TRY 90th percentile)				
FEES Heavy	26.0	21.1	6.8	0.1	28.7	15.6	18.8	20	5.4	31.6
PH Heavy	2.2	10.4	5.3	0	27.7	0.4	9.1	18.8	3.9	30.6
PH Medium	2.6	9.9	6.2	0.1	28.4	0.7	8.1	19	4.4	31.5
PH Light	3.0	6.0	9.6	0.8	29.8	0.9	4.4	20.1	7.2	32.9
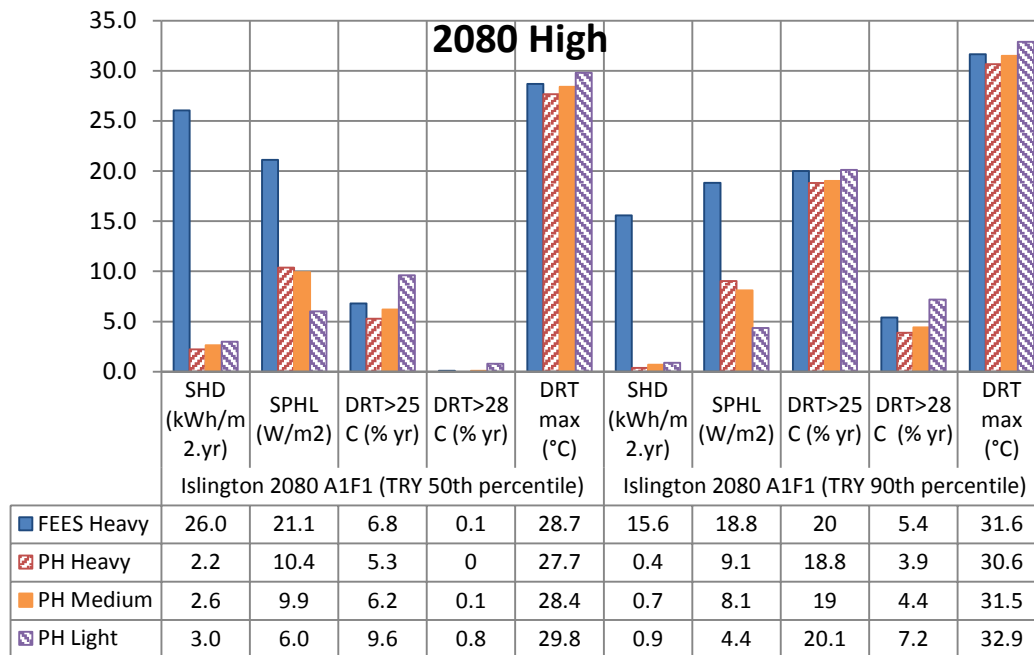
Figure 8.Key outputs 4 dwellings (Islington, 5350185), TRY50th and TRY90th percentile (2080 High)

Figure 4 illustrates that the FEES dwelling is performing in accordance with the limiting Specific Heat Demand (SHD) criteria, for an end of terrace FEES dwelling of ≤46 kWh/m^2.yr [10]. Similarly all of the Passivhaus dwellings fulfil the Passivhaus SHD criteria of ≤15 kWh/ m^2.yr [28]. The general trends illustrated by figures 4-8 show that SHD will fall significantly in all of the four dwellings (under a High Emissions scenario) between the historic control period and the 2080's. In the case of the FEES dwellings under a 50th percentile TRY the SHD is predicted to fall by approximately 34% whilst the Passivhaus dwellings SHD falls by 63% on average.

The overall trend in Specific Peak Heating Load (SHL) is far less pronounced than the evolution in SHD, suggesting that whilst the overall climatic trend is warming significant cold periods will continue to exert an influence on the peak heating loads in all of the dwellings through to 2080. Beyond the present day period (CIBSE London 2005) the peak loads in all Passivhaus dwellings remained ≤10 W/m^2 even when assessed at an hourly time step. By contrast the SHL in the FEES dwelling fell slightly over the same period but remained above 20W/m^2.

In contrast to falling heating demand, the risk of overheating rose in all dwellings from the control period through to 2080. The transition towards an increased risk of overheating under both a 50th and 90th percentile TRY as predicted by three performance indicators (OT$_{25}$, OT$_{28}$ and OT$_{max}$) is illustrated in Figure 9.
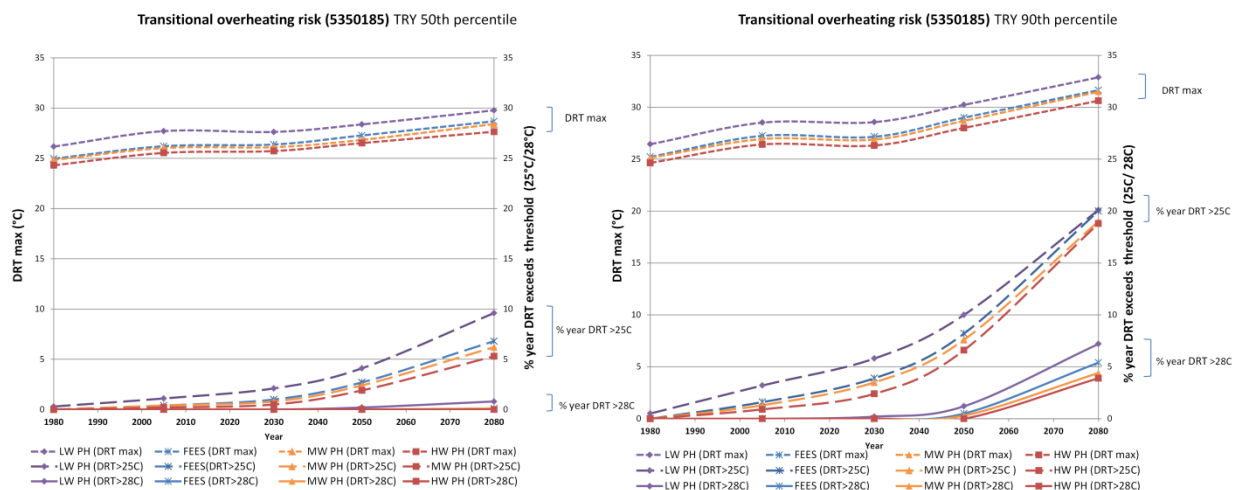
Figure 9. Transitional overheating risk for 4 dwellings at 50th (left) and 90th (right) percentile TRY under 'High Emissions' scenario (1980-2080)

In terms of overheating risk it is notable that the FEES (heavyweight) dwelling performed only slightly worse than the MW Passivhaus overall. This finding suggests that the Passivhaus concept (without additional shading or cooling systems) offers only a slight advantage over the more conventional FEES dwelling typology in respect to overheating risk mitigation (assuming comparable design strategies).

It can be seen (figure 8) that by 2050 under the 90th percentile TRY scenario all of the dwellings are exceeding both the HHSRS criteria [94] and Voss's 25°C criteria [52] for more than 5% of the year, with the LW Passivhaus also exceeding the PHI 10% overheating criteria at this stage. By 2050 the LW passivhaus has also exceeded the CIBSE 28°C threshold for more than 1% of the year, and by 2060 all of the dwellings are predicted to overheat beyond the CIBSE 28°C threshold for more than 1% of the year. Under a 50th percentile TRY scenario the same overheating frequencies are not likely to occur until 2080. By 2080 even in an average (50th percentile) year all of the dwellings will be at risk of overheating beyond 25°C for more than 5% of the year. For the period up to 2050 these findings are in agreement with the findings for overheating risks in dwellings published in CIBSE TM36 which suggests that "buildings with very good control of solar shading, ventilation and internal heat gains can meet targets until the 2050s" [82, p1]. However where CIBSE TM36 states 'In living areas, use of high mass construction enabled the performance targets to be met into the 2080s…' [82,p1] this study found that the same performance targets could not be met by the 2080's in any of the dwelling typologies analysed even under an average 50th percentile TRY scenario. It is notable however that the TM36 (2005) assessments were based on earlier UKCIP02 Medium-High emission scenario climatic predictions, in comparison to the UKCP09 High emission scenario used in this study.

In practical terms these findings suggest that, even with moderate areas of south facing glazing (33 % by internal façade area), restricted natural ventilation strategies (see section 3.1.2) alone are unlikely to provide sufficient means of eliminating the risk associated with prolonged periods of overheating in any of the low energy dwelling types.

In living areas it is apparent that thermal mass appears to offer some benefit both in terms of reducing the frequency of overheating and also the amplitude of the maximum internal temperature (by approximately 2°C on average). By 2080, as the duration of warmer temperatures become more prolonged, the benefits of thermal mass in reducing the frequencies of temperatures above 28°C appears to diminish (Figure 8). In the bedrooms the benefits of thermal mass in reducing overheating risks are less obvious. Despite higher daytime temperatures the lightweight Passivhaus cools more rapidly during the night-time period than the heavier weight dwellings (Figure 10). As a result for approximately half of the occupied period (11pm – 7am) the lightweight Passivhaus achieves a lower

Predicted Percentage Dissatisfied (PPD) vote than the other dwellings. The precise point at which the dwellings begin to cool is affected by the thermal inertia of the building and the timing of the peak external dry bulb temperatures. In an urban context the duration and intensity of the afternoon temperature peak may be strongly influenced by the magnitude and the timing of the peak intensity of the UHI effect (section 3.3.1), and hence it is essential to assess the benefits of thermal mass in a context specific manner.
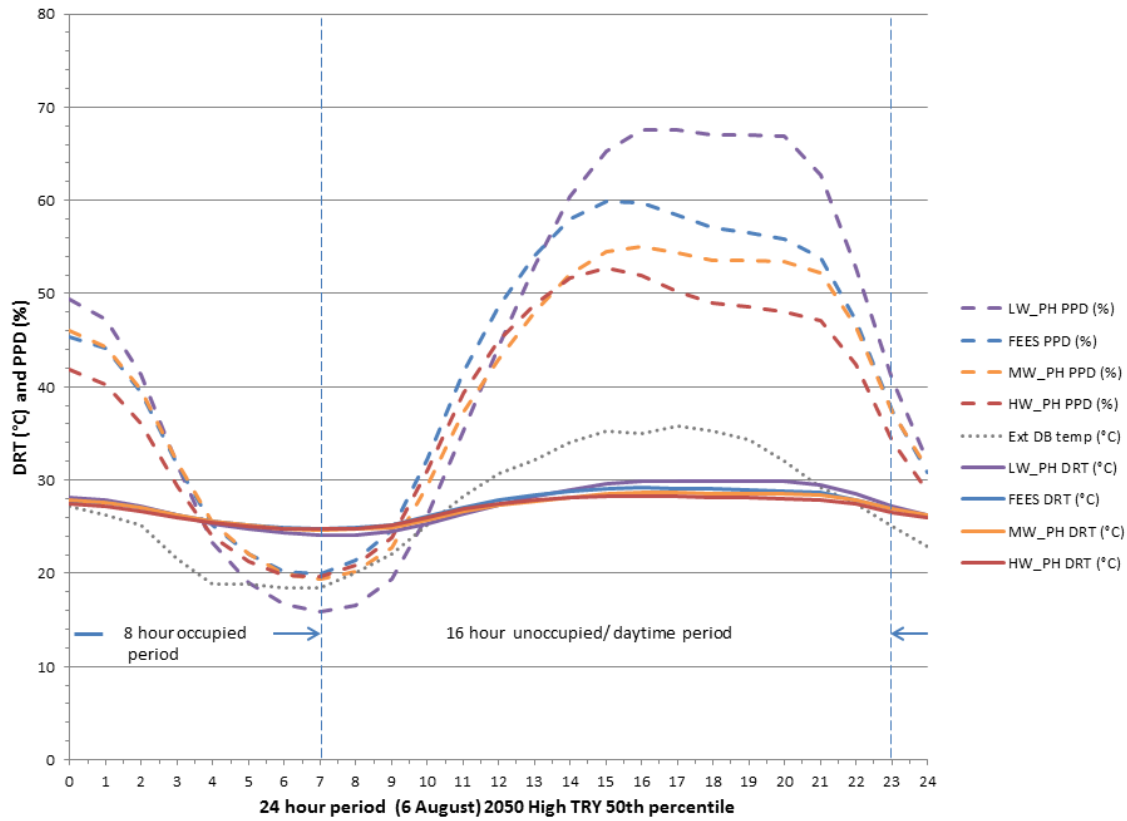
Figure 10. 24 hour cycle showing Bedroom Dry Resultant Temperatures (°C) and Predicted Percentage Dissatisfied (%) during the hottest period of 2050 High (TRY 50th percentile) year

Whilst thermal mass can be seen to play a useful role in dampening maximum internal temperatures (Figure 9) it can also delay the rate and extent of night-time cooling (Figure 10). Overall these finding suggests that the benefits of thermal mass in reducing the frequency of overheating during prolonged overheating spells may diminish in urban contexts during the latter part of this century and warrants further investigation.

4.2 Sensitivity analysis of key design inputs – 2050 High emission scenario

The results of the EE sensitivity analysis are shown as scatter plots (Fig. 13 a-f) where each point represents the influence of a single individual input variable (i) upon the selected output. The input variables and input variable ranges are shown in table 3. For clarity the number of input variables has been limited to 5 in this initial analysis, although in theory consideration of an unlimited number of variables is possible given sufficient computational resources. The x-axis in the scatter plots (Fig. 13 a-f) represents the absolute mean (μ_i^*) of the EE's, a measure of the absolute importance of the input factor (i). The y-axis represents the standard deviation (σ_i) of the EE's, a measure of the extent which the effects are non-linear or result from interactions with other factors.

The ratio (σ_i/μ_i^*) can thus be seen as an indicator of linearity for the input factor (i), where a true linear response would occur in the case that $\sigma_i/\mu_i^* = 0$. According to the theory of normal distribution,

where the EE's take the form of a general normal distribution then 95% of the EE dispersions will lie within the range of $\mu_i \pm 1.96\,\sigma_i$ [168]. Thus if $\sigma_i \leq 0.1\mu_i$ then 95% of the EE's will lie in a range $\mu_i \pm$ 20%. Where the ratio $\sigma_i/\mu_i \leq 0.5$, most EE's (95% with a normal distribution) will have the same sign and the model response can be considered monotonic with respect to the input variable i [156].

In the context of building simulation models, the distribution of elementary effects for a given input factor is unlikely to follow a theoretical normal distribution, a scatter plot analysis of the relationship between (σ_i/μ_i^{*}) vs. $\sigma_i/abs(\mu_i)$ (Fig. 11) is a useful method of identifying monotonic behaviour in the model [156]. The monotonic interval is found where the (σ_i/μ_i^{*}) vs. $\sigma_i/abs(\mu_i)$ scatter points are located on or near the bisector, which extends slightly beyond $(\sigma_i/\mu_i^{*}) \leq 0.5$ in Figure 9. Highly scattered EE's occur where $\sigma_i/abs(\mu_i) > 1$ indicating factors where marked non linearity and interactions with other factors are taking place, this occurs in the interval $(\sigma_i/\mu_i^{*}) \geq 0.5$, with highly scattered EE's occurring at $(\sigma_i/\mu_i^{*}) \geq 1.0$ (Fig. 11). The delineation of slope lines at $\sigma_i/\mu_i^{*} = 0.1, 0.5,$ and 1 thus provides a useful framework for the assessment of the linearity of the EE's associated with each input variable (Fig. 13 a –f).

σ_i / μ_i^{*} versus $\sigma_i / abs(\mu_i)$
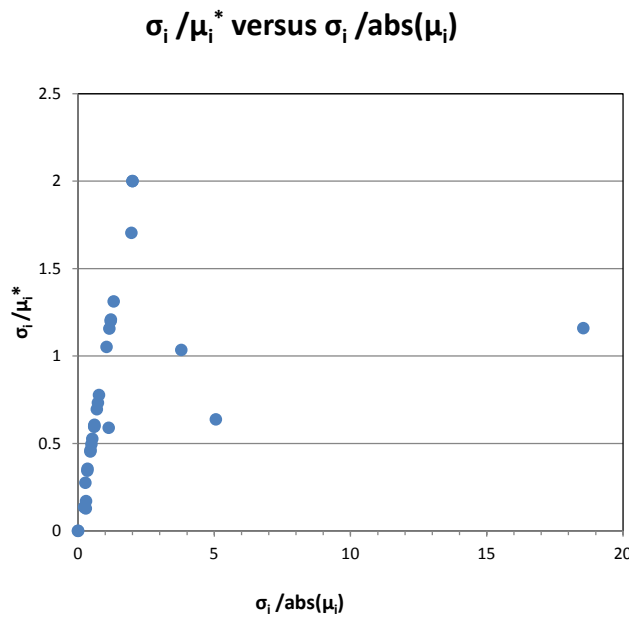
Figure 11. Relationship between σ_i / μ_i^{*} and $\sigma_i / abs(\mu_i)$ for a combination of 30 elementary effects

The absolute mean of the EE's (μ_i^{*}) for each input factor (i) is considered a good proxy of the total sensitivity index (S_T). Figure 12 ranks input/ output sensitivity for a combination of 6 outputs in relation to 5 inputs factors.

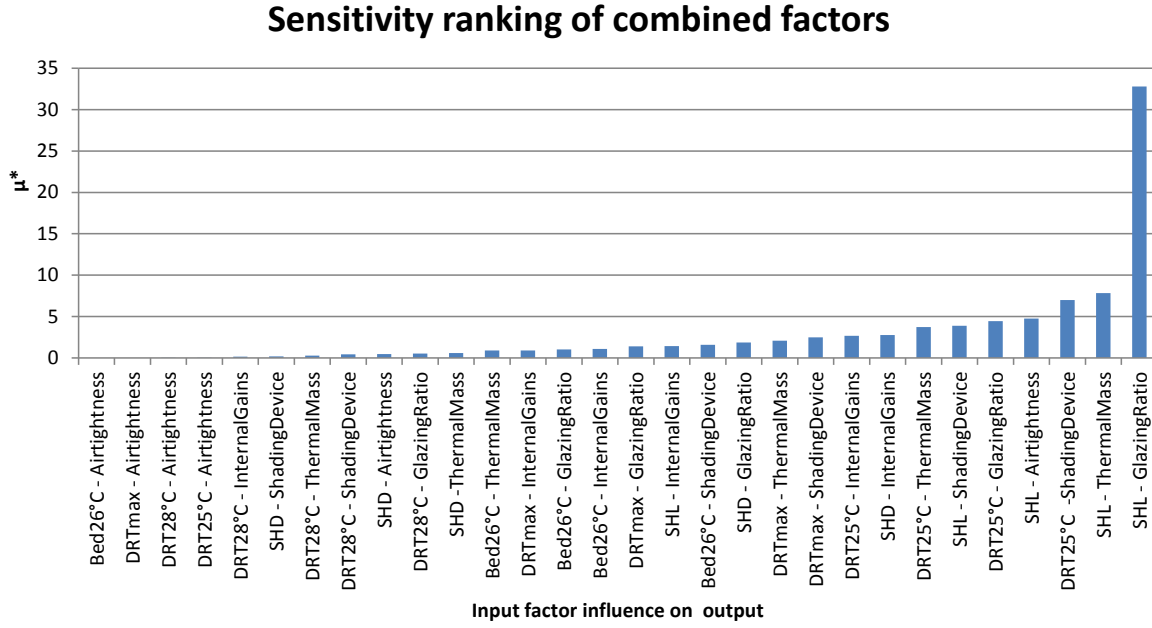## Sensitivity ranking of combined factors

Figure 12. Ranking of output factor sensitivity - combined measures

The output factor sensitivity ranking shown in Figure 12 provides useful information at the conceptual design stage. For example the ranking illustrates that the SHL is highly sensitive to the glazing-to-wall ratio used in the model, and that this factor is four times more important than the dwelling's thermal mass in influencing the SHL (in relation to the ranges assessed in table 3). This information is particular relevant in the planning process where either the SHD ≤ 15kWh/m^2.yr or SHL ≤10W/m^2 criteria may be used to comply with the Passivhaus certification criteria [28].

The ranking of the overheating variables (Fig. 12) provides a hierarchy for minimising the future overheating risk. It can be seen from this analysis that the influence of the external shading device has the greatest potential effect upon the frequency of internal temperatures above 25°C, followed by the (south facing) glazing-to-wall ratio (within the ranges assesses in Table 3). At the opposite end of the scale improving airtightness (beyond n$_{50}$ ≤ 0.6 h^{-1}) can be seen to have negligible impact upon any of the overheating parameters. In practice the use of hierarchical ranking also exposes optimization synergies. For example it can be seen (in Figure 12) that designs optimized in relation to the SHL shows a better correlation with factors that will also result in reduced overheating risks, than designs optimized in favour of the SHD.

In a first order analysis, the value of an elementary effect for an individual input variable (i) corresponds to the output variation when the input i moves from the minimum scalar function (0) to the maximum (1). By averaging the EE's of r random trajectories the dependence on a single sampling point is removed and μ_i^* becomes a good proxy for the mean output variation corresponding to the input i. By plotting μ_i^* against σ_i (Fig. 13a-f) it is possible to graphically identify factors which are almost linear (below $\sigma_i/\mu_i^* = 0.1$), monotonic ($0.1 < \sigma_i/\mu_i^* < 0.5$), almost monotonic ($0.5 < \sigma_i/\mu_i^* < 1.0$), and factors with which are highly non-linear or interacting with other factors ($\sigma_i/\mu_i^* > 1$).
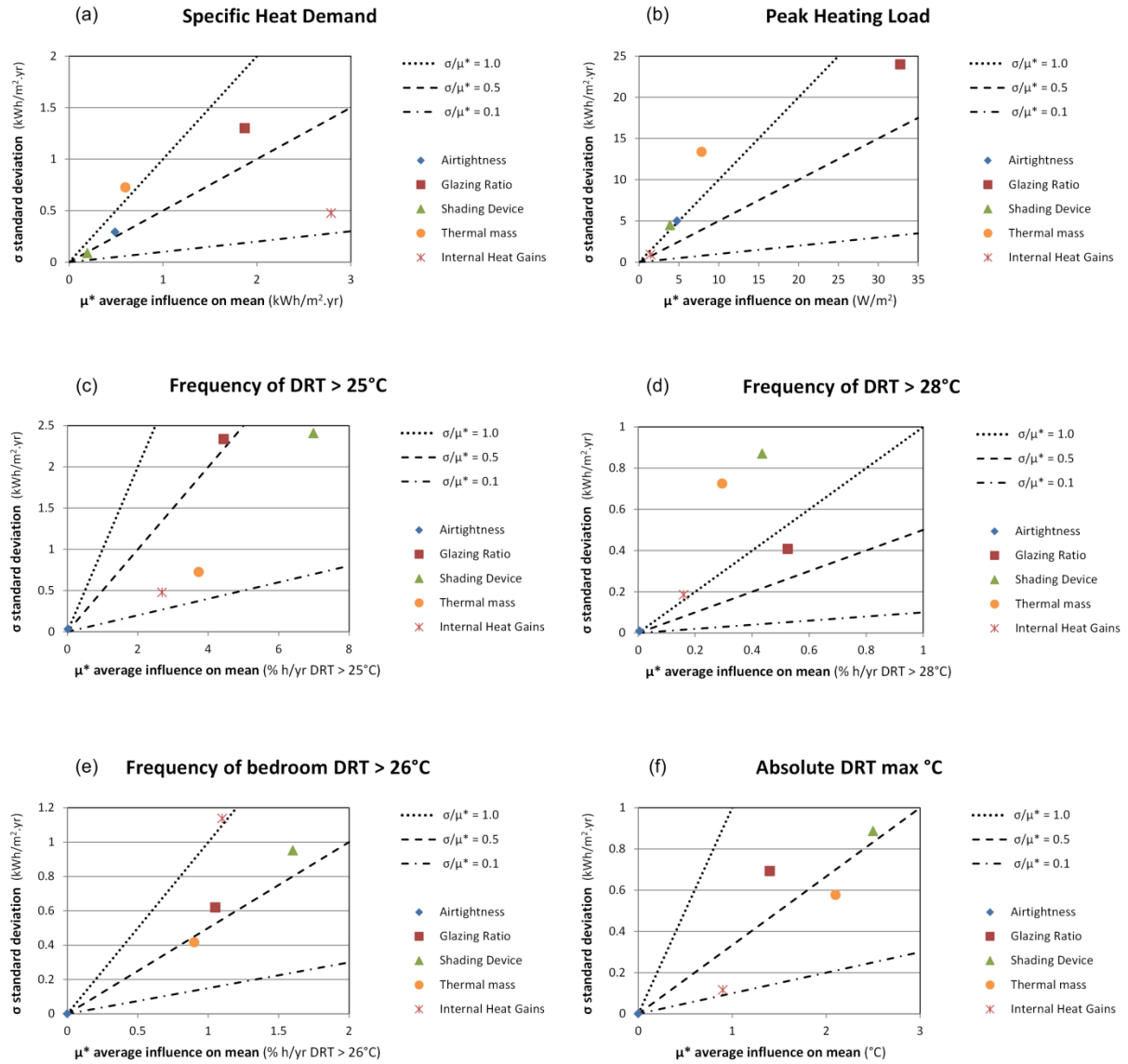
Figure 13. Enhanced Morris analysis of absolute mean (μ^*) and standard deviation (σ) of first order elementary effects for (a) space heating demand (b) peak heating load (c) living area DRT above 25°C (d) living area DRT above 28°C (e) bedroom DRT above 26°C and (f) living area maximum DRT

Figure 13(a) shows that internal gains have a significant and monotonic effect on the SHD, yet play only a small role in influencing the SHL. The SHL (Figure 13b), is most strongly influenced by the glazing ratio (as shown by Figure.10) in an almost monotonic manner. In contrast thermal mass also exerts a significant influence on the SHL (Figure 13b), however its influence is highly non-linear suggesting that possible interactions with other factors are occurring.

In terms of the overheating parameters the most pronounced influence of the input parameters can be seen on the frequency of the OT_{25} (Figure 13c), since the influence of all passive design factors diminishes as the overheating threshold is elevated (Figures 13d,e,f). The shading device has the most pronounced influence upon the frequency of OT_{25} and also the frequency of $BedOT_{26}$. Interestingly internal gains appear to play a more significant role in influencing the frequency of $BedOT_{26}$ (Figure 13e) than in the combined living area overheating parameters. One possible explanation of this finding is that internal sources of heat are likely to contribute to internal air temperature stratification which will be experienced more strongly in the first floor bedrooms due to the buoyancy effect. Overall the SHL (Figure 13b) sensitivity analysis is better correlated with the overheating parameters than the SHD (Figure 13a). This finding suggests that there are likely to be fewer parameter conflicts

in a Passivhaus dwelling that is optimised to achieve a low SHL and low overheating risks than for a dwelling designed for low SHD and low overheating risks.

5   CONCLUSIONS

Evidence suggests that Passivhaus and super insulted dwellings are already at risk of overheating in the UK, Ireland and Northern Europe. In the rapid transition to 'zero carbon' building in the UK, designers of Passivhaus and low energy dwellings may be in jeopardy of pursuing ultra-low space heating targets at the expense of whole life thermal performance. According to the results of this paper by 2050 a warmer than average summer could see average internal temperatures (in Passivhaus and low energy FEES dwellings) in London exceeding 25°C for between 5 and 10% of the year. Beyond 2050, in warmer than average summer conditions, the duration of mean internal temperatures above 28°C rises sharply in all of the dwelling types studied. Unless there is a move towards whole life design optimisation based on minimising future overheating risks, active cooling systems may become a de-facto requirement in urban Passivhaus and low energy dwellings in the UK within the next 30-40 years.

If global GHG emissions continue to follow a 'High' (A1FI) emissions scenario trajectory then the average SHD of Passivhaus dwellings in London is likely to fall considerably (by approximately 40%) by the middle of this century, whilst at the same time the SHL is likely to remain substantially unchanged. In relation to overheating risk factors, the Passivhaus concept (when used without active cooling systems) appears to provide only slight additional protection in comparison to an almost identical naturally ventilated FEES dwelling.

The performance of the Passivhaus dwellings in this study was shown to be highly sensitive to a small number of design inputs. In particular the risk of overheating (OT frequency above 25°C) was shown to be highly dependent upon the solar transmission reduction provided by a full external shading device, as well as the glazing to wall ratio on the South façade. Glazing to wall ratios also played a dominant role in relation to the peak heating load. It follows therefore that design optimisation in relation to the SHL, as opposed to SHD, is likely to produce better outcomes in relation to overheating risk reduction. Thermal mass played a clear role in reducing the overall duration of overheating in the Passivhaus dwellings, and was also correlated with a reduction in the SHL. In relation to reducing the SHD however, thermal mass had only a minor effect. Further research investigating the effects of thermal mass in relation to the timing of the dampening effect (decrement delay) during prolonged heatwaves (where night purge ventilation possibilities are limited) is needed. The results here suggest that the use of thermal mass may be counter indicated in relation to overheating risks in bedrooms in some cases. More sophisticated systems involving the use of displaced thermal mass (via earth air heat exchangers) or Thermally Active Building Systems (TABS) may overcome these problems and be worthy of further investigation.

Careful attention must be paid to the design assumptions and assessment criteria used to evaluate future overheating risks. In urban contexts, the possibilities of purge ventilation through opening windows may be limited or non-existent and internal gains in a UK social housing context may be significantly higher than PHPP default assumptions suggest. Clearer guidance on acceptable overheating criteria with respect to morbidity and mortality risks as a function of OT's and IAQ is urgently required. Further research is also needed to establish the full extent of the future overheating risk in a broad range of Passivhaus dwelling typologies and urban contexts. This work is particularly important in relation to dwellings housing vulnerable occupants; including apartments and care homes where a combination of high internal gains, large glazed areas and reduced purge ventilation possibilities are likely to co-exist. Simple sensitivity analysis techniques, used in conjunction with probabilistic scenario modelling, provide a means of facilitating transient design optimization in the face of rapid climatic change.

Acknowledgements

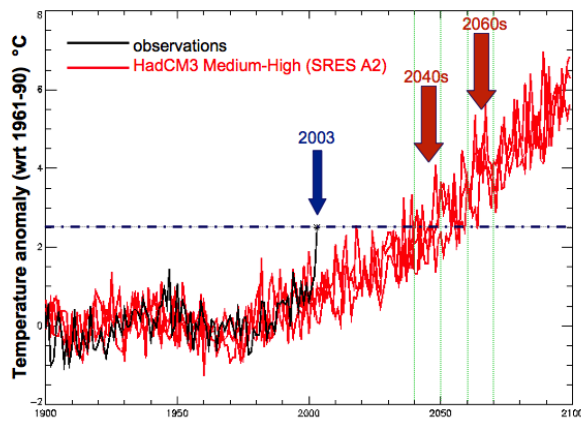List of Figures

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Figure 1. Temperature anomaly of 2003 heat wave in relation to Medium High emission trend, © Crown Copyright, Met Office.

Figure 2.Floor plans and IES model view showing end terrace dwelling (South elevation)

Model characteristics	Dwelling Type			
	FEES heavy	PH heavy	PH medium	PH light
Construction type	Cavity wall wet plastered	Full-fill cavity wet plastered	TGI stud double lined	SIPS panel dry lined
U- value walls [W/m²K]	0.23[1]	0.14	0.14	0.14
U- value roof [W/m²K]	0.18[1]	0.10	0.10	0.10
U- value ground floor [W/m²K]	0.23[1]	0.10	0.10	0.10
Thickness walls [m]	0.3569	0.4860	0.3222	0.2383
Thickness roof [m]	0.2545	0.4262	0.4823	0.3882
Thickness ground floor [m]	0.224	0.511	0.511	0.511
Total heat capacity walls [kJ/(m²K)]	293.4	341.6	95.3	65.5
Uninsulated heat capacity walls [kJ/(m²K)]	153.6	154.7	48.2	15.8
Total heat capacity roof [kJ/(m²K)]	60.4	100.7	92.7	72.8
Uninsulated heat capacity roof [kJ/(m²K)]	15.8	15.8	15.8	15.8
Total heat capacity ground floor [kJ/(m²K)]	240.84	511.1	511.1	511.1
Uninsulated heat capacity ground floor [kJ/(m²K)]	37.2	501.2	501.2	501.2
Total heat capacity internal walls [kJ/(m²K)]*	157.2	157.2	81.7	31.7
Total heat capacity internal floor [kJ/(m²K)]	185.84	185.84	91.43	31.4
U_w value whole window [W/m²K]	1.4	0.7942	0.7942	0.7942
U_g value glass [W/m²K]	1.4053	0.8017	0.8017	0.8017
g value	0.721	0.618	0.618	0.618
Infiltration [effective ac/h]	0.152	0.035	0.035	0.035
Efficiency of MVHR Unit [-]	-	85%	85%	85%
Mechanical supply air flow rate	-	30m³/pp.h	30m³/pp.h	30m³/pp.h
Natural vent strategy	see profile	see profile	see profile	see profile
Psi value or y-value incorporated	Y value incl.	bridge free	bridge free	bridge free
Ground coupling integrated	via EPW	via EPW	via EPW	via EPW
Cooling coil used	see scenario	see scenario	see scenario	see scenario
Humidity control for cooling	see scenario	see scenario	see scenario	see scenario

[1]Includes y value adjustment of 0.05 [W/(m²K)] (ZCH, 2009)   * assumes internal walls have two exposed sides

Table 1. Principal performance characteristics of 4 dwelling types (3 complying with the Passivhaus standard and 1 modelled according to the FEES Standard)

Dwelling Type	Ventilation requirement Ventilation profile	Ventilation profile
FEES model	1. Indoor air quality	Windows ramp open for ventilation when CO_2 >1000ppm. Window opening restrictors are assumed to limit the maximum opening angle to 10°. If CO_2 >2000ppm then the opening angle is increased to 45°

		temporarily to maintain air quality. Windows are closed when $CO_2 \leq 1000$ppm or outside air temperature $\leq 5°C$ or wind speed is $>7ms^{-1}$
	2. Purge ventilation	When the internal temperature $> 22°C$ and the internal temperature is $>$ external temperature the windows open progressively (using ramped profile) with maximum opening of all windows when the internal temperature reaches $26°C$. Window opening restrictors are assumed to limit the maximum opening angle to $10°$
PH models	1. Indoor air quality	If the outside temperature is $\leq 20°C$ then the ventilation air is provided via the heat exchanger operating at 85% efficiency at a constant flow rate of $30m^3$ per person per hour. If the outside temperature is $> 20°C$ the heat exchanger is bypassed and the same flow rate is supplied at the ambient temperature
	2. Purge ventilation	(As per FEES model)

Table 2. Ventilation profiles according to dwelling type

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