An investigation into the energy and control implications of adaptive comfort in a modern office building

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Abstract

An investigation into the potentials of adaptive comfort in an office building is carried out using fine grained primary data and computer modelling. A comprehensive literature review and background study into energy and comfort aspects of building management provides the backdrop against which a target building is subjected to energy and comfort audit, virtual simulation and impact assessment of adaptive comfort standard (BS EN 15251: 2007). Building fabric design is also brought into focus by examining 2006 and 2010 Approved Document part L potentials against Passive House design. This is to reflect the general direction of regulatory development which tends toward zero carbon design by the end of this decade. In finishing a study of modern controls in buildings is carried out to assess the strongest contenders that next generation heating, ventilation and air-conditioning technologies will come to rely on in future buildings.

An actual target building constitutes the vehicle for the work described above. A virtual model of this building was calibrated against an extensive set of actual data using version control method. The results were improved to surpass ASHRAE Guide 14. A set of different scenarios were constructed to account for improved fabric design as well as historical weather files and future weather predictions. These scenarios enabled a comparative study to investigate the effect of BS EN 15251:2007 when compared to conventional space controls.

The main finding is that modern commercial buildings built to the latest UK statutory regulations can achieve considerable carbon savings through adaptive comfort standard. However these savings are only modestly improved if fabric design is enhanced to passive house levels. Adaptive comfort can also be readily deployed using current web-enabled control applications. However an actual field study is necessary to provide invaluable insight into occupants' acceptance of this standard since winter-time space temperature results derived from BS EN 15251:2007 constitute a notable departure from CIBSE environmental guidelines.

To the memory of my grandparents.

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Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Network
AP	Approved Document (Building Regulation)
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BAS	Building Automation Systems
BIM	Building Information Modeling
BMS	Building Management System
BREEAM	Building Research Establishment Environmental Assessment Method
CAV	Constant Air Volume
CCS	Carbon Capture and Storage
CDF	Cumulative Distribution function
CIBSE	Chartered Institution of Building Services Engineers
CVRMSE	Cumulative Variation of Root Mean Squared Error
DALI	Digital Addressable Lighting Interface
DDC	Direct Digital Control
DGNB	Deutsche Gesellschaft fuer Nachhaltiges Bauen
DMX512	Digital Multiplex (512 information input)
DRY	Design Reference Year
EPBD	Energy Performance Building Directive
FL	Fuzzy Logic

FS	Finkelstein- Schafer (statistics)
GA	Genetic Algorithm
G Value	Total solar heat transmittance
HQE	HauteQualité Environnementale
HVAC	Heating, Ventilation and Air Conditioning
HVAC&R	Heating, Ventilation, Air Conditioning and Refrigeration
IEA	International Energy Agency
LTHW	Low temperature hot water
MBE	Mean Bias Error
MPC	Model Predictive Control
NZEB	Net Zero Energy Buildings
PDF	Probability Density Function
PID	Proportional, Integral and Derivative
PIR	Passive Infra-Red
PMV	Predicted Mean Vote
POE	Post Occupancy Evaluation
PPM	Parts per Million
PSO	Particle Swarm Optimisation
RFID	Radio Frequency Identification
RL	Reinforcement Learning
RMSE	Root Mean Square Error
TRY	Test Reference Year
UKCP	United Kingdom Climate Impact Programme
VAV	Variable Air Volume

WSN	Wireless sensor networks
WWW	World Wide Web

Nomenclature

ACH	Air Change per hour
F	Air exchange rate conversion factor
F	Decrement Factor of a building structure
G	Natural Gas
P	Power (electrical)
Q	Heating energy demand
$\bar{T}$	Temperature (running mean)
$T_{operative}^{+}$	Upper limit of acceptable operative temperature
$T_{operative}^{-}$	Lower limit of acceptable operative temperature
Y	Building category (1, 2, 3 or 4)

Sub and superscripts

ao	Outside air (dry bulb)
$atmospheric/50$	Building air change rate at atmospheric (or 50 Pascal) pressures
ave	Average
h	Heating
i	hours of analysis (0 to 8760)
m/M	Measured data
s/S	Simulated data
$\sum$	Sum
σ	Standard deviation

ε	Statistical error
Ø	Building material heat transfer time lag

Chapter 1 Introduction

1.1 Background

Few would dispute that it was Britain who gave birth to the industrial revolution, where profound socio-economic changes followed the replacement of manual labour with industrial machinery. The need to generate power therefore came as a function of an energy hungry economy, and the order of this relationship has stayed the same ever since.

The last few decades however have witnessed radical shifts in attitudes towards energy consumption. Prior to the 1970s oil crisis, energy management was an alien concept. Very few organisations or governments had any energy targets and the industrial world held the view that abundant oil, together with rapid advances and deployment in nuclear technology were the gateways to a new era of cheap energy. What is generally referred to as OPEC oil crises, together with the realisation of the complex nature of nuclear technology profoundly challenged this view, and continues to shape policies internationally to date. What adds to the political will to push for reform - in the articulate words of David JC MacKay- is that posterity will not have the benefit of two billion years of accumulated energy reserves [1].

This work offers a comprehensive field-based investigation of all aspects of human comfort that currently dictate industry best practice standards using a commercial building as the study platform. The main focus, however, is maintained on thermal comfort and the merits of the adaptive comfort were it to replace the static CIBSE guidance. In the UK, comfort guidelines are most comprehensively encapsulated in the best practice standards outlined by Chartered Institute of Building Services Engineers (CIBSE), which inform and govern the work of architects and building designers. The prominent comfort index, namely that of thermal aspect is examined more closely to enable the focus of this work which concerns the concept of adaptive comfort and its potentials within high performance building fabrics. To that effect an evaluation is undertaken of the practicality and acceptability of BS EN 15251: 2007, as well as its energy saving potentials. In conclusion an evaluation of control strategies is carried out with a view to establish weather current building control strategies can accommodate such a time-variant measure of space control as stipulated by BS EN 15251: 2007.

1.2 Aims, Objectives and contribution to knowledge

The aim of this work is the investigation of comfort and energy implication of adaptive comfort as stipulated by BS EN ISO 7730:2005. This investigation is carried out using an office building built to exceed the requirements of approved document part L 2006 by 30%. The reason behind the selection of this building is that such a high performance fabric is representative of the future building design requirements.

The ability of building models to accurately predict energy and comfort related building criteria has been a matter of infinitesimal improvement as most current simulation packages are improved versions of the legacy systems largely developed at a time of comparatively small computing powers. The package examined in this work is EnergyPlus that itself is an accumulation of four decades of incremental improvement, and has arguably been the most widely used tool within research and design sectors. More recently post construction energy conservation studies and technology appraisal works require greater confidence in the prediction of energy packages. This work has strived to provide a further contribution to building model calibration by adding annual space temperature prediction results to what previously has solely concentrated on energy prediction accuracies.

Additionally, it is abundantly clear that the tightening of air infiltration and better insulation values are continuing trends within the UK regulatory system [2, 3]. This work therefore offers an examination of carbon reduction potentials of two regulatory and scientific trends. First that of improved fabric design to passive house level and second the merits of adaptive comfort as outlined by EN 15251. Given that the design of a building should also take a whole life perspective, medium and long term weather files are used to project the results into the future. Associated energy and comfort implications of these two concepts are examined within both current and future climate change scenarios by offering the magnitude of carbon reduction potentials of both. Human thermal comfort values resulting from BS EN ISO 7730:2005 fall short of CIBSE static thermal comfort recommendations and the results are outlined in section

7.4.2. This contribution to the existing state of occupant comfort is therefore pursued within the following objectives:

- Collection of longitudinal environmental data within an office building over annual cycles, and deployment of this to conduct a two tier model calibration (energy and temperature calibration).
- A simultaneous undertaking of an internal post occupancy building occupant audit to benchmark the environmental performance of the office design and charter any relationship that age and gender might have to the occupants' perception of comfort.
- Further utilising the calibrated EnergyPlus model to conduct a comparative study of the effects of improved fabric design to Passive house levels.
- A comprehensive simulation-based examination of the energy and comfort impact of changing the control regime from static zone target temperatures as dictated by current CIBSE standards to that of weekly running mean derived from adaptive temperatures as proposed by BS EN 15251: 2007.
- The increasingly automated nature of HVAC control systems and the drive for widespread adaption of BEMs means that a time-variant space conditioning will have to be delivered through integrated building management systems. A review is therefore undertaken of the state of the art building controls development in conjunction with an industrial survey of the controls application specialists to determine how far and at what intervals the existing building control systems are capable of accommodating a time-varying weather dependant zone temperature delivery within an office building.

To achieve the objectives of this study, a newly built commercial office building is selected and introduced in Chapter 3. Four streams of data are subsequently gathered from this building; first, local weather data using a scientific weather station on the building rooftop, second energy information using building's BMS, third the views of the occupant of the building over 4 main seasons and finally internal environmental conditions using a combination of WSN and auditing material. This ‘real-world’ information is used to conduct an in-depth occupant perception study of the working environment, set against CIBSE best practice data. The result of this study is covered in Chapter 5.

The real world performance of the building is then used as a bench mark to conduct energy and comfort analysis of the concept of adaptive comfort as enshrined in BS EN 15251: 2007. As energy intensive occupant behaviour has highlighted major effects of occupant-building interaction on lighting related energy consumption [4], visual comfort is also investigated within the case study building. Section 4.4 sets out the steps taken towards calibration of target building virtual model (constructed in EnergyPlus) which in turn provides the platform for an energy and comfort assessment of adaptive comfort standard. Actual energy and temperature data collected from the building facilitate the calibration of the virtual model to surpass the requirement of ASHRAE guide 14. As UK is heading towards zero carbon domestic and commercial buildings in 2016 and 2019 respectively, an attempt is also made to examine to what extent passive house design standards can be a part of the creation of zero carbon commercial buildings. This recognition informs a simulation-based comparative study of the two building forms, first that of the actual building and second of the passive house standard, both in freefloat stage and also with plant intervention to decide the extent to which comfort conditions are met and also the energy savings achieved. In the same way adaptive comfort standard is further evaluated within the aforementioned building fabric forms.

In finishing, a comprehensive review is undertaken within Chapter 8 of the current state of the art building control developments to gauge the potential of existing set of technologies to accommodate adaptive comfort standard. A survey of the control application engineers within the industry is also carried out to assess the views of the practitioners on most promising control strategies that will dominate future horizons, as well as their ability to accommodate adaptive comfort within the building management system. Although the main findings of this work, concerning calibration to ASHREA Guide 14, the effect of age and gender in the perception of comfort and the industrial control survey involves real world primary data, the merits of adaptive comfort and passive house standards were derived from simulation based exercises. The simulation based results are therefore ‘limited’ in that real world examples are missing. This remains the limitation of this work and therefore the natural progress of this study is a real world field trial of the adaptive regime in an actual office building in a similar climate to that of UK.

Chapter 2 Literature review

2.1 Introduction

Given their simplest expression, buildings consume energy in order to provide comfortable environment for their occupants. Most modern buildings and their associated plants (increasingly even on domestic scale) come with microprocessor-controllers (sometimes referred to as ‘on-board’ intelligence) [5]. This, along with the growing reach of internet has opened up a new horizon of energy generation, storage and management. The technology therefore now exists to make the integration of local renewable energy generation, smart end-user appliances, and local storage facilities possible [6]. At the same time the concept of thermal comfort and its management in buildings is evolving to challenge the previously dominant PMV-PPD model developed by Fanger [7] and widely adapted by all international bodies. In this chapter an overview is provided into the concept of human comfort, and more specifically the thermal element of comfort. Recent developments on the science of adaptive comfort is reviewed and based on the current state of research a scope of work is developed to examine this concept within an existing office building (as outlined in Chapter 7). As renewable integration forms an integral part of UK ambition to ultimately achieve a carbon neutral status [8], the latest scientific effort to improve renewable generation and associated storage mechanisms is also offered (Appendix I and J).

2.2 Constituents of Human Comfort

Human comfort has been defined as ‘that condition of mind that expresses satisfaction with the ... environment’[9]. However individual differences in perception and subjective evaluation of ‘environmental comfort’ add layers of complexity to how such a state can be achieved in a building. CIBSE Guide A lists the following elements as major determinants defining human comfort:

- Thermal
- Visual
- Acoustic
- Electromagnetic and electrostatic

A comprehensive body of work is available on the first three of these elements. However, the scope of work undertaken here warrants greater coverage of the first two, as they most actively dictate the daily energy consumption of buildings.

2.2.1 Thermal comfort

The human thermo-regulatory system attempts to maintain a deep-body temperature of about 37°C. With any departure from this temperature, the body initiates a series of heat control mechanisms. Thermal comfort is a comprehensive science in its own right; although among work undertaken to define it in buildings, Professor Povl Ole Fanger's work remains the most authoritative and is widely adapted in publications that provide guidance for building designers [10]. In his original paper [11] he defined thermal comfort as a thermally neutral state; in which the occupant doesn't know if he prefers a higher or lower ambient temperature level. Fanger, through extensive field study, examined the effect of clothing, air movement, temperature, humidity and activity level on building occupants and devised a mathematical model of human thermal physiology. In his model, characteristic of thermal environment together with human physiological sensation lead to the calculation of a predicted mean vote (PMV_ see Figure 1). This, in turn informs what percentage of people will be dissatisfied in that particular scenario (predicted percentage dissatisfied or PPD). Fanger's model is the most widely used indicator of thermal comfort and his model has come to underpin most early building occupant comfort standards including ISO 7730.

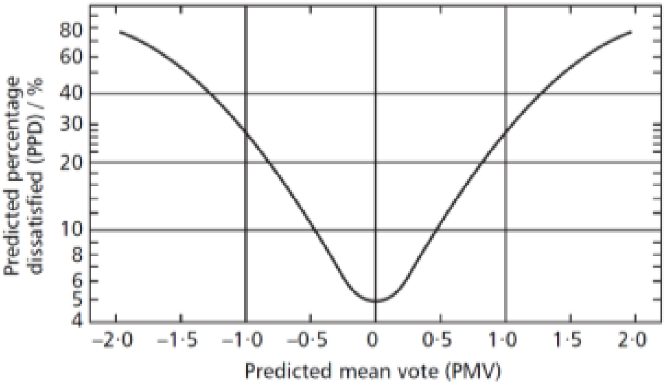

Figure 1 PPD as a function of PMV (CIBSE Guide A: Fig 1.3)

Current best practice standard (as stipulated by CIBSE Guide A) states that good design attempts to achieve a PMV of ±0.5 (i.e. no more than 10% of building occupants will be dissatisfied).

As evident from Figure 1, no thermal condition can satisfy all the occupants of a space (5% always dissatisfied). The aim of good building design therefore remains to create the optimum for the entire occupants; as well as attempting to minimise the energy use. A specific illustration of this balancing act is the work of Corgnati,S.P., et al who considered the relationship between human comfort and energy consumption in buildings [12]. Politecnico di Torino university campus was dynamically simulated using Energy Plus version 1.2.1.The results demonstrated that for the same number of dissatisfied people (10%) the total building energy demand (heating & cooling) can be reduced by up to 50%. This was achieved by having an optimum monthly comfort temperature set point, as opposed to only two set points for winter and summer, an approach akin to the adaptive comfort that is covered later.

2.2.2 PMV and PPD

Ole Fanger first developed a means for assessing the thermal environment that resulted in the ASHREA seven point thermal sensation scale [13]. This was accomplished by collecting the responses of more than 1000 participants examined in various environmental conditions. As a result Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices were developed [7]. Therefore both indices contain an ideal state of thermal comfort which is often referred to as ‘neutrality’. This state is where the flow of heat to and from the participants’ body is in a state of equilibrium.

2.2.3 Acoustic comfort

Building design is mostly governed by ideas of visual beauty, quite often to the determent of their acoustical performance. Building Regulation part E (2003: resistance to the passage of sound) outlines the acoustic requirements in dwellings. Similarly a whole series of British and European Standards, as well as several Building bulletins lay out design guidance for noise sensitive non-domestic environments. Intrusive noise and vibration levels represent a complex challenge that falls outside this work. Suffice to say that despite extensive guidelines there is no shortage of poorly designed and laid out buildings in which acoustic discomfort is a major cause of occupant dissatisfaction. Research shows that in addition to increased stress levels, disengagement and job dissatisfaction, unsatisfactory acoustic environments can further count for up to 8% performance loss among the occupants [14].

2.2.4 Visual comfort

Lighting enables the correct and safe execution of work in any building. This is mostly achieved through a combination of natural and artificial lighting which differ widely depending on the nature of the building. The components that determine visual comfort in a building are very complex and closely intertwined with human psychology, although a general consensus exists that high daylight levels coupled with reduced glare risk is preferred by most building occupants[15].

Building occupancy outside daylight hours, particularly in higher latitudes, together with inadequate daylight levels require artificial lighting in all buildings. This is responsible for approximately 20% of electrical energy supplied to the commercial sector [16]; and has led to a number of EU directives and UK regulations to reduce lighting energy consumptions. The current regulation demands 45 luminaire-Lumens per circuit Watt [17]; to achieve a recommended level of 300-500 lux[1]. But principally it encourages measures to ensure greater use of daylight and better control of electric lighting.

The response of the human visual system to illuminance (total light falling on a surface) is broadly logarithmic, while the influence of changing illuminance on electricity demand is for the most part linear [18] . For instance a reduction of 50% illuminance (hence 50% electrical demand reduction) is perceived as 10% reduction in light level by human eyes. Peter Boyce argues that office lighting level therefore could be reduced without significant occupant dissatisfaction. The self-luminous nature of PC monitors that constitutes most of today’s office activity further supports his proposition. Latest visual comfort research is calling for a biological response metrics to be included as an index of human comfort, reflecting particularly the non-visual effects of daylight responsible for human circadian system regulation[19, 20].

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[1] CIBSE Guide A (table 1-5).

2.3 Adaptive Comfort

Adaptive comfort has been developed to address the weakness and inflexibility of conventional (and static) building climate management by offering a more dynamic and 'micro-climate-linked' template. This approach has attracted greater attention in recent years in recognition of greater resilience that buildings require in warmer and more erratic weather patterns that climatologists anticipate. Principally suited to naturally ventilated or mixed mode buildings, adaptive comfort related indoor temperatures to a single variable, namely outdoor running mean air temperature. As there is strong evidence that thermal comfort is ranked as the highest determinant of human comfort [21], we principally examine the influence of adaptive 'thermal' comfort in a commercial building.

2.3.1 History

It was primarily the wider recognition of dynamic and time dependant nature of thermal comfort that resulted in the development of adaptive comfort. Essentially adaptive comfort removes the 'static' constraints of conventional comfort theory and provides guidance for a more dynamic space conditioning technique. Although earliest known works on adaptive comfort stretch as far back as 1930s , it has only come to command a greater concentration of interest in recent years [22].

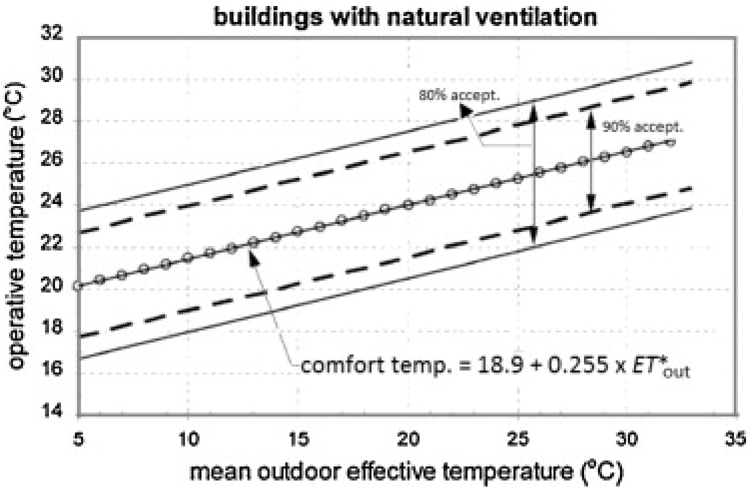

Figure 2 The original adaptive comfort chart outlined in ASHRAE Standard 55-2004

As noted earlier Ole Fanger's' method of defining thermal comfort and assigning a vote to the sensation felt by the occupant was derived from the study of participants in climate chambers. Although initially very influential, this approach was later subjected to considerable scientific criticisms as the design of such experiments essentially regards the participants as 'sensor' and does not make any allowance for the considerable level of interaction between the building user and the building or the cultural aspects of comfort[23]. Similarly further works demonstrated that neutral temperature could vary from one country to the other, and indeed even within similar climates [24].

Unlike Fanger's static approach (derived from work undertaken in close controlled climate chambers), adaptive comfort states that contextual factors and past thermal history modifies the occupant's thermal expectations and preferences. Those in warmer climates prefer higher indoor temperatures than those in colder climates. This proposition is in contrast to the foundations of PMV/PPD model that fails to address cultural and contextual elements of thermal comfort [25]. In doing so adaptive comfort assumes an adaption by the individual to his/her environment that entails a gradual lessening of his/her response to repeated environmental stimulation. Such adaption may be behavioural (clothing, windows, ventilators), physiological (acclimatisation) or psychological (expectations)[25]. Interestingly this approach is the exact opposite of the thermally monotonous environments that are created in air conditioned buildings, aptly referred to as 'comfort capsules' by Wilhite [26].

In recognition of all these reasons a climate dependant model was first developed by MA Humphries that has been refined by other notable contributors such as (but not limited to)J. Fergus Nicol and de Dear & Brager[27].

The most prominent standards that currently offer an incorporated method of adaptive thermal evaluations are ASHRAE Standard 55 [13] which is the principle guideline adapted in North America and indeed beyond .Countries such as Netherland [28]and Brazil [29, 30] have been particularly been active in trying to adapt adaptive comfort as new thermal model guideline in naturally ventilated buildings. Second to ASHREA, EN15251 also incorporates the adaptive philosophy but the two standards differ in the following ways:

1. ASHRAE Standard 55 was derived from a data set (and subsequent publication outlined in RP-884 material[25] whereas EN 15251 was born out of an extensive office experiment in several EU countries[31, 32].

2. ASHRAE chart applies only to naturally ventilated buildings whereas EN 15251 accommodates all building types in free-running mode.
3. The derivation of the neutral temperature is different within the two standards.
4. The outdoor temperature (the single source out of which the comfort temperature range is defined) is derived differently within the two standards. While ASHRAE uses the monthly mean outdoor temperature as the basis of its definition, EN15251 uses a more accurate weighted running mean of the outdoor temperatures[33].

2.3.2 Mathematical expressions

A clear conceptual development of the relationship between outdoor temperature and indoor comfort was first expressed in the work of MA Humphries[34] who developed the following relationship between neutral temperature (T_n) and the corresponding outdoor temperature (T_o) both in °C:

$$T_n = 11.9 + 0.534\, T_o \qquad (R^2 = 0.94) \qquad [1]$$

Later attempts by the previous author produced formulas 2 and 4 [35]. de Dear & Brager also separately used data from 21,000 sites (from 160 buildings) to develop similar adaptive models which are expressed as formula 3 and 5 [36, 37].

Naturally ventilated buildings

$$T_n = 13.2 + 0.534\, T_o \qquad (R^2 = 0.94) \qquad [2]$$

$$T_n = 13.5 + 0.546\, T_o \qquad (R^2 = 0.91) \qquad [3]$$

Air-conditioned buildings

$$T_n = 20.1 + 0.0077 T_o^2 \qquad (R^2 = 0.44) \qquad [4]$$

$$T_n = 22.2 + 0.003 T_o^2 \qquad (R^2 = 0.49) \qquad [5]$$

Where T_n and T_o are both expressed in °C. Quite clearly the coefficient of determination (R^2) for the air conditioned formulas are much lower than that of a naturally ventilated building. Given that R^2 is the confidence in the accuracy of model prediction, these lower values indicates that adaptive formulas don't predict the neutral temperature with the same accuracy in air-conditioned spaces. Expressed differently, neutral temperature in air-conditioned space has a narrower range than in a naturally ventilated space.

This phenomenal is evident from the comfort charts (Figure 3) that resulted from the work of de Dear and Brager [38]. The overall interpretation that could be drawn from fig 3 is that when an occupant is afforded a greater control over their environment, then he or she will attempt to steer the results such that it will satisfy their personal preferences (Fig 3-b). Conversely the occupants of an air-conditioned building rely mainly on the centrally controlled set points over which they have very little control (Fig 3-a). Hence there is a degree of resignation and lowering of the expectation as the occupants are not able to interact with their environment (see expectation hypothesis on section 2.3.3)

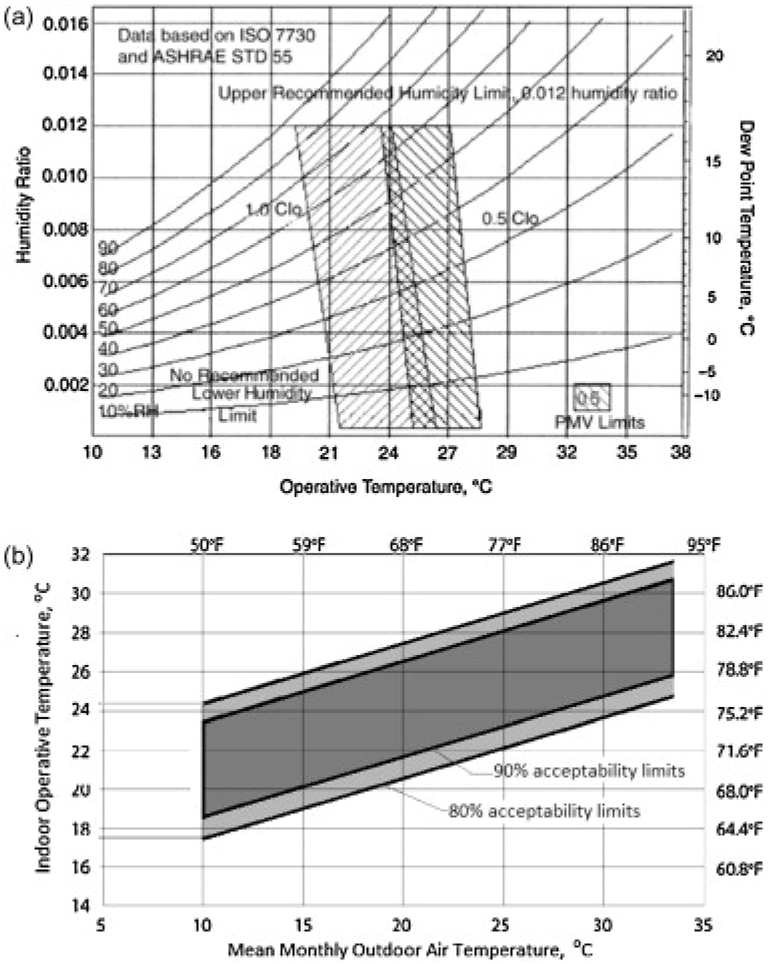

Figure 3 ASHRAE comfort chart for (a) air-conditioned building and (b) naturally ventilated building

Today several organisation with an international reach have incorporated adaptive comfort into their corresponding standards; most notably ASHRAE 55, ISSO 74 and EN 15251 [13, 39, 40]. A succinct yet precise coverage of these standards is available from Olesen and Parsons [41].

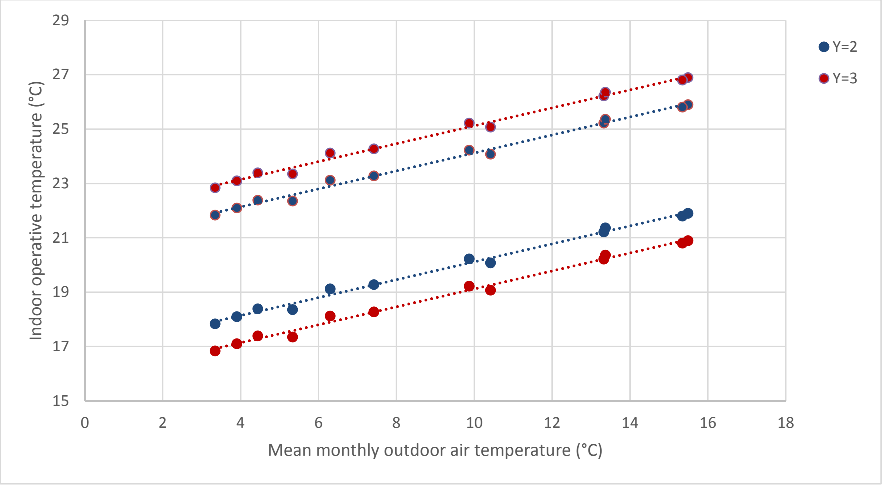

Figure 4 Adaptive comfort charts constructed using King's Gate rooftop Weather data (2013)

Three distinct theories combine to leave the 'static' theory of human thermal comfort behind for a dynamic approach. Firstly the recognition of the link between local climate and occupant thermal satisfaction, secondly variable nature of indoor comfort expectations from one occupant to another, and finally the ability of each occupant to take corrective actions to deal with the natural variability of indoor environmental conditions [42, 43]. Therefore adaptive comfort seeks to actively respond to external climatic developments and in doing so define a lower and upper band of allowable temperature limits for a space which is informed by (and 'adapts' to) the weather conditions. This theory therefore defines a time variant band for comfort and the rate of change of this comfort band can be characterised by the running mean of the outdoor temperature.

Current research shows that adaptive comfort has the ability to significantly reduce building energy consumption [44, 45]. More specifically recent attempts found adaptive approach to offer both resilience and adaptability as the climate change begins to impact on building stocks in the UK [46]; with a notable emphasis on reducing overheating as a function of taking heed of rising summertime temperatures. In chapter 5 adaptive comfort is used as a platform to investigate future weather patterns as well as passive house design capabilities. The comfort bands constructed for this study follows the definitions outlined in BS EN 15251:2007 (for brevity this standard will be referred to as

EN 15251). This standard lists four building categories which are defined based on high, normal and moderate levels of occupant expectations (categories I,II and III) and concludes by category IV where for limited time environmental comfort values may fall outside those defined by the first 3 categories. Category II is recommended as the norm unless the building falls clearly into a different classification. Chapter 5 will outline the steps taken to use this standard for an examination of building energy and comfort performance.

2.3.3 The expectation hypothesis

According to the expectation hypothesis, an expectation (or anticipatory attitude) affects the people attitude towards thermal comfort attainment [47]. This phenomenon demonstrates itself through a person's personality, their expectations and the activity that they are engaged in at the time. In relation to an environment with fluctuating temperature Fountain et al. [48] estates:

> *"when a person's individual 'comfort setpoints' (or preferred temperature) track the cycles and variations in indoor climates, which in turn may follow the diurnal or seasonal outdoor climate patterns, or indeed, longer-term climatic changes. After repeated exposure to variation in environmental conditions, a person's expectations of those conditions may become more relaxed – even anticipatory of temporal changes."*

And where an environment is air-conditioned to achive close control target temperatures, de Dear [49] adds:

> *"Facilities managers in charge of conventional HVAC buildings are often perplexed by the frequency of occupant complaints whenever temperature strays as little as a single degree from the usual set-point. Why have occupants of such buildings become so sensitive, or even hypersensitive, to such subtle fluctuations in workplace temperature? The adaptive hypothesis is that they have come to expect thermal constancy and even the slightest departure away from that expectation is sufficient to prompt complaint."*

The two outlooks expressed above clearly articulate the degree to which human psychology plays a part in the perception of human comfort. It must however be noted that scientific community are not unified in accepting this hypothesis as Nicole and Humphreys [50]. They argue that if people who occupy a space that suffers unacceptable temperature excursions should - by the logic stipulated by expectation hypothesis – anticipate the unsatisfactory thermal experience and in doing so readjust their expectations to the prevailing reality.

2.3.4 Agreements with Fanger

It has been found that in moderate climates the Fanger's PMV-PPD model can predict (and in doing so agree) with the results of adaptive comfort studies. Where the external diurnal temperatures do not fluctuate very widely (as in moderate maritime climates) the comfort band constructed using the external temperature may have a range similar to PMV-PPD range of Fanger's work. An example is a adaptive model developed for a study in Cuba with temperatures ranging from 26.8°C to 28.2°C [51]. Similar attempts found upper and lower ranges of 3K depending on the parameter input[52]. It is therefore perfectly feasible that in climates where daytime and night-time temperatures vary in moderate degrees, the two models can overlap in their assessments of thermal comfort.

2.3.5 Departures from Fanger

The comfort and PMV equation derived by Fanger from the study of 1396 subjects are cumbersome and complicated. Reference could however be made to his original work that outlines this relationship [53]. However this relationship is captured within his original work in the following concise expression:

$$PMV = f(t_a, t_{mrt}, v, p_a, M, I_{cl}) \qquad [6]$$

Borrowing from the above expression, in Fanger's heat balance approach, thermal comfort experienced by an occupant is a function of:

1- Environmental factors (i.e air temperature(t_a), mean radiant temperature (t_{mrt}), air velocity (v) and vapour pressure (p_a)).
2- Personal factors (activity level or metabolic rate (M)and clothing type(I_{cl}))

In contrast to this model, adaptive comfort relates the sensation of comfort to one (and only one) other variable and that is outdoor air temperature.

2.3.6 Criticism

In response to these criticisms, Nicol and Humphreys (two of the major contributors of this standard) argue that some of the variables captured by the

Fanger's model are in one way or another related to the outdoor air temperature[50], notably clothing insulation, posture and metabolic rate for any given activity. Although relative air velocity and mean radiant air temperature are not clearly accounted for.

Fisherman and Pimbert demonstrated how daily outdoor temperature influences the clothing insulation values particularly in women[54], and later Morgan and de Dear provided evidence of a strong correlation between the two [55]. However no research attempt has provided explanation (or justification) for the absence of mean radiant temperature and air velocity in adaptive comfort philosophy[27]. The notion of adaptive comfort's 'over-simplification' of Fanger's work was put forward by E. Halawa and J. Van Hoof who argue the illustration of adaptive notion in ASHRAE Standard 55 lacks the clarity and degree of granularity that Fanger's proposal of human comfort entailed [27]. With reference to Fig. 3-b, this presentation of human comfort sets the mean radiant temperature to be equal to air temperature, the metabolic rate to be ≤1.2 met, clothing to be 1 Clo in winder and half that in summer and finally air velocity to be set ≤0.15 m/s. In contrast to this Fanger's work attempted to express human comfort as a fluctuating function of all the elements that are set at constant in ASHRAE's work. A demonstration of this is Figure 5 that illustrates how increasing air velocity affects mean radiant temperature at various air speeds [7].

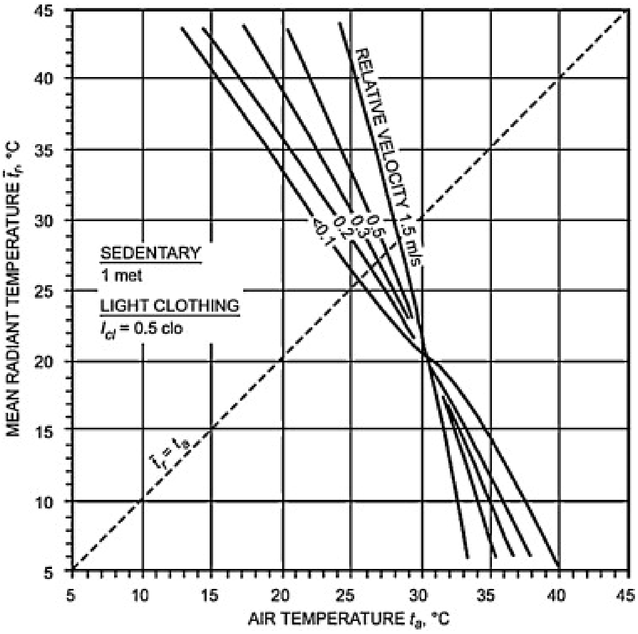

Figure 5 The effect of air relative velocity on the optimum MRT at various air temperatures.

Further criticisms were also levelled against the adaptive approach due to the statistical nature of it. This statistical foundation implies that the derived equations are only valid if the target boundary conditions are similar to those found in the original studies[56]. This however could also be said about the Fanger's model which is derived from college-age students partaking in climate chamber studies.

2.3.7 Merits

Fanger's PMV-PPD model was essentially a chamber based model of human thermo-regulatory behaviour and preference. The adaptive approach however is based on a more credible working environment sets of data that takes occupant integration with the environment into account. As noted above the criticism that is primarily levelled against the adaptive approach is that it reduces the Fanger's thermal model with its 6 independent variables (see formula 6) to a single variable (i.e. outdoor running mean temperature). Yet it could also be argued that the adaptive approach relies more actively in the dynamics of human behaviour that the chamber-based derivatives of Fanger's doesn't. In most of the work put forward by Fanger for instance the level of clothing of the occupant is set at 1 (winter) or 0.5 (summer)[53]. Yet the adaptive approach makes allowances for the occupant to adjust his clothing level in the course of a single day in response to the prevailing thermal conditions. This is a closer reflection of reality and although the adaptive formulae derive the target temperature from a single variable (namely the outdoor temperature), in essence the 'adaptive' notion captures the dynamic and responsive nature of occupant behaviour in the space through its implicit philosophy, that which states that to the changing environmental conditions there will be a set of reactions from the occupants that are aimed at restoring their thermal comfort, be it opening a window or putting on a jacket.

2.3.8 EN 15251

Essentially the current ASHRAE standard 55 and EN 15251 are the main regularity and standardisation bodies that promote the adaptive comfort philosophy. Although stemming from different research attempts and databases, both standards put forward a conceptually similar expression of adaptive comfort philosophy. EN15251 was a product of a longitudinal study in

26 European countries where occupant comfort was comprehensively examined outside the heating season in offices operating in free-running mode. The collective results were presented by McCartney and Humphreys and later adapted into EN 15251 [32, 57]. This standard forms the foundation of the work conducted in this submission and therefore it is studied under greater focus. B. W. Olsen provides a detailed coverage outlining the logic, philosophy and feasibility of this standard is two successive publications on the subject [58, 59], and further evaluated by Nicol and Wilson [60].

The basic equation incorporated into the equation is:

$$T_{co} = 0.33 \times T_{ext,ref} + 18.8 \qquad [7]$$

With T_{co} being the comfort temperature and $T_{ext,ref}$ being the outdoor reference temperature calculated as the running mean of the last 7 days. It is however important to note that this formulae is considered adequate for outdoor reference temperatures of between 10°C to 30°C. $T_{ext,ref}$ is calculated using the following formulae:

$$T_{rm} = \frac{1}{3.8}\left(T_{dm,n-1} + 0.8\,.\,T_{dm,n-2} + 0.6\,.\,T_{dm,n-3} + 0.5\,.\,T_{dm,n-4} + 0.4\,.\,T_{dm,n-5} + 0.3\,.\,T_{dm,n-6} + 0.2\,.\,T_{dm,n-7}\right) \qquad [8]$$

This rather convoluted equation calculates the average mean running temperature (T_{rm}) by simply rounding the last 7 days in reference weather file with a weighting coefficient that diminishes as the reference day ($_{dm,n-i}$) moves further back in time.

The accessibility of EN15251 is defined for four building category

1- Category I: high expectation levels (i.e. sensitive and fragile occupants) with a PPD<6%. Temperature interval: ±2°C.
2- Category II: normal levels of expectation (new buildings) with a PPD<10%. Temperature interval: ±3°C.
3- Category III: moderate levels of expectations (existing buildings) with a PPD<15%. Temperature interval: ±4°C.
4- Category IV: Departures are allowed (i.e. warehouses) with a PPD>15%.

Despite CEN'[2]s decision to incorporate this standard into EN15251, the applicability is narrowed further to:

1- Summer season only
2- Buildings with low metabolic rate activities (<1.3MET)
3- Buildings where occupants can freely open the windows and change their clothing levels
4- Where no HVAC system operates.

The resultant acceptable temperature range is summarised in Figure 6.

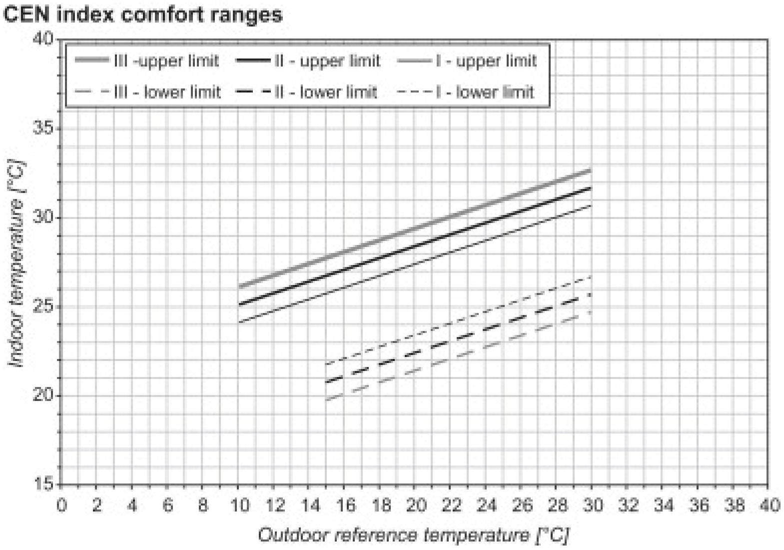

Figure 6 CEN adaptive comfort acceptability range

2.3.9 *ASHRAE Standard 55*

ASHRAE standard 55 was the first regulatory body that incorporated the adaptive concept. As noted earlier, it based its formulation of the adaptive comfort on the monthly mean of outdoor temperature (as opposed to the progressive values that ISO 7730 and EN 15251 use; that is the running mean of outdoor temperature).

It was originally in 1990s that field study data from a wide range of locations worldwide were collated into a corpus of 21,000 data points to derive the following two equations [25]:

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[2] European Committee for Standardisation

For a naturally ventilated building (when outside temperature falls within 5-32°C range):

$$T_{co} = 0.31 \times T_{ext,ref} + 17.8 \qquad [9]$$

In the case of a HVAC building

$$T_{co} = 0.11 \times T_{ext,ref} + 21.45 \qquad [10]$$

Where $T_{ext,\,ref}$ is the monthly average outdoor temperature. Two acceptable ranges of comfort was also found and expressed at constant values. First at 80% satisfied where a temperature interval of ±3.5°C prevails (concerning typical conditions) and then a 90% satisfied which carried a narrower temperature interval of ±2.5°C to accommodate a higher level of occupant expectations. The ASHREA standard however carries the following limitations:

- It is primarily to be applied with a $T_{ext,\,ref}$ of 10-33.5°C
- The occupants need to be able to directly operate the windows
- The occupant activity should not exceed 1.3 MET.

2.3.10 ISSO74:2005

The Dutch guideline was described by van der Linden et al. [28]where only two building types (ALPHA and BETA) define naturally ventilated and air conditioned buildings. The emphasis is for the naturally ventilated building to accommodate active occupant participation in climate management together with flexible clothing policy. In line with the adaptive comfort philosophy this guideline defines room temperature as a function of outdoor temperature but what distinguishes it from ASHRAE index is that this guideline allows winter interpretation and deployment in buildings (note that ASHREA Standard 55 is defined for summertime only).

2.3.11 Applicability

The adaptive comfort is primarily targeted at naturally ventilated and mixed mode buildings by the three main bodies that incorporate this model [61-63]. The field trials from which the standard was derived found that the band of comfort existed over a wide range of temperatures but grew narrower as the temperatures became warmer [31]. Recent studies however found that the adaptive dynamics are as effective in mixed mode buildings as in naturally ventilated ones[64, 65].

As noted earlier several countries have adapted this approach with an expression that most satisfies the regional climatic and cultural conditions. In the Netherlands, the findings of de Dear and Brager were used to develop local standards[25]. This interpretation is referred to as the Adaptive Temperature Limit (ATG) and is based on a time interval of 4 days[28].

2.4 Scientific studies of adaptive comfort

2.4.1 Comparative studies

Several attempts have been made to decide how the main proponents of adaptive comfort, namely ASHREA, CEN and the adaptive temperature limit in the Netherlands (ATG) compare in terms of the comfort values generated. One such example was a study where upper band adaptive temperatures were calculated for three cities in Italy and found that CEN index is overall more forgiving than ASHRAE due to its formulation (ASHREA uses the monthly mean to calculate allowable bands as opposed to a running mean used by CEN)[56]. A similar conclusion was drawn by Sourbron, M. and Helsen, L. [66] who concluded that EN 15251 can deliver lower cooling energy when compared with ASHRAE 55 and ISSO74[28]. This was achieved by constructing TMY reference files for years 2001 to 2008 for Maastricht (the Netherlands). This study also concluded that for moderate climates, the adaptive ASHRAE 55 and ISSO 74 don't offer much cooling energy reduction when compared to the static Fanger model captured in ISO 7730:2005. Interestingly however both ASHREA 55 and ISSO 74 have lower 'upper-band' for winter and midseason than that of the static ISO 7730 (hence 'heating' energy savings might be achieved by them, although Raison d'être for both adaptive models are cooling energy reduction).

Similarly there are calls on the different interpretation of various approaches to be brought closer together, since such unification will make for easier and more meaningful interpretation by analysts[67].

2.4.2 Simulation efforts

In a simulation based study fundamentally centred on comparing static and adaptive comfort results, de Wilde examined an existing office building's performance within current and future weather conditions taking into account the climate warming trend [46]. His work concluded that by 2020 the base model building (located in Plymouth) showed a tenfold magnitude of overheating risk when conditioned to static indoor zone controls, whereas the over-heating risk drops to two fold if adaptive comfort approach is implemented. Also the cooling load of the building will drop by 50% due to the adaptive approach.

2.4.3 Field studies

The results of a 4-week summer field study of adaptive thermal comfort in a naturally ventilated German office provided some interesting results. It was observed that the votes cast by 50 subjects under study were in good agreement with adaptive comfort models, but they did not correspond to calculated Predicted Mean Votes [68]. A similar study of the summertime performance of 12 German offices over a period of 3 years demonstrated that when adaptive comfort (as defined by EN 15251) is implemented, the comfort criteria is only exceeded for less than 5% of the ‘operational time’ [69]. Although the researchers do not specify whether this comfort criteria was perceived by the occupants of the building to be satisfactory.

Although climatically quite different, results of adaptive comfort research in India also demonstrated that when scope for adaption is available, building occupants regard much higher temperatures as their neutral temperature[70]. This effort included a total of 113 occupants in 45 apartments and a neutral temperature of 29.23°C was derived demonstrating the wide range of environmental comfort that climatic conditions and adaptability may bring about [71].

2.4.4 The effects of age and gender

No clear consensus exists on the effects of age and gender on building occupants. A field study of dwellings in India (where the main problem is providing cooling) found poor correlation between the perception of age and gender with thermal comfort (n=100) [72]. It however found woman and older subjects were more accepting of higher temperatures. A 20 strong laboratory based trial conversely found women to be less tolerant of low temperatures when using either convective or radiant cooling methods to the extent that an average temperature increase of 1.2K was required to obtain satisfaction in females [73]. Women were also found more likely to report building related sickness syndromes in a student dormitory (n= 3712) [74].Women were also found less satisfied with thermal environment and preferred higher thermostat settings in Finish offices and homes (n=3094)[75]. It is therefore in the extremities of acceptable thermal environment that gender differences become notable. A UK based laboratory study found that for identical clothing and activity level, male and females exhibit little differences in neutral and slightly warm conditions [76]. It is only in cooler conditions that females tend to feel colder. When studied at hot and arid climates, again females were found to be more inclined to feel warm (n=589)[77]. Therefore there seems to be a detectable pattern where gender has no influence except at the more extreme boundaries of thermal environments (i.e. too hot or too cold). Other research work are calling for the inclusion of other aspects (such as body fat) in the assessment of thermal sensation [78], adding a further layer of complexity to a subject where definite and overall conclusion are difficult to find.

Field studies of age and gender effects on thermal sensation, unless conducted using very large sample pools across several climatic zones, carry a degree of bias because of the non-standardised clothing and activity level of the participants. Given that a definite scientific verdict on the differences of men and women (or age) requires setting up elaborate laboratory test while standardising all other aspects of thermal sensation, there still seems to be a great scope for research work in this area.

2.4.5 Scope for work

The implementation of adaptive approach in the comfort standard has so far been restricted to summer assessments of naturally ventilated or unconditioned buildings where people have (at least perceived) adaptive opportunities[64, 79]. Yet for this philosophy to be able to provide carbon reduction and climate adaptability solutions it looks reasonable to allow its implementation in all building types and all climates. This can take the shape of either a global formulae that could be incorporated in all different climates (which inevitably will lead to a less flexible solution), or a number of formulae that could be referenced for different building types and climatic conditions. What is abundantly clear from the investigation of the literature is that the scientific community is still far from a consensus on how this notion could be applied universally, and if there are ways by which the legacies of PMV-PPD model can also be incorporated to any such attempts.

2.5 Summary

Two broad philosophies emerge from the work covered in this chapter which define the thermal aspect of occupant comfort, first Ole Fanger's influential PMV-PPD models developed by collecting votes in closely controlled climate chambers, and second the regression-based adaptive theory derived from extensive field studies.

It was noted that PMV-PPD model is criticised for its regarding of the occupant as a sensor, ignoring the considerable levels of interaction between the occupant and the building, whereas the adaptive concept is criticised for reducing Fanger's complex heat balance model to a single variable, namely that of external running mean temperature. Yes research covered in this chapter shows that adaptive comfort has the ability to reduce building energy consumption notably due to reducing overheating as a function of taking heed of rising summertime temperatures [44, 45]. Further since the adaptive approach widens the range of acceptable temperatures, it offers both resilience and adaptability against warmer and more erratic weather patterns anticipated by the climatologists both in the UK [46] and beyond [80, 81].

This work offers an examination of the adaptive comfort potential in current and future UK climate, by using a modern office building as case study. The office building (introduced in chapter 3) was built to exceed part L 2006 requirements by 30% and therefore is representative of both current and future regulatory requirements in the UK. An Energyplus model of the case study building is constructed and calibrated to ASHRAE guide 14 (Section 5.2). The calibrated model is then used to examine adaptive comfort as outlined by EN 152510 and the energy and comfort results are presented. As referred to in section 2.4.3, the focus is particularly maintained on the inconsistencies of the adaptive approach when compared to PMV-PPD model to see if the differences between the two models might be reconciled within the scope of the work undertaken here.

Chapter 3 The Target Building

3.1 Introduction

For the purpose of data collection, monitoring and occupants' feedback study, as well as local weather data analysis a new prestige office development was selected within Newcastle University estates portfolio. This office building was built to supersede the regulatory requirements at the time of construction and as such acts as a representative sample of what current and future regulatory forces in the UK will demand. The case study building is a 5-storey office block with natural sand-stone masonry finish inaugurated in Sep 2009. This development (referred to as King's Gate building) was intended to bring a number of different student services under one roof. It also provides accommodation to the university senior management team. Designed by Bond Bryan Architects to a total cost of £35m, the building is divided into mostly open plan but also cellular workstations. The building also has a heavily glazed front façade (+34°from due south; see Figure 7) that is shaded by extruded aluminium brise soleil. At north, east, south and west orientations solar control glazing facades cover 54, 29, 87 and 42 per cent of the entire skin respectively (hence overall the building's external facade is 53% glazed).

Figure 7 King's Gate heavily glazed front faces +34° from due south.

This office building has a complex architecture which includes two large southerly and westerly voids, two internal atriums facilitating displacement ventilations and a blend of cellular and open plan offices (a total of 131 different spaces housing around 500 staff). To cater for this, a combination of radiators, trench and perimeter heaters, under floor heating and tempered air are used to provide space heating. Two overall philosophies guided the design of the building; firstly thermally induced displacement ventilation enabled by internal atria, and secondly heavyweight construction with exposed concrete mass to absorb and store a substantial amount of thermal energy internally. Deploying thermal mass in order to moderate higher summertime temperatures has gained a wide architectural audience and following several successful field studies is also recommended by professional bodies in the UK [82, 83].

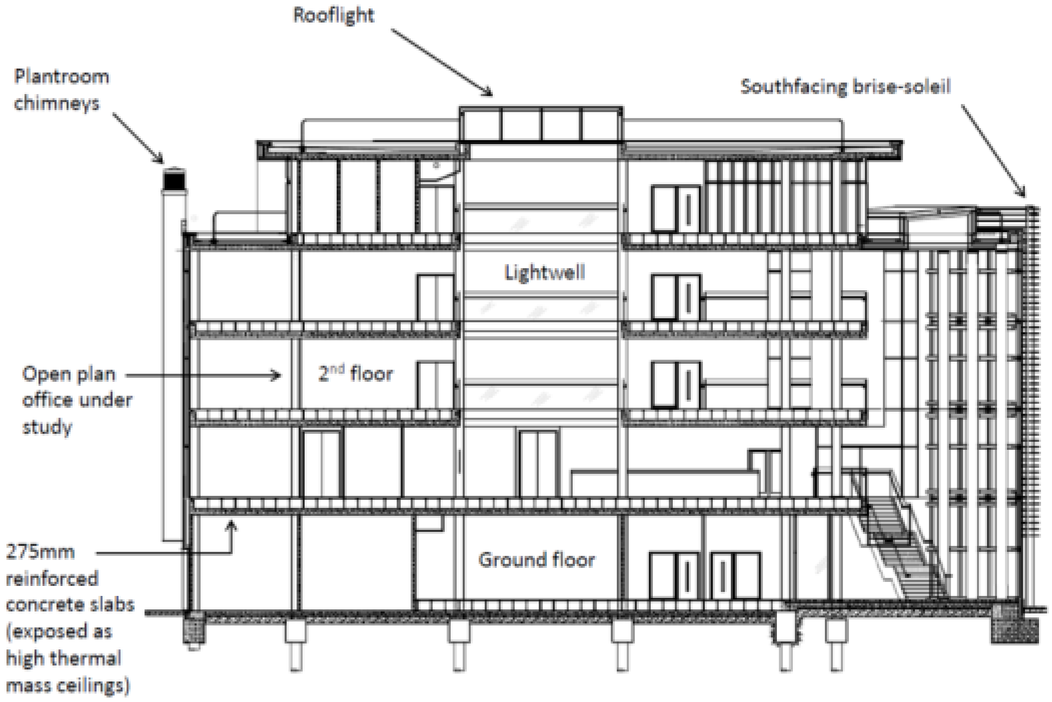

Figure 8 Section drawing of King's Gate

Within the building, thermal mass is ‘close-coupled’ with the heating and cooling plants as displacement ventilation air enters the building via integral floor concrete ducts. Research has demonstrated that close coupling strategy can improve demand side energy management and the integration of local renewables [84, 85].

3.2 Rooftop weather station

Detailed local weather data is essential for accurate calibration and analysis of energy consumption of a building model over the examination period. A Gill's MetPak Pro weather station (Figure 9) combined with a SPN1 pyranometer were mounted on the rooftop of this building to provide the following outputs:

1- Global solar radiation (W/m² - accuracy ±5%)
2- Diffused radiation (W/m² - accuracy ±5%)
3- Wind speed (m/s - accuracy ±2% at 12 m/s)
4- Wind direction (accuracy ±3°)
5- Air temperature (accuracy ±0.1 °C)
6- Relative humidity (accuracy ± 0.8% at 23°C)
7- Dew point (accuracy ±0.15°C at 23°C with a dew point of 20°C)
8- Barometric pressure (accuracy ±0.5 hpa)

Readings are taken on a 10 minute frequency intervals and logged in CSV format. 2 complete annual files were available to aid with model calibration against actual data. Further data from this installation includes 4 separate external radiant temperature readings taken at 4 different building orientations (see image 15).

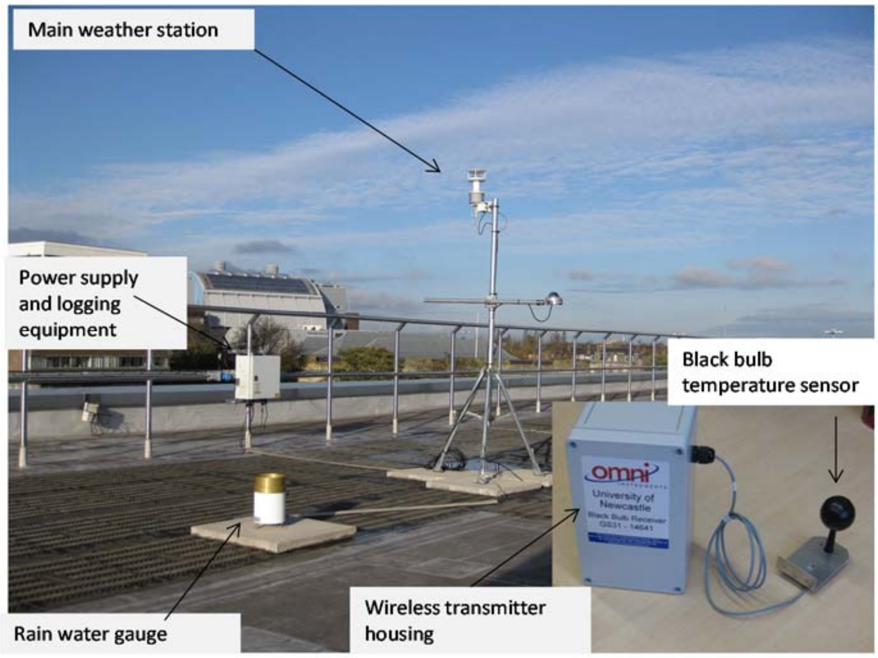

Figure 9 Scientific weather station on King's Gate rooftop (inset: one of 4 black bulb packages)

The black bulb sensors are mounted 30 cm below the top edge of each orientation of the building (facing roughly south, west, north and east) and communicate their reading to the central data logger via 4 wireless transmitters.

3.3 Building servicing strategy

3.3.1 Heating

Three equally sized condensing boilers provide a total of 744 kW of heating and hot water capacity. King's Gate has a complex architecture which includes a heavily glazed southerly facade, the inclusion of 2 internal voids and 2 full-height south and westerly atriums and a blend of cellular and open plan offices. To cater for this, a combination of radiators, trench and perimeter heaters, under floor heating and tempered air are used to provide space heating. Heating system is designed to a winter-time outside temperature of -4°C.

3.3.2 Ventilation

Two central air handling units (AHU) with 2-stage heat recovery facilitate displacement ventilation at a total rate of 11.32 m^3/s with 90% of the supplied volume being recirculated. Air is introduced into floor voids and discharged via floor supply diffusers. Ventilation air then rises to be extracted by two large grills at the top of each atrium for heat recovery. Within section 4.3 monitoring temperature data will outline how these atria manage to create an average annual vertical temperature gradient of 2K across 5 storeys of King's Gate. CIBSE guide A's recommendation of 12 litres per second per person of ventilation air was used for fresh air design and operation. As each AHU extracts 90% of the supplied volume, the building is therefore under a slight positive pressure.

Figure 10 Roof-top atria intended to admit daylight and facilitate natural ventilation

3.3.3 Cooling

The overall philosophy that guided the design of the building relied on inducing thermal stack effect facilitated by the two aforementioned internal atria to provide mixed mode ventilation. This was intended to work in synergy with exposed internal concrete slabs in order to prevent summer-time overheating, and in doing so eradicating any need for refrigerant-driven cooling. Despite this a small degree of back-up cooling capacity is provided first by adiabatic evaporative coils acting directly on the summertime air intake; and then direct expansion vapour compression coils (which have a relatively small capacity of 100 kW). Cooling was designed to cater for an external dry-bulb summertime design temperature of 29°C (20.5 ° C Wet bulb).

The building's fundamental reliance on displacement natural ventilation and night cooling removes substantial amount of summer cooling requirements. If vapour compression technology was to be used to cool the building, then summer time electrical power consumption would change dramatically. Electrical power for central cooling plants equates to 0.5 kW_e per kW of cooling delivered[3]. If vapour compression-based cooling were installed, an additional footprint of electrical load would have existed that culminated in peaks of about 220 kW of electricity (derived from calibrated virtual model). This would have

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[3] BSRIA Guide BG 14/2003, page 12, Table 2: Cooling plants

constituted a 130% increase in electrical consumption of the building (which currently follows a fairly stable office-hour value of 170 kW). It is clear that vapour compression cooling would have been hugely disadvantages.

3.3.4 Electrical services

A 1MVA transformer supplies the building via the main MCCB intake unit (connected using a 11KV/400V transformer). Because of extensive IT use in the building, power factor correction and surge suppression facilities are incorporated into electrical supply. Two 400Amp vertical bus-bars located within east and westerly electrical risers supply the distribution boards on all floors. Main plant room items, as well as lighting and small power on each floor are sub-metered. All emergency lightings are fed via a centralised 3-hour standby battery located within the plantroom. The battery unit also serves fire alarms and opens vent windows in the case of fire. Lighting is operated by presence detection and is equipped with daylight compensation sensors.

3.4 Load profiles

3.4.1 Electricity

The building has a rather consistent power pattern all throughout the year; as illustrated in Figure 11.

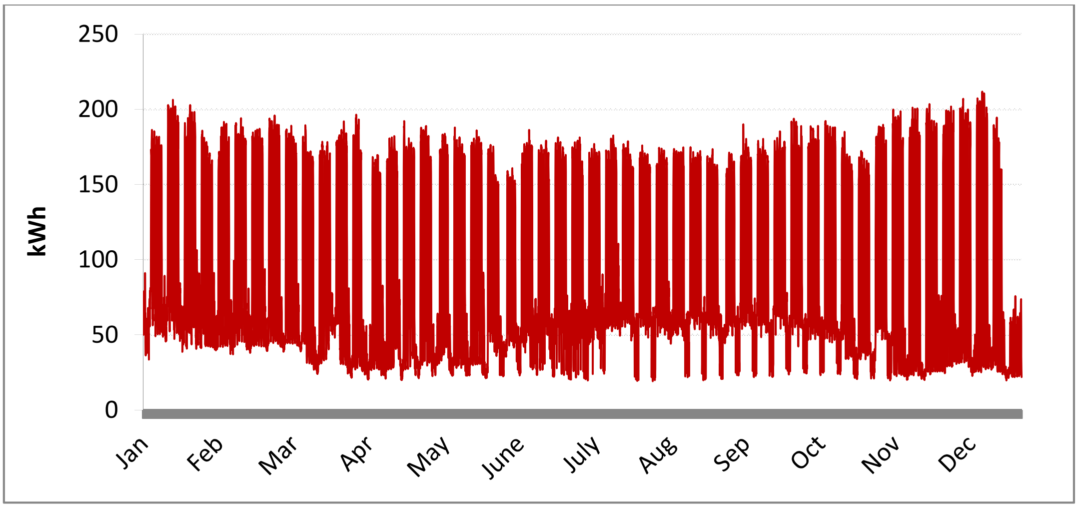


Figure 11 Metered active hourly power demand (2012)

On average, working-hour electrical loads float at around 170 kW, falling to about 45 kW at night time. The night time load is pushed up to around 60 kW in mid and late summer months. This is a result of night purge ventilation strategy that deploys mechanical fans to pre-cool the ‘thermally heavy’ building fabric for the next working day. Greater wintertime lighting and HVAC requirements increases the daily peak values to around 200kW. Typical weekly winter and summertime consumption patterns are set out in the following two figures.

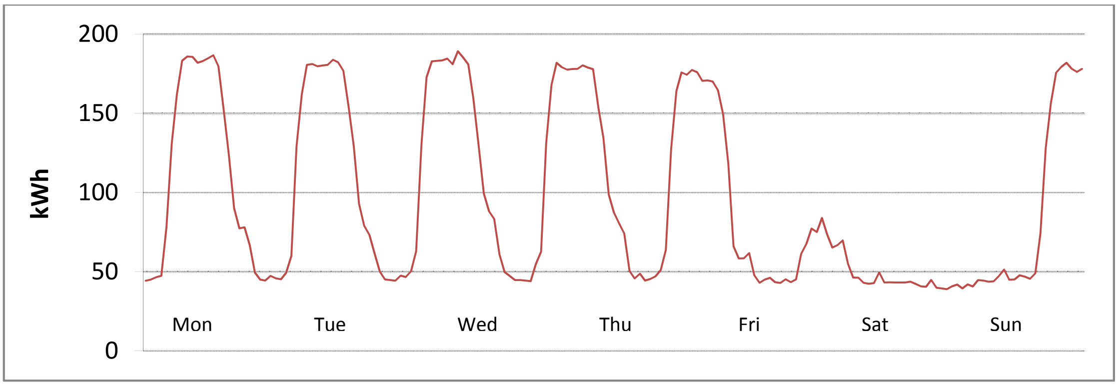


Figure 12 Hourly metered electricity consumption (1st -8th March 2012)

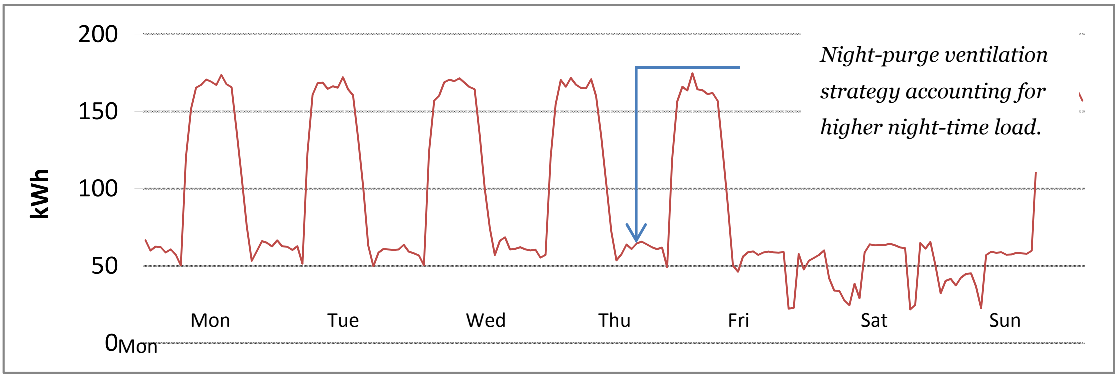


Figure 13 Hourly metered electricity consumption (8th -16th Aug 2012)

The more erratic pattern of weekend demand during summer months (Figure 13) stems from AHU duties responding to high internal temperatures. These units are brought into duty to ventilate the space after set-back summer-time temperature in the space is exceeded.

3.4.2 Gas

Quite understandably the building annual heating demand is far more erratic than the rather stable electrical loads, as a functional of seasonal weather changes. Figure 21 demonstrates 2012’s hourly gas consumption data. Note that the summer-time heat load occurred in late June is the result of hydronic system anti-corrosion dozing that the facilities management company had provided. Given that summertime space conditioning is achieved through provision of tempered air, no heating load occurs due to the incorporation of heat exchangers in the AHUs supplying the building.

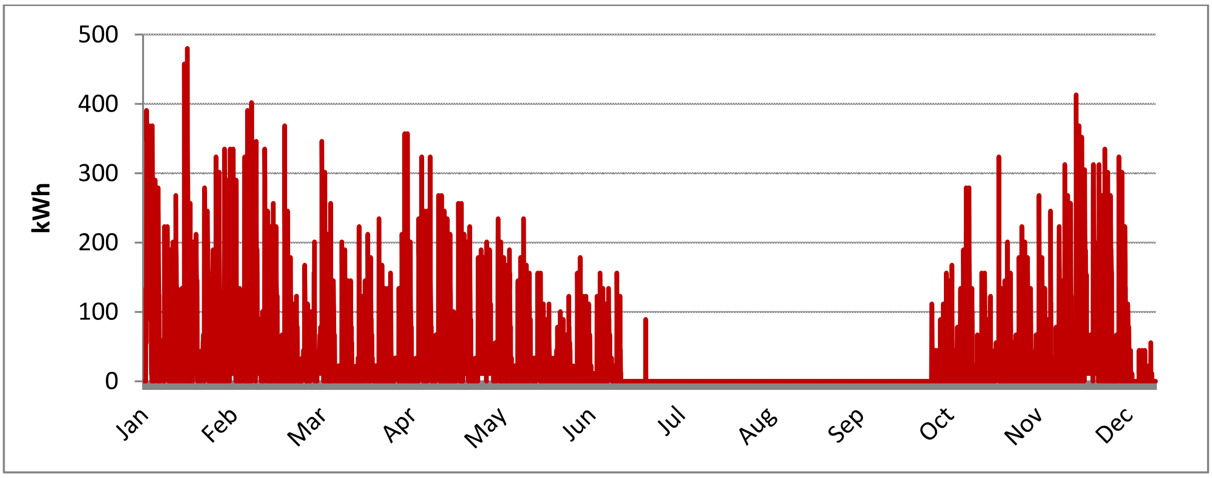


Figure 14 Metered hourly gas demand (2012)

A better appreciation of the average hourly demand at various times of the year is achieved by viewing monthly values broken into 8am-5pm hourly averages (Figure 15).

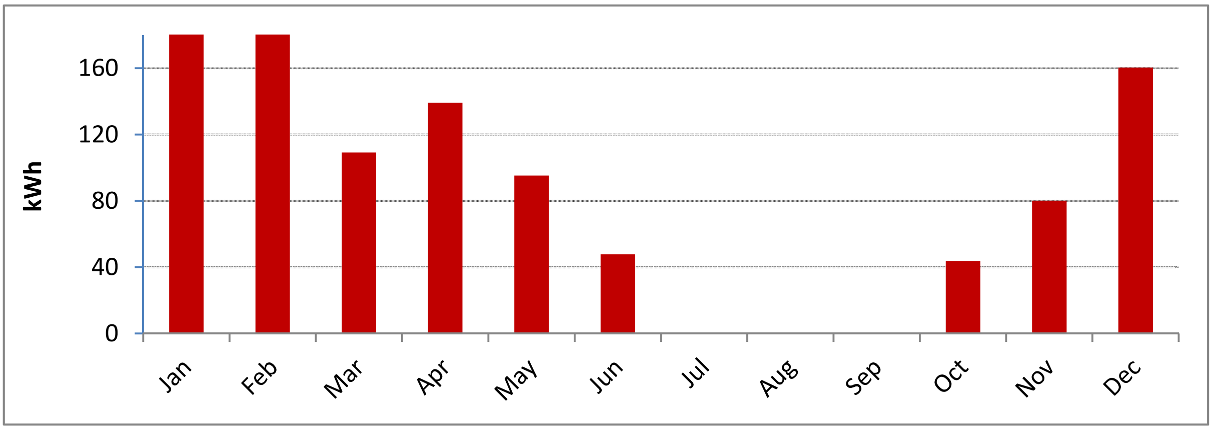


Figure 15 Average operational time hourly gas consumption over the 2012 annual period (actual data)

The chart above demonstrates that the building is quite well-managed as no space heating load occurs in summer months. A degree day analysis outlined in appendix E similarly demonstrated that King's Gate gas consumption is a close function of weather data and no discrepancies existed to point towards poor energy management.

3.5 Thermography and fabric study

A portfolio of thermal images from King's Gate was collected to enable the study of the fabric of the building, and inspect the insulation continuity. These images were collected over a period of 3 years during all seasons. Similarly internal images were also required to decide on the extent t of radiant asymmetry in the space. Wide discrepancies between air and radiant temperature in a space also change the index of human thermal comfort and to that effect, it was helpful to examine this dynamic inside the building too (see section 3.5.2). The results allow undertaking occupancy audit (chapter 4) and model calibration (Chapter 5) with greater confidence. Each thermal image is presented together with a reference visual image.

3.5.1 External fabric

Several separate external thermal audits needed to be completed to completely capture the behaviour of external fabric in a variety of different climatic conditions. What is illustrated below is just an overall summary which aid highlighting the main findings.

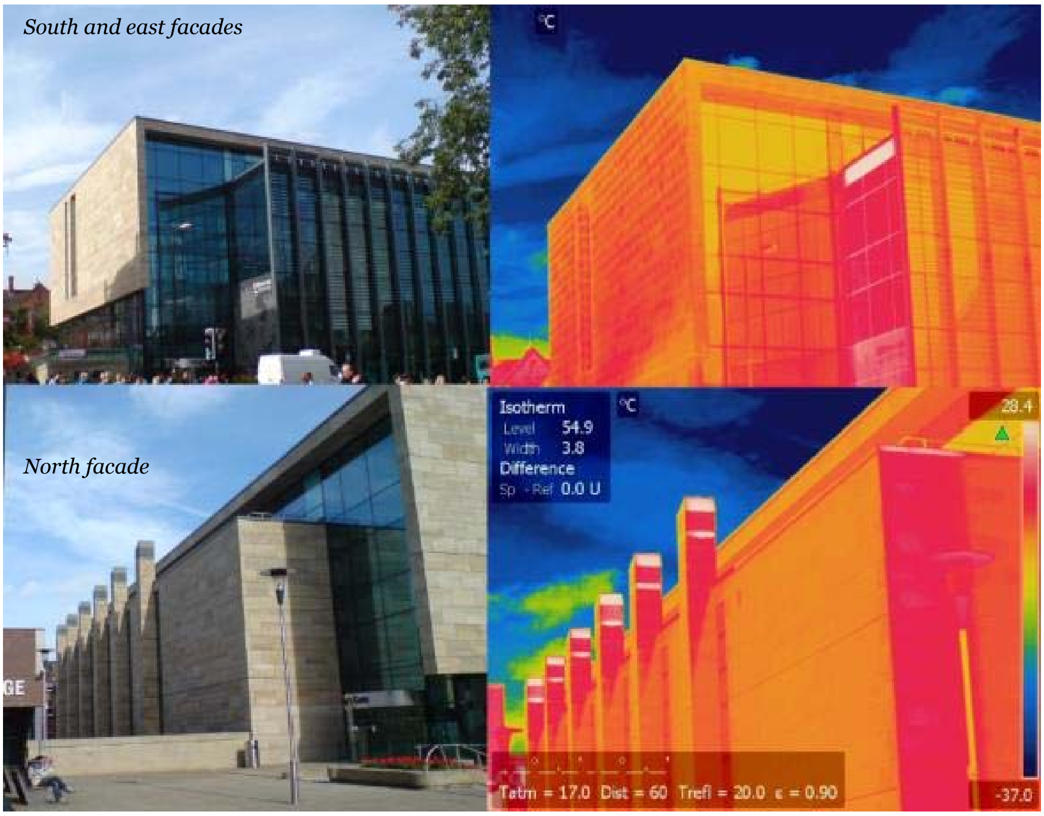


Figure 16 External fabric in a partly sunny late-September afternoon (22 Sep 2011- 1407 hrs.). External air temperature: 17˚C.

Figure 16 demonstrates the effect of solar loading on the external fabric of the building. Parts of the external masonry wall that receive the direct solar beam show up evidently warmer. Solar loading can make the examination of the properties of the fabric difficult (elaborated on next paragraph). The temperature of the exposed sky even in late summer is very low (-37°C in this instance). Parts of the building fabric that are exposed to cold clear sky will therefore have an accelerated rate of heat loss.

On a mild summer day (4 June 2013) with the air temperature standing at 16.3°C, the west facing masonry façade of King's Gate building reached a peak temperature of 41.9°C, while the metal frame of windows stood at 50.9°C (Figure 17). Masonry is capable of absorbing most of the energy of the sun, which is turn builds up its temperature well beyond ambient air temperature. As This –as previously mentioned- is referred to as solar loading and for any fabric type will ultimately partly manifest itself in the form of internal heat gain. The timing of this manifestation is a function of a fabric decrement factor (f) and associated time lag (Ø) and the extent of this manifestation is a function of fabric thermal conductivity properties (CIBSE guide A- 3.8). In sub-section 3.5.4 an illustration of the solar loading built up on the uninterrupted westerly and easterly facades are presented where the resultant solar loads manifest themselves in the form of a higher annual temperature average.

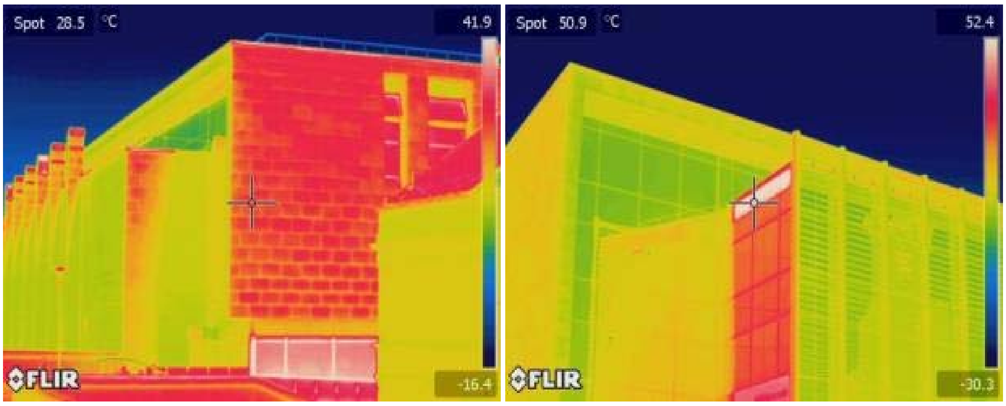


Figure 17 Extreme solar loading in midsummer (4 June 2013-1555 hrs.) showing the great extent of thermal stress that is built up on the external fabric. External air temperature: 16.3˚C

In contrast, Figure 18 was produced on a cold early spring day with an external air temperature of 3˚C. Windows are quite evidently shown to be the weakest thermal links within the structure while their frame offer even less thermal resistance (i.e. more heat is lost through the aluminium frames). The external fabric has a completely uniform temperature colour code that verifies high levels of insulation continuity.

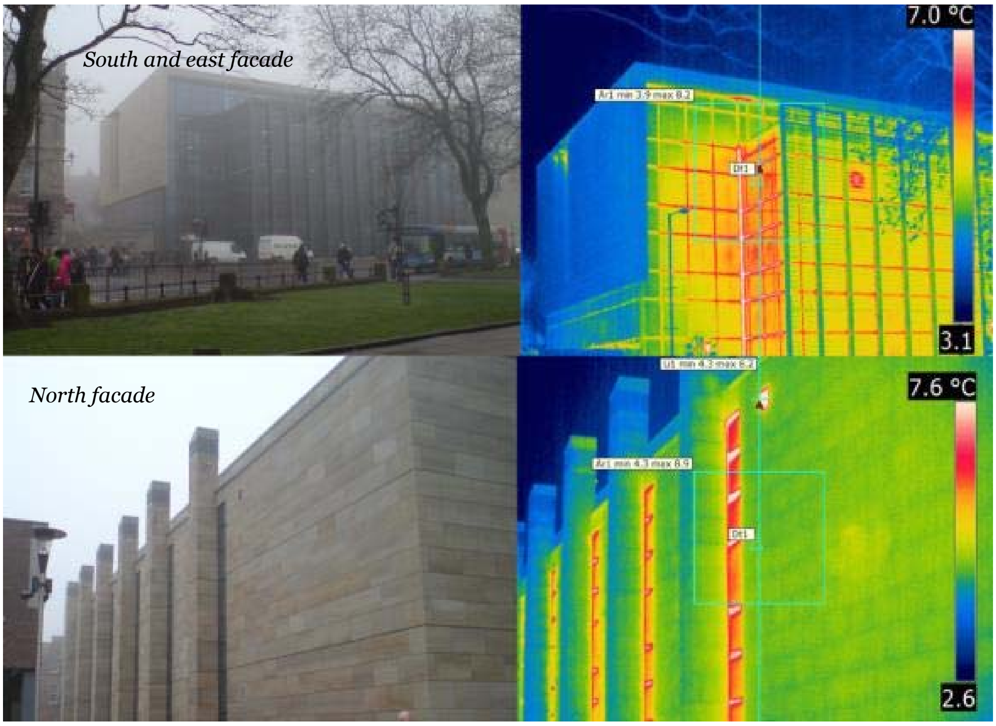


Figure 18 External fabric in a cold late winter morning (16 March 2011-1149 hrs.). External air temperature: 3˚C.

King's Gate fabric design parameters exceed part L building regulation (2006) by 29%. The evident continuity of insulation points at appropriate detailing, material specification and installation. It would however be much more difficult to establish the real building U-Values.

3.5.2 MRT vs. air temperature

The adaptive comfort results which are generated in Chapter 5 are by definition operative temperature values expressed as follows:

$$\theta_c = \frac{\theta_{ai}\sqrt{10v}+\theta_r}{1+\sqrt{10v}} \qquad [11]$$

In which θ_c, θ_{ai}, θ_r and v *are* operative, air , mean radiant temperatures and air velocity respectively [10]. At indoor air speeds below 0.1 m/s, natural convection is assumed to be equivalent to v=0.1 and equation 11 becomes:

$$\theta_c = \frac{1}{2}\,\theta_{ai} + \frac{1}{2}\theta_r \qquad [12]$$

Therefore it could be argued that if air and radiant temperatures in the space are quite close to one another, each could be taken as the representative of the operative temperatures. Using a TESTO Globe probe Ø 150mm (TC Type K) traceable mean radiant temperature values were generated, against which the corresponding air temperature readings are outlined in table 1.

Date	Time	Location	MRT (°C)	Air temperature (°C)	Residual value (K)
29-Mar-12	11:20	Level 1	21.2	20.5	0.7
29-Mar-12	11:50	Level 3	20.5	20	0.5
29-Mar-12	11:35	Level 5	21.1	22	-0.9
24-Apr-12	12:05	Level 1	21.9	21.9	0
24-Apr-12	13:00	Level 3	20.8	20	0.8
24-Apr-12	13:08	Level 5	21.5	22.5	-1
09-May-12	09:15	Level 1	21.8	21.6	0.2
09-May-12	09:27	Level 3	21	20	1
09-May-12	09:36	Level 5	21.8	22.3	-0.5
19-Jun-12	13:00	Level 1	20.1	19.9	0.2
19-Jun-12	13:10	Level 3	20.8	20.75	0.05
19-Jun-12	13:25	Level 5	22.1	22.36	-0.26
31-Jul-12	12:08	Level 1	20.5	20.6	-0.1
31-Jul-12	12:26	Level 3	22.4	22.5	-0.1
31-Jul-12	12:58	Level 5	24.8	24	0.8
10-Dec-12	11:30	Level 1	22.8	22.47	0.33
10-Dec-12	12:01	Level 3	20.5	20.8	-0.3
10-Dec-12	13:00	Level 5	21.8	22	-0.2
13-Feb-13	09:30	Level 1	22.4	22	0.4
13-Feb-13	09:02	Level 3	20.5	21	-0.5
13-Feb-13	08:05	Level 5	21.1	22.4	-1.3

Table 1 Air vs Mean Radiant temperature

As evident only in one occasion within the spaces audited the difference between air and mean radiant temperatures exceed 1°C (13 Feb 2013 at level 5). Air and mean radiant temperature values are within ±1°C deviations from one another and hence each one of these two indexes could be taken to be representative of the operative temperature providing that air velocities stay below 0.1 m/s. Figure 19 summarises temperature entries at table1.

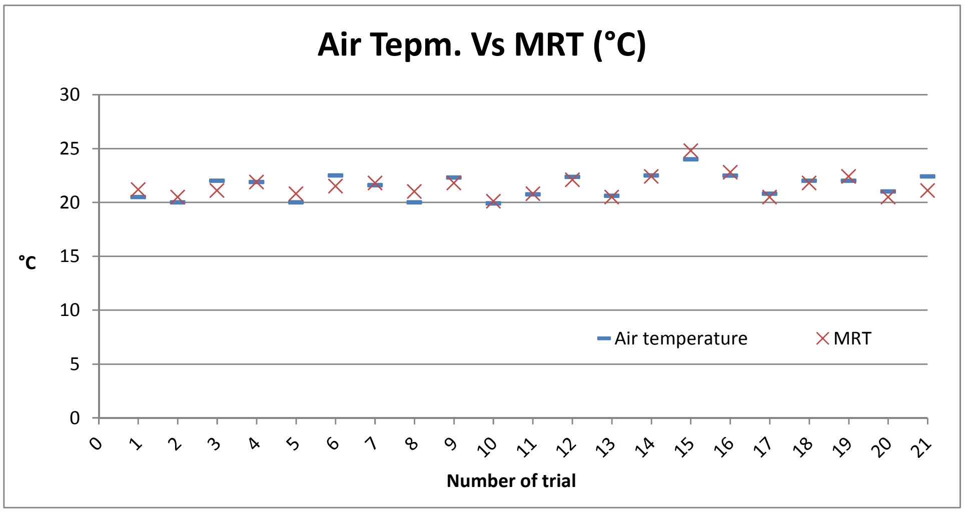


Figure 19 Air and radiant temperature readings at King's Gate

3.5.3 *Internal fabric*

Similarly, an internal investigation of the space was carried out that illustrates the heat sources in the space, and allows the inspection of any major radiant asymmetry in the space. The following thermal image (Figure 20) for instance reveals the underfloor heating system an hour into its operation, together with the solar loading elevating parts of the internal fabric temperatures to 36.3°C. The mean radiant temperature (MRT) in this instance was 22.1°C (compared with air temperature of 21.7°C).

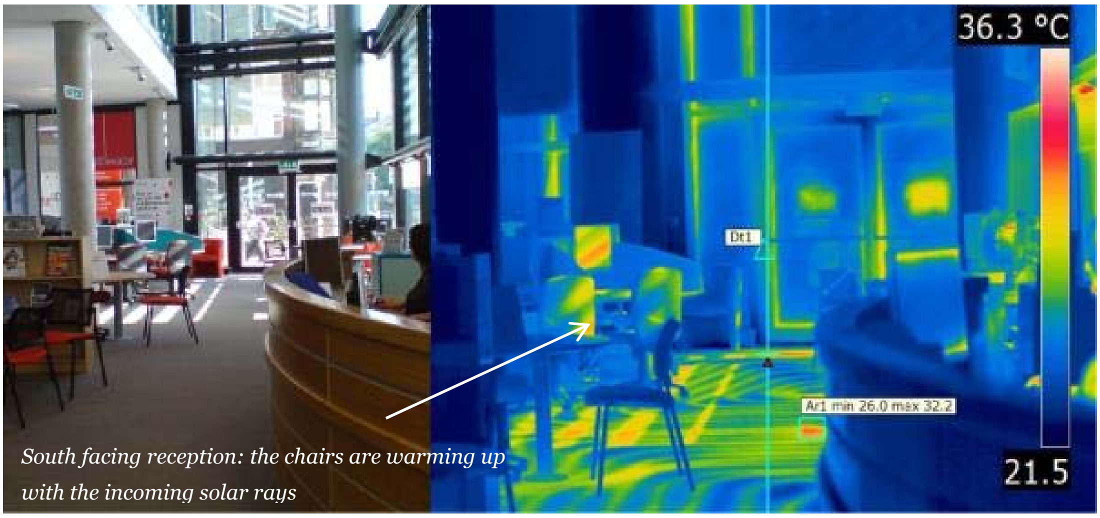

South facing reception: the chairs are warming up with the incoming solar rays

Figure 20 Internal image (4 May 2011- 0852 hrs.). Indoor air temperature 21.7˚C.

Next image (Figure 21) outlines level 3 (2nd floor of the building) open plan office space. Interestingly it serves to clearly illustrate the philosophy that underlines the design of King's Gate. Exposed ceiling soffits have a much cooler mean radiant temperature than the rest of the internal space, namely the adjacent light trunks. While the inside air temperature was 23˚C, the exposed concrete soffits MRT was 21˚C. This clearly shows the moderating influence of heavyweight thermal mass within a structure. The overall mean radiant temperature of the entire space (23.2°C) was however nearly identical to the air temperature (23°C).

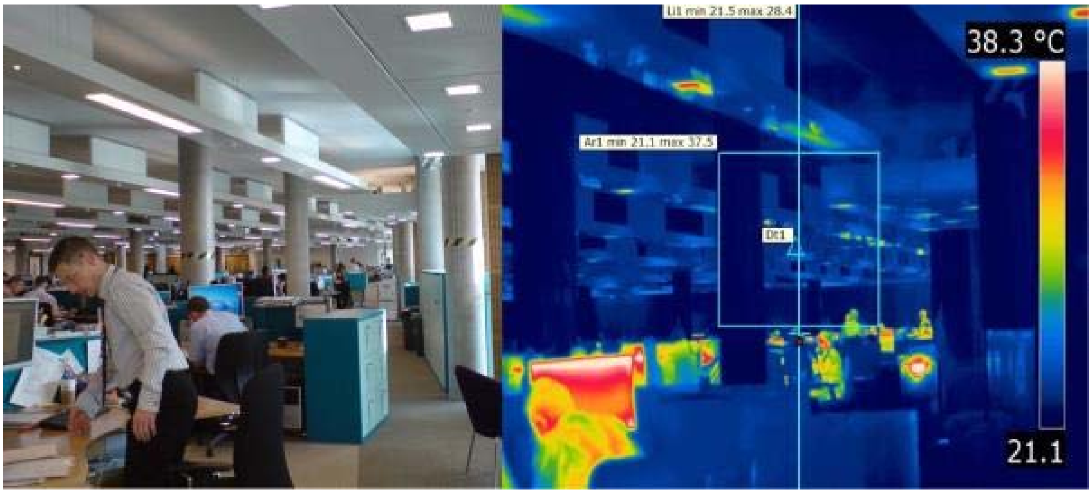


Figure 21 Level 3 internal image (4 May 2011- 0757 hrs). Indoor air temperature 23˚C.

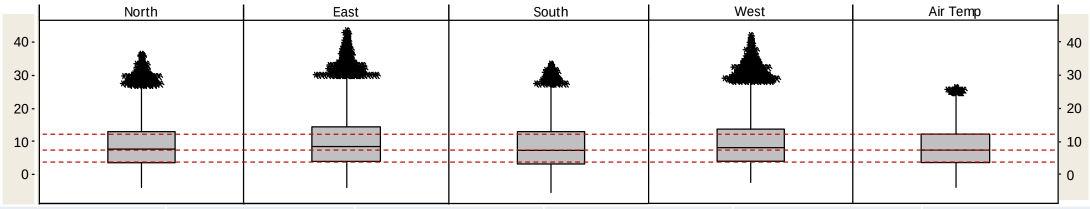
3.5.4 *Black bulb sensor readings*

The readings from black bulb sensors described in sub-section 3.1.2 provide an indication of the different magnitudes of solar thermal loading on the larger west and east orientations. A compilation of 618 days' worth of data was analysed to determine any significant pattern of difference between the readings of 4 individual black bulb sensors located on south, west, north and east facing building walls. The east and west facing parts of the building experience a greater accumulation of solar thermal loading as during sunny days solar irradiance manifests itself in the form of heat on the broader spans of external east and west masonry facades (East façade has the highest overall average MRT of 11.1°C followed by west aspect figure of 10.9°C). Surprisingly the southerly aspect of the building has the lowest average of 9.8°C which can be accounted by:

1- The exposed nature of south facade. The shortwave solar radiation absorbed into the building surface is lost through long wave radiation to the surroundings, particularly the cold sky (southerly aspect has the widest view of the sky)

2- South aspects sits on a busy road where traffic constantly creates eddies and turbulence that in parts convectively cool this aspect

3- Much larger part of the energy of the sun migrates through the predominantly glazed southerly aspect into the building envelope



	North	East	South	West	Air tem
Av	10.0	11.1	9.8	10.9	9.5
Min	-2.8	-2.9	-4.3	-1	-2.4
Max	37.7	44.9	34.9	43.3	27.9
σ	6.6	7.4	6.7	7.0	5.5

Figure 22 Boxplots of MRT (°C) on 4 fronts of King's Gate (accompanied by corresponding statistical analysis). Red lines observe lower and upper quartile as well as median for air temperature

The 3 dotted red lines on Figure 22 observe the lower and upper quartile and the median of air temperature boxplot. North and south aspects' lower, upper and 50th quartiles nearly follow the same pattern as air temperature, but east and west both have higher upper quartiles as well as higher concentration of outliers reflecting unusually high summer time temperatures during long sunny days. Both east and west aspects of the building face adjacent constructions of a similar height that partly provide shelter and limit surface long-wave radiant heat loss. Daily build-up of solar heat on the external façade is clear on Figure 23 which sets MRT of 4 sensors against a backdrop of direct solar irradiance.

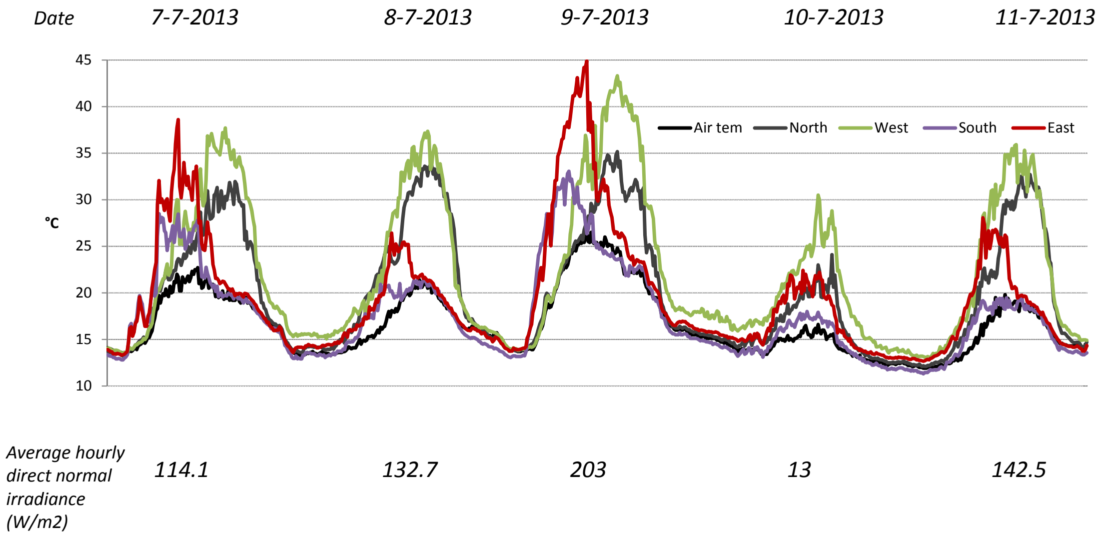


Figure 23 Dry bulb sensor readings as a function of direct component of solar irradiance.

The data on Figure 23 refers to the second week of July 2013. Quite clearly when the direct component of solar irradiance is at its highest (i.e. sunny day with low cloud cover), MRT on facades with greater masonry ratio rise well above the air temperature. East and west surfaces are 29 and 42% glazed respectively, as opposed to glazed ratios of 54 and 87 for north and south aspects. These results could aid the incorporation of building integrated PVs and are significant in informing a more purposeful fabric design.

3.6 Summery

On the whole King’s Gate is a well-constructed and well-managed building. As noted the building fabric U-value performance exceeds the statutory building requirements of the time with an average of 29%. The audit here also demonstrates that the building fabric maintains a consistent uniformity of insulation. In the next chapter we gauge the views of the occupant of the building regarding various environmental comfort indices before the concept of adaptive comfort is applied to the target building through virtual simulation.

Chapter 4 Method

4.1 Introduction

The energy and comfort implications of adaptive comfort, when deployed within high performance fabrics, is the aim of this work. To peruse this aim, six streams of actual primary data are collected in order to enable building performance modelling, calibration and comparative studies that offer an examination of EN 15251 merits and feasibility. These are:

1- Quantitative environmental conditions within the building
2- Qualitative occupant rating of the building
3- Weather data collected at the site
4- Building actual energy consumption
5- Building zone air temperature
6- Qualitative feedback from controls expert survey participants

The first two streams are outlined in chapter 5 and enable an assessment of the building design and controls in its current state. Streams 3-5 are outlined in section 6 and collectively enable the calibration of a detailed EnergyPlus model. The calibrated model is then used to examine the replacement of existing static CIBSE Guide control strategies with a dynamic adaptive comfort method (presented in chapter 7). Chapter 7 results therefore outline the energy savings that adaptive controls can offer using a calibrated model. The final stream of actual data is presented in chapter 8, where the ability of current control methods to facilitate the implementation of adaptive comfort is examined, and the associated views of industrial experts are thereafter outlined.

All methods used to arrive at the results are further explained in the following 4 sections.

4.2 Building audit

King's Gate environmental building audit was carried out over a period of a year. The purpose of the audit was to establish - within the constraints of time and the participant sample size– the following:

1- The prevailing environmental condition within the building envelope, and how they compare with industrial best practice recommendations.

2- Overall degree of satisfaction expressed by the survey participants with their working environment.
3- Detection of any of the elements of comfort that are highlighted by survey participants as unsatisfactory.

As noted previously, displacement ventilation informs the detailed design of King's Gate building and as a result, a degree of temperature gradient is experienced across the five open plan levels. Three streams of annual temperature data collected at 15 minute intervals were compiled using the building energy management system (BEM), against which an occupant survey was conducted to chart the experience of the occupants (see 5.2).

Out of a total workforce of around 500, a sample of 60 participants was selected, which fall into 20 volunteers at each level studied. Participants were required to have worked in the building from its inauguration or a period of more than 2 years in order to have formed a broad view of the qualities of the space. The selection was conducted using a systematic sampling method in order to maintain the highest possible degree of similarity between the workstations at different levels (subsequently enabling a direct comparison). Individuals were interviewed privately to avoid any cognitive bias (anchoring effect[4]). In the interest of brevity the raw data is not included however appendices B and D contain the space audit raw data and appendix F contains the survey questionnaire. Comfort votes were treated and analysed as qualitative data of ordinal type.

The dependency between two sets of random variables of observed data is mathematically defined by correlation coefficient (ρ); and in this work was calculated by the following

$$\rho_{X,Y} = corr(X,Y) = \frac{E[(X-\mu_X)(Y-\mu_Y)]}{\sigma_X \sigma_Y} \qquad [13]$$

Error margin in this study is defined as the following:

$$\hat{P} - \frac{Z_{a/2}\sqrt{\hat{P}(1-\hat{P})}}{\sqrt{n}} \leq \mathrm{p} \leq \hat{P} + \frac{Z_{a/2}\sqrt{\hat{P}(1-\hat{P})}}{\sqrt{n}} \qquad [14]$$

---

[4] This is the tendency of individual participants to be effected by other people's votes.

Where $\frac{\sqrt{\hat{P}(1-\hat{P})}}{\sqrt{n}}$ is the standard error of the population. 46 out of 60 participants rated their environment as comfortable (i.e. 76.66%), which using formula 14 and a confidence interval of 95% produces boundary values of 65.96% to 87.36% for the entire population (i.e. nearly ±10% error margin).

4.2.1 Space and BMS description

Levels 1, 3 and 5 were selected to sample the view of the participants. Each level contained a series of cellular as well as open plan offices but since the actual temperature data was only available for the open plan space the participants were selected from open plan desk stations only (Figure 24).

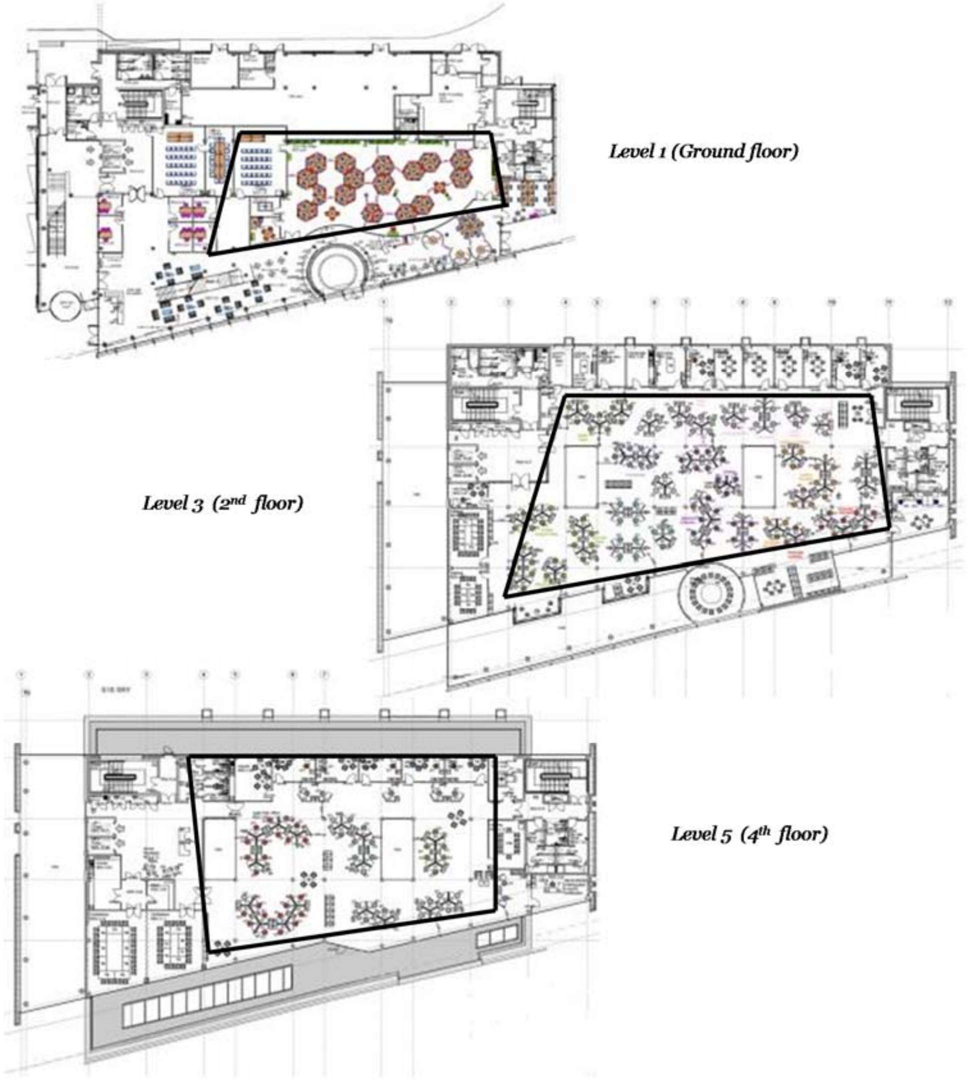


Figure 24 Black lines denote the areas within three different levels where participants were based.

The BEM system for the entire real estate portfolio at Newcastle University is provided by Siemens Desigo Insight software. Figure 25 outlines the software's user interface. This figure also highlights the 3 void temperature sensors that provided the data for space audit.

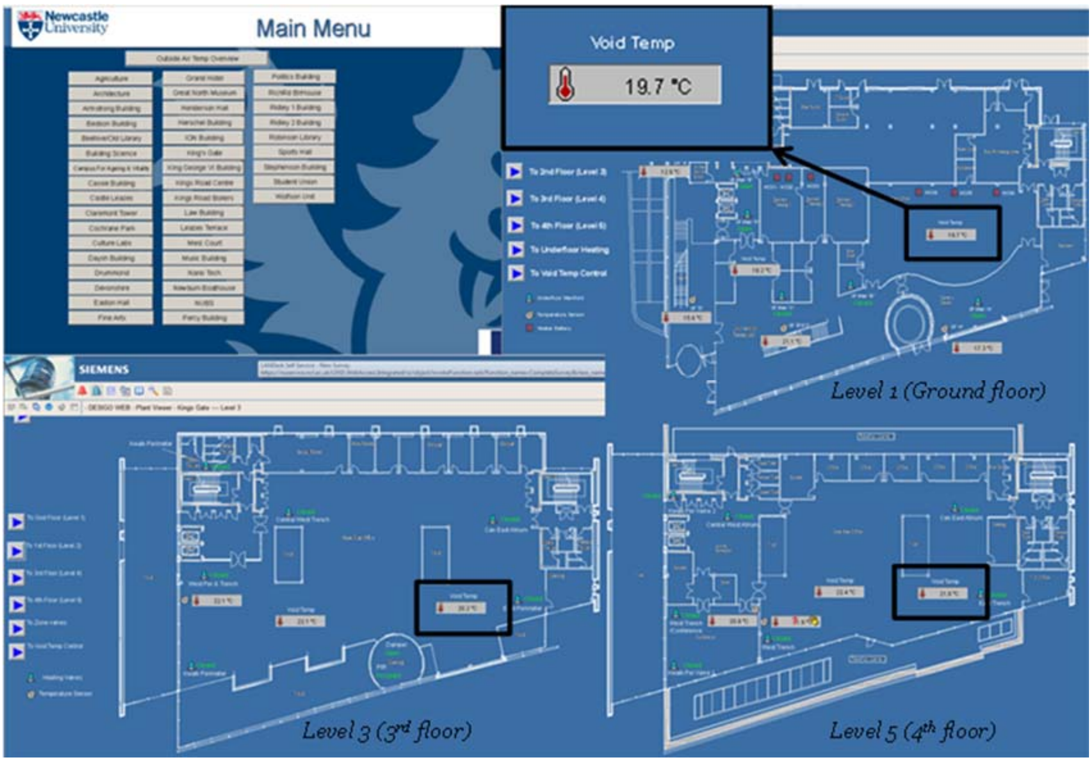


Figure 25 BEM main menu (top left) and 3 levels where audit was conducted.

The sensor type responsible for logging temperature data are Siemens QAA24 which at room temperature carry a maximum error margin of ±0.6°C (Appendix C). The inclusion of error margin in the audit presented here was of no value as even the extremity of actual temperatures discussed here did not violate best practice standards that provide the guidance for this work.

4.3 Model development

4.3.1 Software description

For the purpose of this work EnergyPlus Version 7.2.0 was used with Design Builder version 3.2.0.067 acting as the graphical interface to create the initial models. EnergyPlus is the official building simulation programme of the United States Department of Energy. It is a first principle based tool that is extensively used and examined by the international research community to investigate detailed building energy performance [86, 87]. This software is capable of modelling heating, cooling, ventilation as well as lighting and also water consumption using a state-space method (the thermal load of the building is simulated using a heat balance method). This enables comprehensive disaggregation of energy and water flow within a building, which in turn allows comprehensive evaluations of simulated versus measured performance data.

4.3.2 Formatting requirements

Several formatting steps were required to allow future weather files to be used in EnergyPlus models, the most important of which was the need to generate '.stat' files using EnergyPlus weather statistics and conversions' program. These steps were repeated for both historical files (used in calibration) and future weather files using EnergyPlus Version 7.2.0 (with Design Builder version 3.2.0.067 acting as the graphical interface) to create all models (Figure 26). The virtual model was first calibrated using primary data before providing the platform to investigate the potentials of adaptive comfort and fabric improvements using a wide range of weather files.

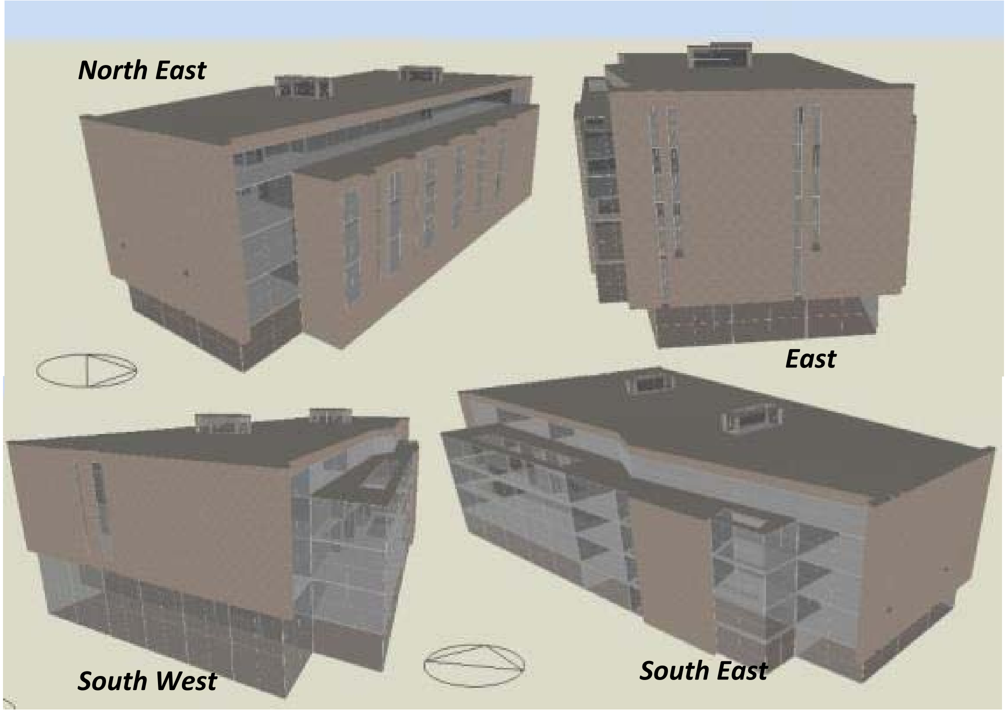


Figure 26 King's Gate external facades

4.3.3 Theoretical considerations

The local weather station (described in sub-section 3.1.2) provided the hourly weather files for calibration only and UKCP09 provided the inputs for all adaptive comfort based simulations. Building operational details were sought from the building manager and users (as outlined in 4.3.4.1). In addition to the virtual model of the actual building, a passive house model was also made while maintaining the same glazing to wall ratio as the actual building model. This was achieved by improving the fabric u-values to enable passive house heating and cooling energy targets of below 15W/m2 to be achieved [88] (see 4.3.4.4 for fabric values). An acknowledgment is also made that cooling was included in the passive house model only to enable the comparative study to be based on similar operational regimes. Figures used for passive house design are provided by the International Passive House Association [89]. Except for the fabric U-values, all other parameters including occupancy, HVAC and operational details were kept consistent for both the base model and passive house design in order to allow a meaningful comparative study of the results. This also meant that very low opaque fabric U values had to be used to achieve passive house energy targets, particularly given the extensive building glazing ratio. All model inputs are identified in section 4.3.

The most notable uncertainties in model preparation are natural ventilation and infiltration rates. In the absence of measured data, most analysts seeking to calibrate building models resort to defining an objective function (e.g. error criterion generated from model results when compared to experimental data) and seek to minimise the error criterion by input parameter adjustment. For this study the results of an infiltration smoke test (carried out at the time of inauguration under 50Pa pressure) provided the input. A point particularly noteworthy is the conversion of measured building's air change rates (expressed at 50 Pa) to normalised air leakage at atmospheric pressure. This was achieved using formula 15:

$$ACH_{Atmospheric} \approx \frac{ACH_{50}}{F} \qquad [15]$$

Where F is a factor used to relate the air exchange rate under typical conditions ($ACH_{\text{atmospheric}}$) to the air exchange rate at 50 Pascal (ACH_{50}) [90] . An average F value of 20 was used as given by Sherman, M [91]. Following the creation of the base model, a version control method was used to calibrate the virtual model against the existing metered data. A succession of 49 models each with incremental adjustments paved the way to arrive at the final version which was used as the simulation tool for the comparative study.

4.3.4 Parameter input

To enable the description of the operational profiles that are outlined below, the following two bespoke weekly and weekend operational schedules (Figure 27) where created and implemented in the design builder. King’s Gate Weekday (KGWD) and Kings Gate Weekend (KGWE) operational schedules refer to the following two custom-profiles that enabled the calibration results of the building to achieve ASHREA Guide 14 acceptance limits.

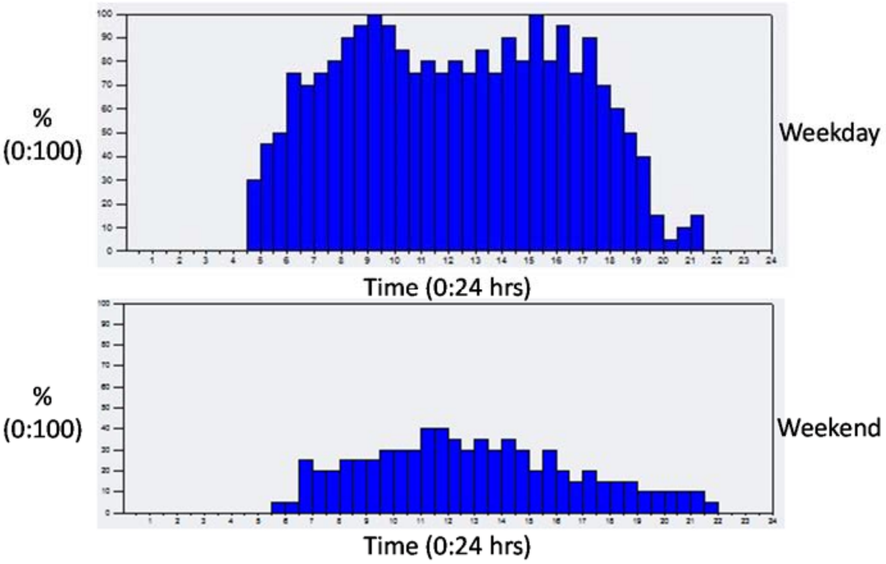


Figure 27 King's Gate customised operational profiles

The following four schedules describe the final variation in the operational profiles of various schedules that were made in order to achieve the ASHRAE Guide 14 acceptance criteria:

1. Activity (occupancy) schedules:

Weekdays: KGWD
Weekends: Saturday: KGWE, Sunday: off

2. Computer and office equipment Schedule:

Weekdays: 0700- 1800 hrs 1
1800 -0700 hrs 0
Weekends: KGWE

3. Lighting Schedule:

Daylight compensated system:
Weekdays: Until 0700 hrs 0
Until 1900 hrs 1
Until 2400 hrs 0
Weekends: Until 0700 hrs 0
Until 1900 hrs 0.35
Until 2400 hrs 0

4. HVAC Schedule:

Weekdays: KGWD
Weekends: KGWE

4.3.4.1 Activity

Activity:	Base model (BM)	Passive House model
Occupancy density (People/m^2)	0.04	As BM
Heat gain per person (W)	123	As BM
Hg Setback temperature (°C)	12	As BM
Clg Setback temperature (°C)	N/A	N/A

Table 2 Activity description in King's Gate

4.3.4.2 Small power and lighting

	Base model (BM)	Passive House model
Luminaire Type	Suspended	As BM
Lighting consumption (W/m^2)	3	As BM
Radiant fraction	0.42	As BM
Convective fraction	0.40	As BM
Visible fraction	0.18	As BM
Lighting control	Linear daylight linked	As BM
Computer gains (W/m^2)	6	As BM
Office equipment (W/m^2)	4	As BM

Table 3 Electrical power consumption in King's Gate

4.3.4.3 HVAC

HVAC:	Base model (BM)	Passive House model
Heating system type	LTHW[1] with combined Radiant/convective terminals	As BM
Prime mover	Natural gas boiler	As BM
Boiler Seasonal CoP	0.80	As BM
Auxiliary energy (kWh/m²)	47	As BM
DHW consumption (litre/m²/day)	0.197	As BM
DHW Type	Instantaneous [2]	As BM
DHW CoP	0.85	As BM
Ventilation	Tempered air via AHU	As BM
Distribution mode	Mixed	As BM
AHU nominal flow rate (m³/s)	11.32	As BM
Humidity control	CSHR[3]	As BM
Cooling	Adiabatic Evaporative[4]	As BM
Cooling system type	All air	As BM
Minimum supply air (°C)	12	As BM
Cooling system CoP	2.5	As BM

Table 4 Heating, Ventilation and Air Conditioning description in King's Gate

[1] Low Temperature Hot Water
[2] Electricity from grid to deliver DHW at 65°C from a mains supply of 10°C
[3] Constant Supply Humidity Ratio (maintaining min:30% max 70% RH)
[4] Acting on supply air

4.3.4.4 Construction

Layers are all described from the outer to inner skins.

Construction	Base model (BM)	Passive House model
Walls U value (W/m^{2}K)	0.292[1]	0.093 [2]
Roof U Value (W/m^{2}K)	0.25 [3]	0.109 [4]
Floor U Value(W/m^{2}K)	0.13 [5]	0.094 [6]
Glazing (W/m^{2}K)	1.772 [7]	0.78 [8]
Glazing G value [9]	0.38	0.48 [10]
Infiltration (ac/h)	0.33	0.03

Table 5 Description of fabric composition in King's Gate

[1]:	Layer 1:	Fletcher sandstone (2354 Kg/m^2)	215×100×440 mm
	Layer 2:	Kingspan TW50 Urethane (Zero ODP)	60 mm
	Layer 3:	Tarmac concrete block (1450 Kg/m2)	440×215×100 mm
	Layer 4:	Gyproc plasterboard	12.5 mm

(Thermally bridged by 50mm wooden battons: (HF:-B10))

[2]:	Layer 1:	Fletcher sandstone (2354 Kg/m^2)	215×100×440 mm
	Layer 2:	XPS extruded polystyrene	350 mm
	Layer 3:	Tarmac concrete block (1450 Kg/m2)	440×215×100 mm
	Layer 4:	Gyproc plasterboard	12.5 mm

(No thermal bridges)

[3]:	Layer 1:	EPDM waterproof Membrane	2.5 mm
	Layer 2:	Rigid polyurethane foam	200 mm
	Layer 3:	Polyethylene vapour control layer	1000 gauge
	Layer 4:	Concrete Deck	275 mm
	Layer 5:	Gyptone Ceiling tiles	

600×600×50 mm

[4]:	Layer 1:	EPDM waterproof Membrane	2.5 mm
	Layer 2:	MW glass wool rolls	350 mm
	Layer 3:	Polyethylene vapour control layer	1000 gauge
	Layer 4:	Concrete Deck	275 mm
	Layer 5:	Gyptone Ceiling tiles	

600×600×50 mm

[5]:	Layer 1:	Heavy-duty DPM	1000 gauge
	Layer 2:	Reinforced pre-cast concrete foundation	265 mm
	Layer 3:	Kingspan rigid urethane TF70	80 mm
	Layer 4:	Concrete floor soffit	75 mm
	Layer 5:	Heavy grade floor tiles	600×600×32 mm

[6]:	Layer 1:	Heavy-duty DPM	1000 gauge
	Layer 2:	Reinforced pre-cast concrete foundation	265 mm
	Layer 3:	Urea Formaldehyde Foam	400 mm
	Layer 4:	Concrete floor soffit	75 mm
	Layer 5:	Heavy grade floor tiles	600×600×32 mm

[7]: Double glazing of 5mm thick panes with silicone edge coated with solar shading film externally with 20mm air filled gap. Aluminium framed.

[8]: Triple glazing of 5mm thick panes with silicone edge coated with solar shading film externally with two volumes of 13mm argon filled gaps. Aluminium framed.

[9]: Also referred to as solar transmittance.

[10]: As a qualifying note Passive House standards require a minimum G value of 0.5. This could not be reconciled with the overall thermal performance of products currently available on the market. In the interest of accuracy, the closest commercially available product was chosen.

4.4 Calibration

4.4.1 ASHRAE Guide 14

Building energy models suffer a vast ‘under-determined’ parameter space [92, 93] with main areas of inaccuracy being software limitations, input parameter and weather data inaccuracy and difficulties in capturing how exactly a building is operated [94]. Increasingly there has also been a need to develop models of existing buildings to aid research into model-based control strategies as well as BIM studies [95]. The simultaneous existence of buildings’ operational data and its virtual representation requires protocols that set out when a virtual model can be regarded as calibrated (or validated). A limited amount of literature is available on calibration topic and current best practice recommendations primarily focus on how closely simulated results match the metered energy data [96-98], and also allows for the personal judgement of the analyst [99]. In this section ASHRAE Guideline 14-2002 is used to calibrate the building model [96]. This entails determining mean bias error (MBE) and cumulative variation of root mean square error (CV(RMSE)) results for energy and space temperature using hourly data using formulae 16 and 17:

$$MBE = \frac{\sum_1^{8760}(M_i - S_i)}{\sum_1^{8760} M_i} \tag{16}$$

$$CV(RMSE) = \frac{\sqrt{\sum_1^{8760}(M_i - S_i)^2 \times N_i}}{\sum_1^{8760} M_i} \times 100 \tag{17}$$

Where M_i and S_i are measured and simulated data at instance i respectively, and N_i is the count of the number of values used in the calculation, which in the case of hourly simulation equals 8760. CV(RMSE) is the coefficient of variation of the root mean square error. ASHRAE Guide 14 considers a building model calibrated if hourly MBE and CV(RMSE) values fall within ±10% and ±30% spectrums respectively.

While the main calibration criteria is ASHRAE Guide 14 method, an additional set of standard statistical indices are also carried out for each set of results, which includes minimum, maximum, average and standard deviation. Similarly Pearson correlation coefficient between the measured and simulated values together with RMSE and percentage RMSE figures are presented using formulae 18-20:

$$RMSE = \left(\frac{1}{8760}\sum_{i=1}^{8760}(M_i - S_i)^2\right)^{1/2} \qquad [18]$$

$$\%\,RMSE = \left(\frac{1}{8760}\sum_{i=1}^{8760}\left(\frac{M_i - S_i}{M_i}\right)^2\right)^{1/2} \qquad [19]$$

$$Correl\,(M_i, S_i) = \frac{\sum(M_i - \overline{M_\iota}) \times (S_i - \bar{S_\iota})}{\sqrt{\sum(M_i - \overline{M_\iota})^2 \sum(S_i - \bar{S_\iota})^2}} \qquad [20]$$

$\overline{M_\iota}$ and $\bar{S_\iota}$ are the averages of measured and simulated values respectively. RMSE provides a measure of the mean accumulated magnitude of errors in the original data units, whereas percentage method provides an indication of the magnitude of the relative error. The steps taken for generating simulated values are as follows:

1- Following the version control model development, the final model was run using local weather files.
2- Various components of building electrical load were refined to produce the closest simulated electricity profile to the metered data.
3- Keeping all the input parameter's constant, simulated gas consumption was also generated for the building.
4- An annual profile of the temperature data in the target space was also produced to be compared against the actual data.

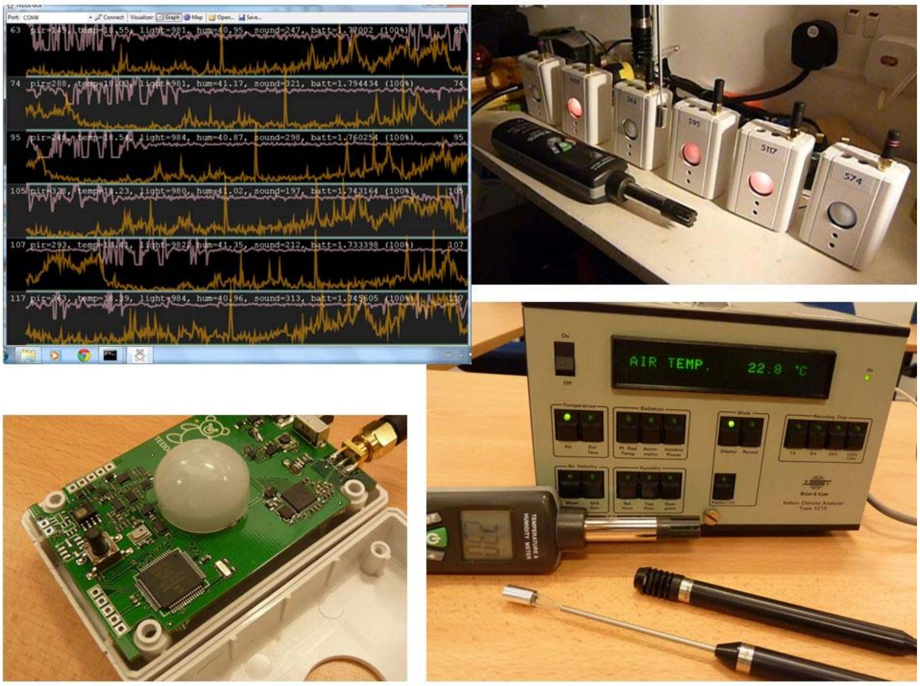
Finally histograms of residuals are constructed for closer examination of model deviations from actual figures using equation 21:

$$\varepsilon_i = M_i - S_i \tag{21}$$

Where M_i and S_i are measured and simulated data at instance i respectively, and ε_i is the magnitude of the instantaneous error at instance i.

4.4.2 Sensor calibration

The research work undertaken here ran alongside a digital technology project that culminated in the development and deployment if multi-functional sensors. These sensors are referred to as TEDDI sensors. These wireless units are capable of logging 5 environmental streams of data (light and noise level, temperature, humidity, PIR) and a comprehensive calibration exercise was undertaken to chart the performance range of sensors units with respect to all measured elements.



```
63  pir=149, temp=18.55, light=981, hum=40.95, sound=247, batt=1.77002 (100%)    63
74  pir=288, temp=18.03, light=981, hum=41.17, sound=321, batt=1.794434 (100%)   74
95  pir=248, temp=18.54, light=984, hum=40.87, sound=298, batt=1.760254 (100%)   95
105 pir=328, temp=18.23, light=980, hum=41.02, sound=197, batt=1.743164 (100%)  105
107 pir=293, temp=18.41, light=982, hum=41.35, sound=212, batt=1.733398 (100%)  107
117 pir=263, temp=18.39, light=984, hum=40.96, sound=313, batt=1.745605 (100%)  117
```

Figure 28 Top left: data output from multifunction sensors, top right: 6 sensors subjected to detailed calibration, bottom left: internal circuitry of the sensor, bottom right: calibration equipment.

The unnecessary coverage of all unrelated steps undertaken won't be reported here but as the temperature readings from sensors on level 3 (2nd floor) of the building enabled the calibration of the virtual model, the temperature calibration results are set out in this section. The two sensors deployed within the 2nd floor meeting room (Figure 29) were tested within a variety of locations with both stable and changing conditions. The response time of the two individual sensors used for the calibration of building model was between 7 to 10 minutes (Figure 30).

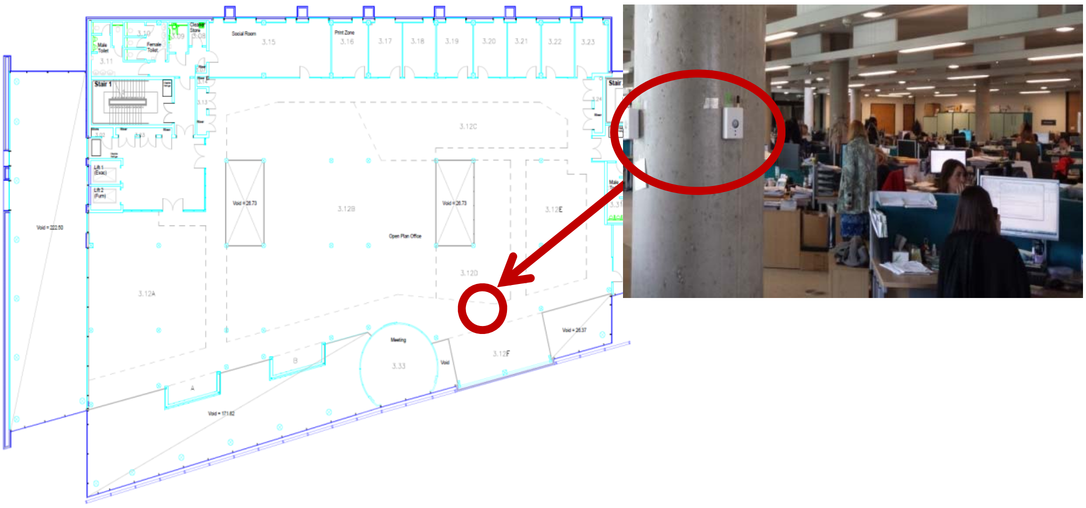


Figure 29 Illustration of TEDDI sensors location within 2nd floor meeting room. The sensors are mounted at 1.5m above floor level and positioned away from direct sunlight rays.

Measurement results were within 0.3°C of each other (Figure 31) and within 0.5°C of the TESTO 435 environmental audit unit (Figure 69). See appendix D for the description of TESTO unit.

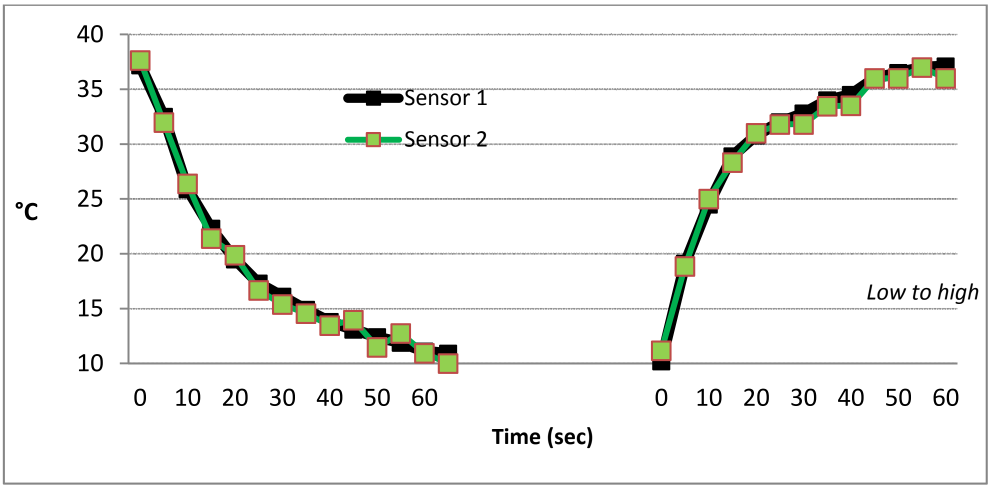


Figure 30 Sensor response time curves within room temperature ranges.

It should be born in mind that modern thermistor type sensors have a response time of as low as 0.12 second. Such fast responses are not required in building environment control applications as the response time of building fabric to energy perturbations never manifests in time spans below that of the response time of TEDDI sensors. It was however suggested that the next generation of these sensors would have a slotted case to improve the response time aspect.

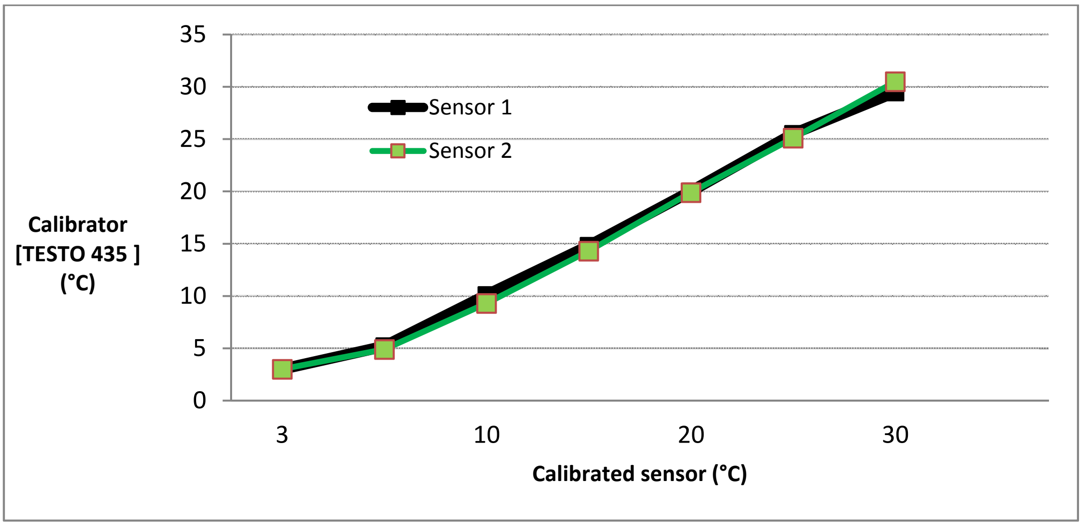


Figure 31 Accuracy graph produced against TESTO 435 measurements.

Both sensors also showed very good repeatability as when examined with similar environmental conditions again, identical results were produced.

4.5 Adaptive comfort

4.5.1 Free float (or passive design) analysis

Free-float analysis enables the analyst to examine the ability of a building to stay within comfort conditions with no HVAC input. In doing so the basic characteristic of a building envelope response and the extent to which a building can be independent from HVAC for part (or all) of the year is determined. Dynamic thermal modelling in Energyplus was used to plot annual operative temperature profiles within the building using site-specific weather data, as well as ventilation and casual heat gains specific to the building. To allow for a visual display of the results, zone averaged operative temperature for conditioned parts of the building is produced. This zone operative temperature profile is then superimposed on adaptive comfort temperature bands as defined by EU EN15251 [40] using formulas 22 and 23.

It is important to note that for the free float analysis the model heating and cooling is turned off, and an increased natural ventilation rate (5 ac/h) is applied. For all instances where the operative zone temperature falls outside adaptive comfort band, further simulations were performed to obtain the energy loads required to bring the space within the adaptive comfort bands, using comfort bands as input hourly target temperatures for the model.

Adaptive comfort standard as stipulated by BS EN 15251:2007 [40] lists four building categories (I-IV). First three categories represent high, normal and low occupant expectations (I-III). Category IV refers to environments where for limited time temperatures may fall outside those defined by the first 3 categories. Category II is recommended as the norm unless the building clearly falls into another classification. Category II and III were used to generate upper and lower adaptive comfort bands in this study using the calibrated EnergyPlus model. The upper and lower bands (T^-, T^+) are defined as follows:

$$T^+_{operative} = 0.33\bar{T}_{ao} + 18.8 + Y \qquad [22]$$

$$T^-_{operative} = 0.33\bar{T}_{ao} + 18.8 - Y \qquad [23]$$

Therefore for EN 15251 building categories II and III using 3 sets of weather files a total of 6 pairs of upper and lower bands are defined. $T^+_{operative}$ *(°C)* is the upper limit of the acceptable space operative temperature and $T^-_{operative}$ *(°C)* is the corresponding lower limit (see Figure 4 for an illustration). $\bar{T}_{ao}$ *(°C)* is the running mean of the outdoor temperature over the previous 7 days (constructed into EPW files using current, 2040 or 2080 site specific weather data) and Y defines the building category (i.e. category II=2, category III=3). The following 6 steps are then followed within each simulation effort:

1. The ‘Base-Model’ representing the existing office building was calibrated to ASHREA Guidance 14 [96] (see ection Calibration4.4)
2. The International Passive House Association (IPHA) recommended figures were used to create a ‘Passive House’ model of the office building while maintaining the same glazing to wall ratio as the base model [89]. This was completed by improving all fabric u-values to achieve passive house energy targets (see section 4.3.4).
3. For each building design, two simulations are performed with and without HVAC input to determine the following:
    a. Freefloat analysis (HVAC turned off): using site-specific current and future weather files, this analyses determines the basic building envelope response for both base and passive designs.

This analysis determines instances of time (t) when the internal space operative temperature ($T_{operative}$) falls within the adaptive comfort band (T^{-}, T^{+}) without any HVAC input. Such instances of time are denoted by the expression $'t_{T_{operative \in (T^{-},T^{+})}}'$. In other words:

$$T_{operative} \in (T^{-}, T^{+}) \quad only\ if \quad T^{-} < T_{operative} < T^{+} \qquad [24]$$

Therefore $T_{operative} \in (T^{-}, T^{+})$ sums the total number of hours in a year during which a building type can stay within upper and lower comfort criteria 'without any HVAC operation'.

b. Load determination analysis (HVAC turned on): A further simulation is performed so that HVAC load required to bring the space temperature within the adaptive comfort bands is calculated for all instances where the operative zone temperature falls outside adaptive comfort band (determined in step a.). Therefore the target temperatures in EnergyPlus would be the hourly lower (for heating) or upper (for cooling) adaptive comfort temperatures resulting in HVAC loads that are denoted by expressions Q_h (heating load; kWh) and Q_c (cooling load; kWh).

4. To gain a measure of HVAC savings achieved at the previous step, static building HVAC loads are also simulated for the current, 2040 and 2080 weather files using CIBSE Guide A's static heating and cooling value of 21°C and 23°C respectively [10].
5. PPD index is constructed for the adaptive comfort bands of all three weather files. Using expression 25, both winter and summer PPD calculations are carried out using method C of EN ISO 7730:2005 document [39] with EnergyPlus as the calculation vehicle [100].

$$PPD = 100 - 95 \times exp(-0.03353 \times PMV^{4} - 0.2179 \times PMV^{2}) \qquad [25]$$

Where PMV is the predicted mean vote, summarised adequately in Fanger's original work as expression 26 [53]:

$$PMV = f(t_{a}, t_{mrt}, v, p_{a}, M, I_{cl}) \qquad [26]$$

This expression summarises an otherwise cumbersome mathematical relationship where PMV is a function of:

3- Environmental factors (i.e air temperature (t_a), mean radiant temperature (t_{mrt}), air velocity (v), water vapour pressure (P_a)).

4- Personal factors (activity level or metabolic rate (M)and clothing type(I_{cl})

More avid readers are referred to the original Fanger's publication [7], ISO-7730 and a worked example [101] that outlines PMV and PPD computations.

4.6 Controls

Building controls suffer a variety of problems associated with hydronic, air and refrigerant based plants and space conditioning regimes which results in non-optimal plant operation and inadequate indoors environment. Given the complex architecture of the case study building under examination, control application expert views were sought to validate the feasibility of deploying adaptive comfort in the aforementioned office. The procedure followed to complete the expert survey was a thematic method as outlined by Arksey, H., & Knight, P. T. [102]. It is however essential to note that in the selection of survey participants, saturation point was not aimed for and the clear intention was the validation of adaptive comfort feasibility in the mixed mode building that was examined here. On that basis an exhaustive work concerning expert views would have been beyond the scope of this work given the critical body of participant numbers and pitfalls associated with qualitative survey participants as outlined by Galvin, R. [103].

The views of the controls designer engineers and academic experts were collected on current and future technologies that are (and will be) shaping building controls and automation. A total of 65 building controls and automation engineers were contacted and the 27 responses are reviewed in section 8.11. The target sample was chosen based on the advice of 2 industry-based and 2 academic experts on controls. Practitioners contacted were based across 5 European countries, with 4 participants also from US. All participants work within the field of HVAC&R and building automation and did not know each other.

Chapter 5 Building Audit

5.1 Introduction

This chapter outlines an audit of the case-study building in conjunction with an occupant survey using a thematic based questionnaire as advised in [102]. As well as attempting to benchmark the performance of the building as it is, a second aim is perused to see if a link exists between age and gender in the way comfort is experienced and rated in the space. The findings in this chapter will provide an insight into what aspects of comfort (if any) are regarded as inadequate which can therefore be improved by the proposed adaptive comfort measures.

5.2 Indoor air quality

To enable an assessment of space and occupant, this section defines heating season similar to that outlined by EN15251. This definition specifies the heating season as instances where outdoor running mean temperature is below 10°C (i.e. $\bar{T}_{ao}$<10°C) [104]. Similarly a running mean temperature of above 15°C ($\bar{T}_{ao}$>15°C) defines the beginning of cooling season.

Figure 32 outlines annual weather data collected from BMS software. Boxplot in Figure 33 offers an overview of differences between the three audited levels.

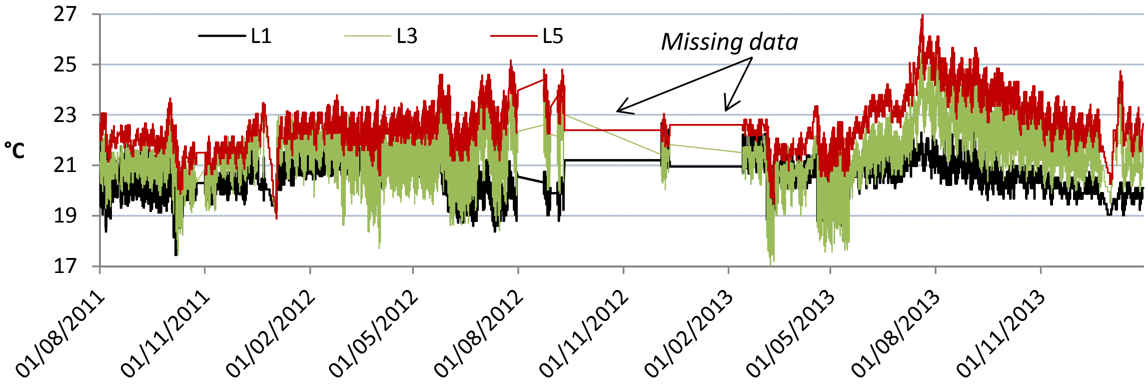


Figure 32 Void temperature data at levels 1, 3 and 5 (1 Aug 2011- 29 Jan 2014)

Overall all office hour (8am-5pm) summertime temperature measurements taken from the building comply with CIBSE best practice recommendations. CIBSE defines overheating if 28°C is exceeded at more than 1% (25-30 hours) of annual operational time [10]. This has not occurred during 29 months for which data was collected (Aug 11-Jan 14). However levels 1 and 3 average winter time temperatures fall very slightly below the recommended values, but do not violate Health and Safety Executive lower limit of 16°C [105]. Even outside office hours the temperature never drops to this lower limit due to the moderating effects of high thermal mass and insulation levels.

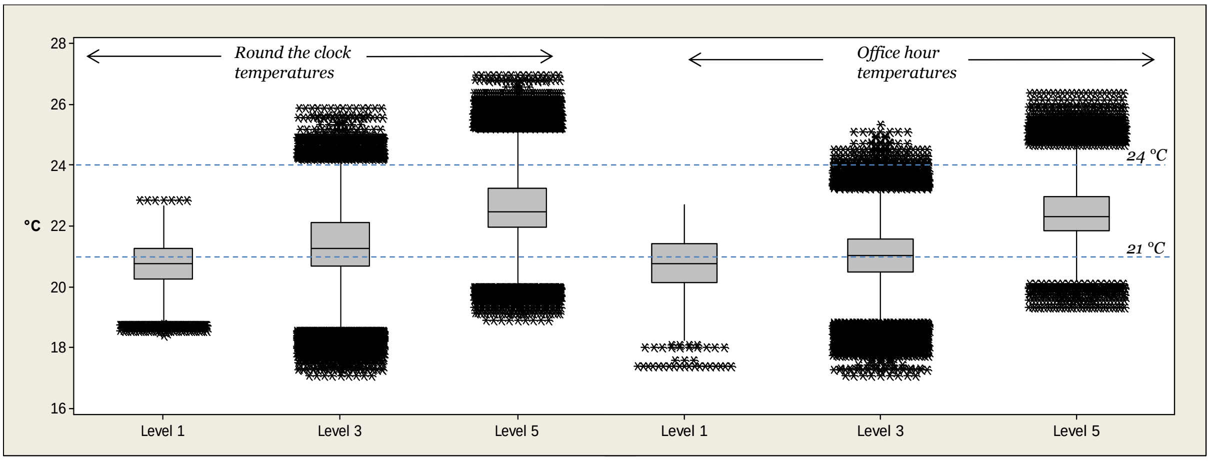


Figure 33 Boxplot of 24 hour and office hour temperatures within King's Gate (Aug 2011-Jan 2014)

Lower and upper quartile lines in the boxes illustrated in Figure 33 are quite close pointing to a closely controlled environment, although the thermal gradient within the building is very much evident, as level 5 in particular displays a trend of temperature values exceeding other levels by about 2°C.

Despite highlighting a low degree of control over their environments, an overall of 77% of occupants stated that their environment is comfortable (i.e. 46 out of 60 participants). Given that the entire workforce at King's Gate is 500 people (and from a purely statistical point of view) the survey results can carry a ±10% error margin (see Chapter 4). However the cellular and executive offices within King's Gate provide radically different working environments. As such the views of survey participants cannot be regarded as representative of the entire building occupants. Statistical error margin calculation was therefore omitted from this report.

5.2.1 Winter comfort

Factoring out the periods of data loss, average wintertime temperature for levels 1, 3 and 5 were 20.8, 20.7 and 22°C respectively. These values are averaged over the 29 months of data collection for office hours in heating season months only.

Against this backdrop 78% of the participants stated that wintertime working environment is comfortable.

Space temperature within levels 1 and 3 therefore slightly below the lower end of the recommended CIBSE figures of 21-23°C [10]. Average office hour temperature on level 5 however lies within the recommended range. It is however interesting that respondents at all levels rate their space in a similar manner as slightly leaning towards the cold end of the spectrum (Figure 34).

Excessive air velocity and/or high levels of humidity can contribute to a sensation of cold despite satisfactory operative temperature[5]. However, once again this could not account for higher expressions of 'cold' as both former parameters were measured at all levels at different times and proved satisfactory (as outlined in table 9 appendix B). It is worth noting that table A.5 of ISO 7730 outlines a maximum mean air velocity of 0.12 and 0.1 m/s in summer and winter respectively for offices [61]. Also Appendix G states there is no 'minimum air velocity' that is required for thermal comfort however increased air velocity can be used to offset increased temperatures. 0.1m/s therefore could be regarded as excessive air velocity in an office in wintertime.

Another explanation might be the lack of personal control over space temperature which causes the occupants to perceive their space as slightly cold. This assumption was however not supported by the results of our survey as the Pearson correlation coefficient between degree of control and heating system 'rating' was 0.14 (a very insignificant direct relationship). In other words the correlation between votes belonging to those who highlighted degree of control as an issue and the votes of those who didn't think of the heating system as adequately designed was 0.14. Therefore providing greater degree of space temperature control to the occupants would not necessarily improve their satisfaction level with the heating system.

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[5] Operative temperature is defined as the average of mean radiant and ambient air temperatures.

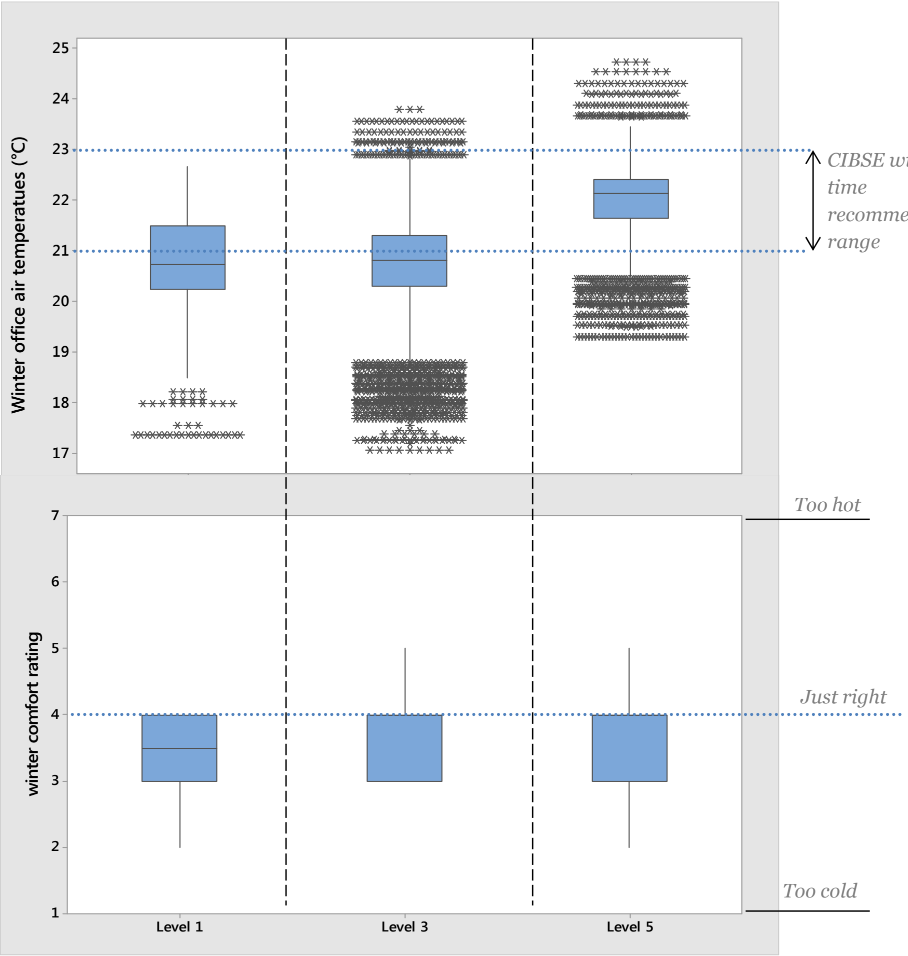

Figure 34 Boxplot of winter temperature comfort rating

A more detailed examination of individual workstations at various levels might have identified draught spots or colder corners that may have assisted in better understanding the viewpoints of the occupants. The scale of such work however would have been beyond this work and somewhat speculative in nature. The focus is therefore maintained here on the overall rating of the space.

A qualifying note is added finally to mention that CIBSE expresses its recommended values in operative temperatures. Put simply, it is the average of air and mean radiant temperatures (see appendix B note 1 for definition). However actual temperature measurements reported here are those of air. Yet as the outlined in section 3.5.3, mean radiant temperatures in offices that are audited do not depart substantially from concurrent air temperatures. Also sample audit of air velocity measurements (Appendix B: table 9) shows space air velocity values are too small to influence the perception of temperature in the space. As such for the purpose of this audit air temperature can be taken as a very good proxy for operative values.

5.2.2 Summer comfort

Similar to the results presented in the previous section, summertime office hour temperatures over the 29-month period of observation for levels 1, 3 and 5 are 20.4, 21.5 and 23.1°C respectively. The reference point for these values is a CIBSE summertime temperature range of 22-24°C. Therefore level 1 in particular has an average summertime temperature cooler than CIBSE suggestion.

Interestingly, a similar participant ratio of 74% stated that they are comfortable in summer (as opposed to 78% satisfied in winter).While levels 3 and 5 tend to vote their space as leaning towards warm in summer, level 1 votes describe the space as leaning towards cold. This is partly accounted for by the fact that cool temperature is introduced at low levels within all floors (incoming ventilation air temperature in summer is set at 19°C). In the cooler environment dominant at level 1 this makes a greater discomfort impact on the sedentary office workers. Additionally level 1 office space does not have any windows (hence no solar heat gains), which excludes any useful summertime heat gains. Figure 35 summarises summer comfort ratings by the occupants.

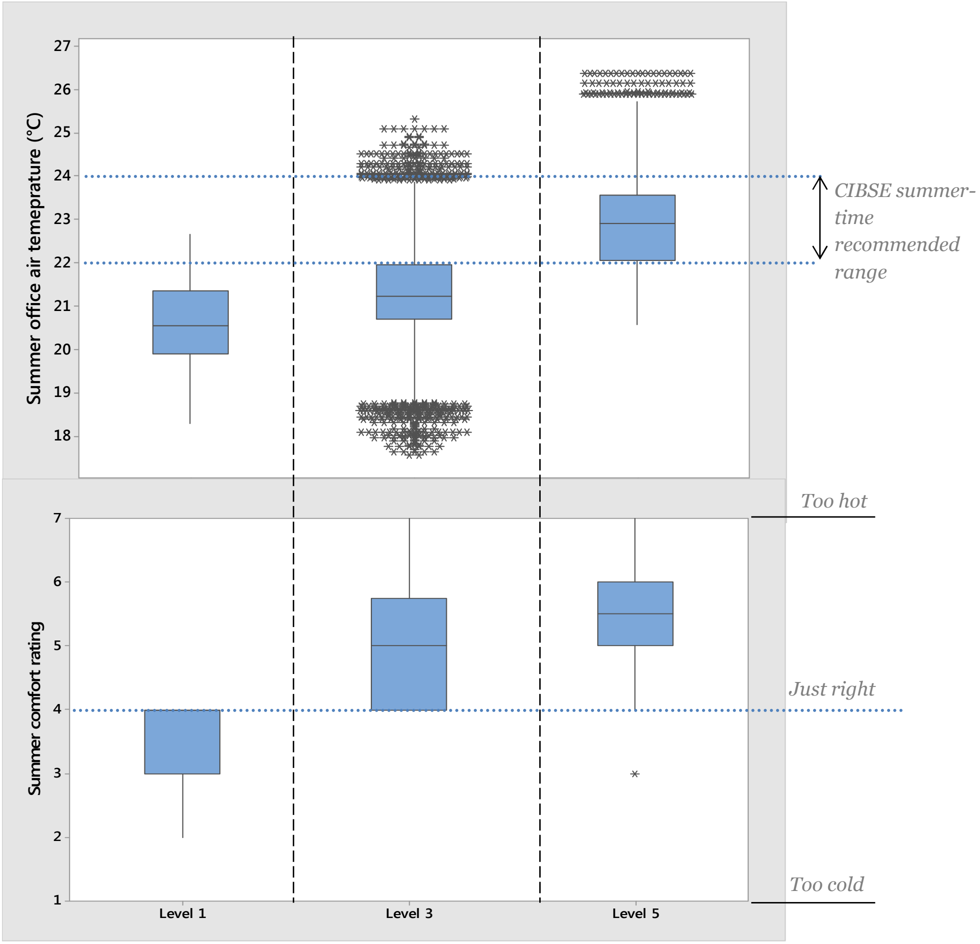

Figure 35 Boxplot of summer temperature comfort rating

Expressions of comfort at work are deeply intertwined with a whole range of aspects beyond the quality of workspace. There are many instances where feedback from building occupants is more readily accounted for by their psychology than mere physiology. Thermal uniformity is also seldom achieved in buildings [106]. That is to say proximity to cold surfaces (i.e. windows) can create a sensation of cold despite satisfactory air temperature [107]. This demonstrates difficulties that are encountered in providing scientific explanation for the occupant views expressed.

Nonetheless overall views concerning the environmental condition captured from King's Gate occupants are mostly in union (there is only one outliner vote in Figure 35, and Figure 34 reflects consistent votes that are in broad agreements) and the views expressed closely reflect the findings of the audit and the properties of the spaces audited.

Other major findings are:

1- No relationship exists between respondents' age and their view of summer or winter comfort (p=0.53, hence <0.05).
2- 89% of participants stated that they have no or very little control over temperature.
3- 96% of participants think that clothing policy is very flexible and allows for seasonal changes.
4- 32% of participants felt excessive draught had a negative effect on their work (Figure 36). There is a great variation in response to the draught question that highlights the localised nature of draughts in this building (mostly experienced at level 5). This is despite the satisfactory air velocities recorded at all levels over three seasons (Appendix B: table 9).

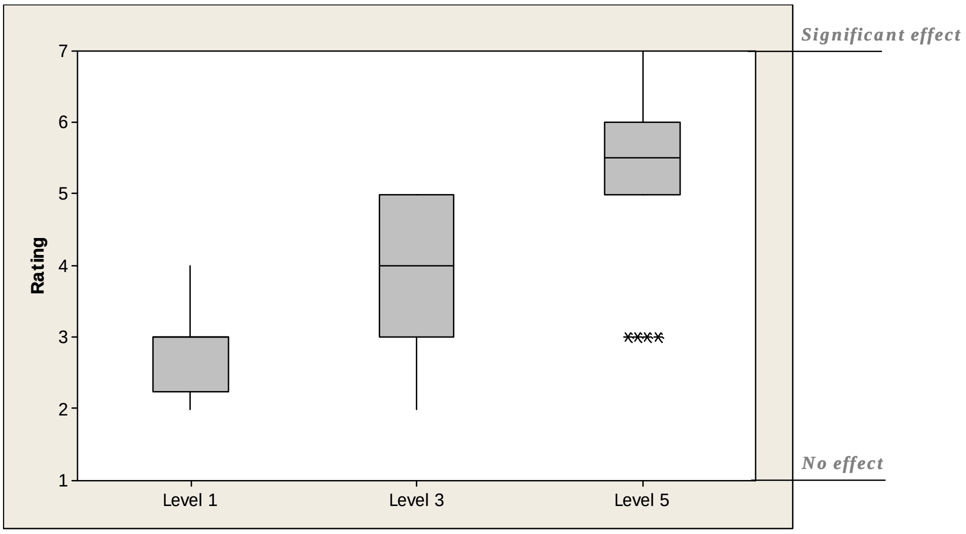

Figure 36 Adverse effects of draft in King's Gate

It should be noted that building environment can never be conditioned to satisfy all, but the purpose is to satisfy the most possible number of occupants. The most authoritative reference work for human thermal comfort (Fanger's Predicted Percentage Dissatisfied model) experimentally proved that even in the best managed environments, 5% of people will still be dissatisfied [11]. A further important note is that gender and age did not have a significant effect on the acceptability of the thermal environment (p>0.05 for both factors).

5.3 Lighting

King’s Gate open plan offices all enjoy high levels of fenestration and therefore daylight levels are quite high within the building. This however is only to the exclusion of level 1 office where the bottom of a 4-storey high atrium provides limited amount of daylight. All offices where audited close to summer and winter solstice, as well as in midseason and all results complied with CIBSE light level recommendations (appendix D). Quite predictably; levels 5 and 3 have the highest illuminance levels due to greater access to daylight. Additionally the uniformity of light distribution exceeds minimum requirements on all levels. Level 1 however has the highest overall uniformity due to the absence of daylight. The space is entirely illuminated by an artificial lighting scheme which provides a consistent level of light all across the office (Figure 37).

Figure 37 King's Gate’s glazed front provides ample daylight in office areas, which are complemented with fluorescent artificial lighting.

Note that occupants do not have any direct control over lighting. The responds showed similar ratings between levels 3 and 5 but level 1 occupants rated their environment slightly below the other two. All votes however rated the comfort of visual environment on or above average line (Figure 38).

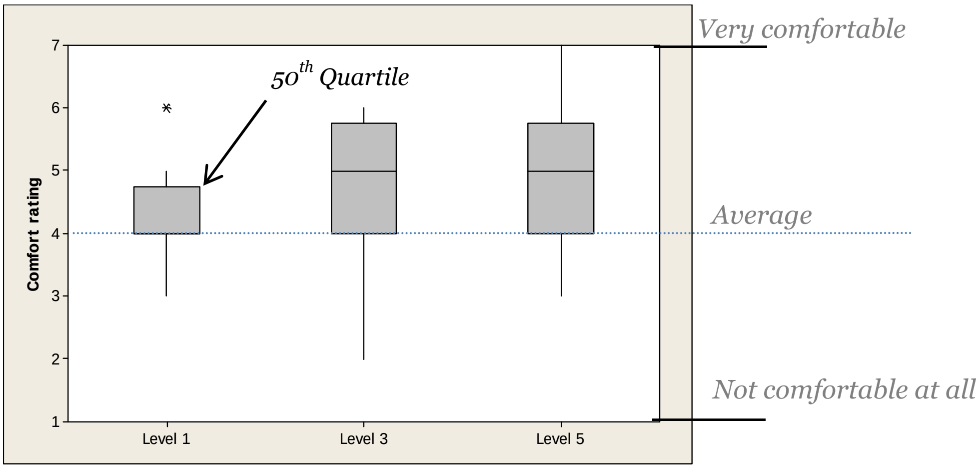

Figure 38 Boxplot of visual comfort rating

No other aspect of building design combines science and art more than lighting design. It is therefore expressed and interpreted in buildings with a greater degree of freedom and personal preference than any other element of human comfort. When asked to rank four different components of lighting design, participants rated the availability of daylight above the rest, with the ability to control lighting, absence of glare and access to views following in the order of importance (Figure 39).

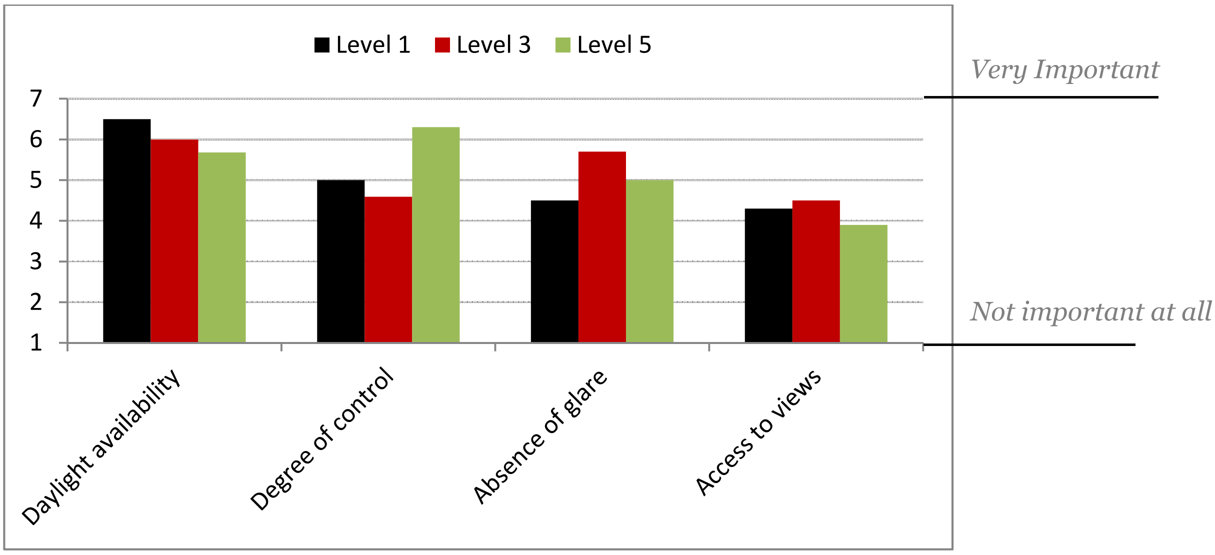

Figure 39 Correlation between satisfaction level and various environmental elements

No significant relationship existed between participants' ratings and the actual light levels on their desk (Pearson correlation of 0.28 that suggests an insignificant direct relationship). Best practice recommended values of light level existed on all desk stations surveyed (mostly a function of high levels of natural light). However high levels of natural light in offices with PC based activities can create major glare problems. Glare is a hugely complex science in its own right (an illustration is SSL handbook which defines 5 types of glare [108]). 21 out of 60 participants identified glare as a slight problem, all of whom had to perform predominantly screen-based activity. No evidence of strong statistical relationship between satisfaction level and gender (or age) of the participants were found (p>0.05 for both gender and age).

5.4 Other environmental factors

Participants were polled on their views of a number of other environmental conditions, including the cleanliness of space, the quality of furniture, accessibility and ease of movement around their environment, the security of the space and finally visual and acoustic privacies. The views expressed are in broad agreement with each other. This is evident in that most box plots cluster closely along the Y axis and also that there are no outliners within the results, except for the perception of cleanliness between 3 participants on levels 1 and 3 (Figure 40).

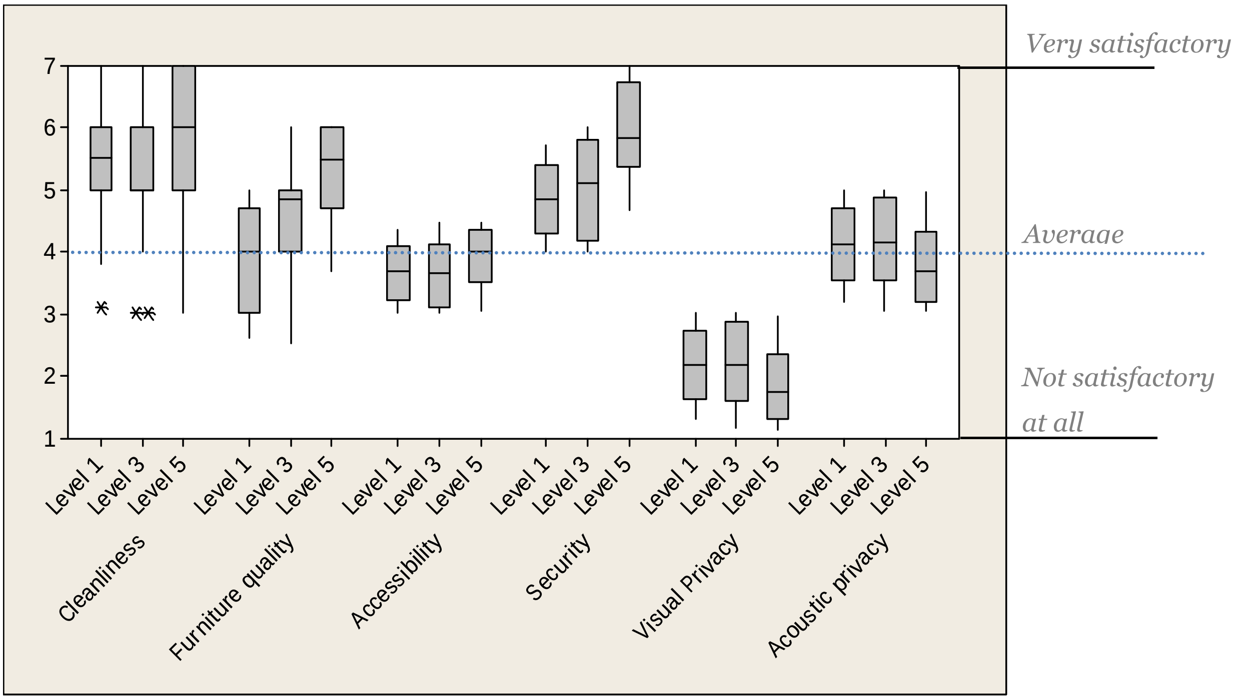

Figure 40 Ratings of general space design considerations

The occupants rate their workstations and surrounding office areas as very clean, believe the furniture quality to be quite good (particularly level 5 participants) and regard their environment as satisfactory for access and moving around. They unanimously regard the office environment as very safe too.

Visual and acoustic privacy however score the lowest, with a unanimous vote of 100% to rate the visual privacy as below average. 58% would also have preferred adjustable panels around their desks to afford them a greater degree of acoustic and visual privacy. Part of the reason acoustic privacy rates higher than that of visual is the availability of meeting and conference rooms for private conversations. No significant statistical relationship was found in relation to the influence of age and gender.

5.5 Summary

There is strong evidence that the relationship between ‘Objective assessment’ of the space and ‘subjective experience’ of its occupants is not linear. This has been quantified at different capacities by varies researchers [109]. Therefore efforts to improve any building to or beyond best practice standards do not necessarily lead to equally greater satisfaction levels. It was observed here that the space temperature in all areas audited stayed within best practice bracket yet occupants perceived their working environment fairly cold in winter and levels 3 and 5 thought it warm in summer. Cognitive bias is strongly present in the way co-workers in a space perceive their environment in particular where certain notions are widely discussed (building occupants were widely aware of the draught and coldness issues covered earlier) .Most interviewees, particularly those on level 5 perceive their space to be slightly cold in winter and slightly warm in summer, despite the satisfactory nature of thermal measurements. The experience of the first summer after the building inauguration which was a particularly warm summer, together with lack of control over the thermal environment might provide partial explanation for this discontent. This study could not find any statistically significant influence of age and gender on thermal, acoustic and visual evaluation of the space studied.

On the whole King’s Gate building reaches acceptance criteria in all environmental factors as defined by CIBSE Guide A (i.e. thermal, visual and acoustic). In order to be able to challenge the viability of the best practice standards that were followed in this work, a wide geographical and climatic spread is required within which a large pool of participants are studied (preferably over long time periods). The scope and strength of the work here therefore does not enable the author to challenge the viability of the CIBSE guides against which the space was audited. Finally difficulties that are encountered in the environmental audit of workplaces go some way to explain why a code that could unify the subjective assessment and objective measurements of a space is yet to be developed.

Chapter 6 Model calibration

6.1 Introduction

Adaptive comfort was introduced in section 2.3 where it was noted that this concept is the natural progression from a 'static' state of thermal comfort definition to a more dynamic and 'micro-climate-linked' template. Next chapter undertakes an examination of adaptive comfort within the case study office building. However to ensure that the results bear as close a resemblance to reality as possible, a comprehensive calibration is carried out in this chapter which offers an insight into how closely the virtual model can predict the energy and environmental condition in the building. The virtual model referred to in section 4.3 is calibrated to ASHRAE guideline 14 against a comprehensive set of measured hourly data. Calibration results show high levels of correlation between the measured and simulated values for the year analysed (2012). The calibrated model is then used to analyse the potential of adaptive comfort as set out by EN 15251 using historic and future site specific weather files generated by UKCP09. The results for the actual building (designed to UK Approved Document part L 2006) are compared with passive house standards.

6.1.1 Zero carbon buildings

Building design has always attempted to satisfy form and function. But successful design in recent years has come to be defined by a more intangible index; namely the ecological footprint. This 'new index' secures greater attention nowhere more than in complex and energy intensive buildings. Collectively, buildings account for 32% of the primary energy worldwide [110]; prompting designers to increasingly attempt to find more effective measures of reducing buildings' energy and carbon costs. These measures generally centre on passive design techniques, fabric improvement and renewable integration. European parliament instructs member states to outline minimum performance standards through its Energy Performance Building Directive (EPBD)[6] and countries such as UK, France and Germany further promote sustainable building design by best practice standards such as BREEM, HQE, NZEB and

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[6] EPBD 2002/91/EC and the latest recast EPBD 36/EC/2012.

DGNB respectively [111, 112].The UK building regulatory bodies are essentially working to pave the way towards zero carbon domestic and commercial buildings (by 2016 and 2019 successively). The current UK administration has a programme particularly focused on streamlining the technical and procedural aspects of the building law [2, 3]. It is however abundantly clear that the tightening of air infiltration and better insulation values are continuing trends. These are primarily enabled by improved construction techniques and advanced materials. As such, passive house standard could be taken as an indication of the shape of future regulatory developments in northern parts of Europe.

Given its simplest expression, the primary role of a building is to create a comfortable working (or living) environment and a large volume of work is available that examines aural, visual and thermal dimensions of human comfort with thermal element being widely accepted as the prime element [21]. Thermal comfort is itself currently at the threshold of a new re-evaluation through the introduction of adaptive comfort standard that promised to rectify the weak and inflexible nature of existing thermal comfort definitions [42, 43].

This chapter attempts to capture these two current regulatory developments, namely improved fabric design and also the concept of adaptive comfort. Both energy and comfort implications of these techno-political trends are examined by using a calibrated model of an office building. Given that the design of a building should also take a whole life perspective, medium and long term weather files are used to project the results into the future. These results are repeated for both 2006 building regulation standards and also a much more arduous passive house standard.

6.1.2 Passive house design

Passive house is a prominent standard developed to offer energy efficiency within moderate and cold climates similar to those of central and northern Europe. This design philosophy saw rapid uptakes in Germany, Austria and Switzerland in 1990s and 2000s [113] and has also come to influence Scandinavian building standards widely [114, 115]. It primarily seeks to significantly reduce building energy use, in particular the heating requirement. The design and orientations are also expected to exploit natural elements to yield energy efficiency. In Germany and Austria, where the standard was first developed, a maximum final space heating requirement of 15 kWh/m^2 per annum and a maximum overall primary energy use of 120 kWh/m^2 is required to comply with this standard [116]. More detailed expressions are included in passive house standards by other countries. For instance the Swedish criteria makes allowances for the much harsher northern regions [117]. A case study of Camden Passive House (in UK) reported that passive house outperformed similar low carbon developments [118].

Over the years research effort has sought to examine passive house when applied in different regions and to different building types. Inevitably the diversity of standards applied and climatic conditions make it difficult to draw definitive conclusions. What is clear however is that there is a trade-off between increasing economic and carbon cost of constructing a high quality passive house building and reaping the rewards in the form of reduced operating energy costs[119, 120]. Similarly, concerns over climate change has led to criticisms of solutions that are predominantly seeking to minimise space heating, as warming climate presents the challenge of planning for entirely passive or low-energy comfort cooling too [121]. This chapter examines the carbon and comfort implications of passive house design when space is governed by adaptive comfort standards.

6.1.3 Current and future weather data

As outlined in sub-section 3.2, 8 streams of data were available from the rooftop weather station at 10-minute intervals and were used in the calibration of the building base model. Several formatting steps were required to allow current and future weather files to be used in EnergyPlus. The most important of which was the need to generate '.stat' files using EnergyPlus weather statistics and conversions' program for both historical files (used for calibration) and future weather files. The detailed calibration of this model in accordance with ASHREA Guide 14 is set out in sub-section 4.4.1.

Figure 41 King's Gate Scientific rooftop weather station (inset left: 2 main dashboards for station's readings)

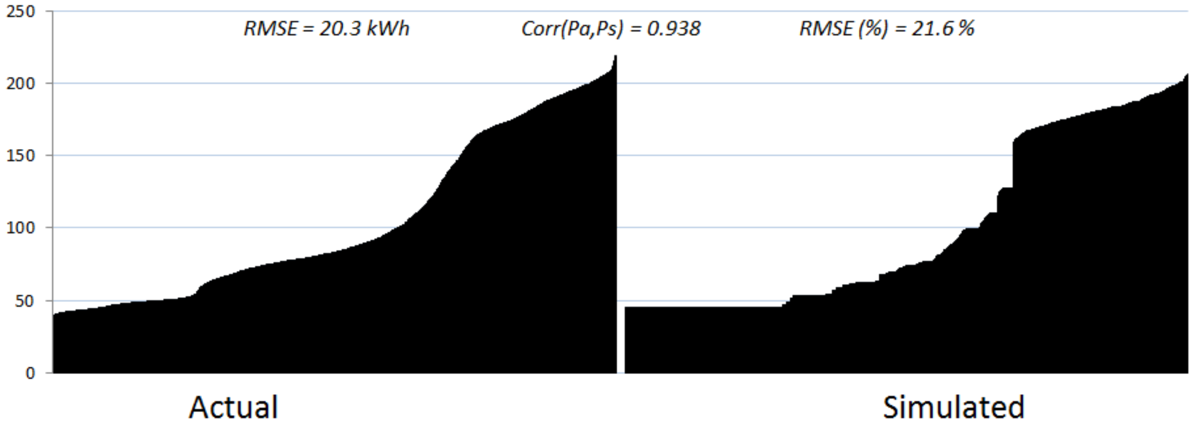
To rigorously examine the resilience of current building design, design solutions should be evaluated within the much warmer anticipated climates. This also takes heed of the complete lifecycle behaviour of a proposed building design. Average global temperature rises of up to 6°C are predicted by climate models to occur during the course of this century [82]. Although climate change is not a 'settled' science, the strongest indications point towards the continuation of the warming trend and the immediate effect of this in the UK will be an increase in summertime temperatures and more sporadic precipitation.

Over the past 2 decades United Kingdom Climate Impact Programme (UKCP) has provided information to all parties interested in developing resilience strategies to cope with the repercussions of climate change. In its latest release (UKCP09) a set of CDF and PDF data sets are provided which are recommended by CIBSE for use in simulation assessment of building thermal performance. UKCP09, the most sophisticated work so far, was developed by UK Meteorological office Hadley Centre Climate model. A weather generator can spatially downscale this data to 5-km grid scales, over either monthly or hourly time steps. Several UK universities (including but not limited to Manchester, Exeter and Northumbria) have also generated TRY and DRY future weather files by a variety of different techniques, mostly pivoting around FS and morphing techniques [122-124]. Results generated from all these sources are in broad agreement on the warming trend with advancing time and carbon emission scenarios. Future weather files in this work are based on the work of Hu Du and C Underwood who used the latest climate projections by UKCP (version 09) to construct 85 and 99 percentile climate data [122]. UKCP uses a baseline period which is the 'observed' trend from 1961 to 2006 (referred to as current weather and denoted 1970 within the charts). Against this baseline a number of future climate scenarios are constructed using an 'assumed' linear relationship which projects observed historical trends into future horizons. The use of high risk climate change scenarios enables lower probability data to be used to assess higher impact levels, whereas low risk scenarios portray higher probability and result in lower impact levels on building and environment [125]. As the focus of this work is the validity of adaptive comfort, medium risk projections for 2040 and 2080 files are used to construct future scenarios. This is also to reflect the fact that both EU and UK policies are formed around global warming scenarios arising from medium temperature rise forecasts [126].

6.2 Results

6.2.1 Electricity

Statistically, electrical power measurement is a continuous quantitative data type. Figure 42 enables a quick visual inspection of measured and simulated values and their statistical variations by arranging them in ascending order.



i	8760	hrs
min	40.7	kWh
Max	218.8	kWh
Ave	105.6	kWh
∑	910,926	kWh
σ	54.2	kWh

i	8760	hrs
min	45.0	kWh
Max	206.2	kWh
Ave	101.5	kWh
∑	901,059	kWh
σ	58.2	kWh

Figure 42 Measured and simulated building electricity consumption in ascending order (kWh)

The building's annual electricity consumption for 2012 is 910,926 kWh. The final calibrated base model returned a value of 901,059 kWh (i.e. a deviation of 1.08%). Electricity carries the biggest RMSE in among other two calibrated streams of data since electrical consumption is most closely related to occupant activity that deviates (in a random manner) from occupancy templates imposed on the virtual model. More definitive conclusions could be drawn if real occupancy data with sub-metered lighting and small power consumptions were available. Figure 43 demonstrates the RMBE and CV(RMSE) results of the calibration process.

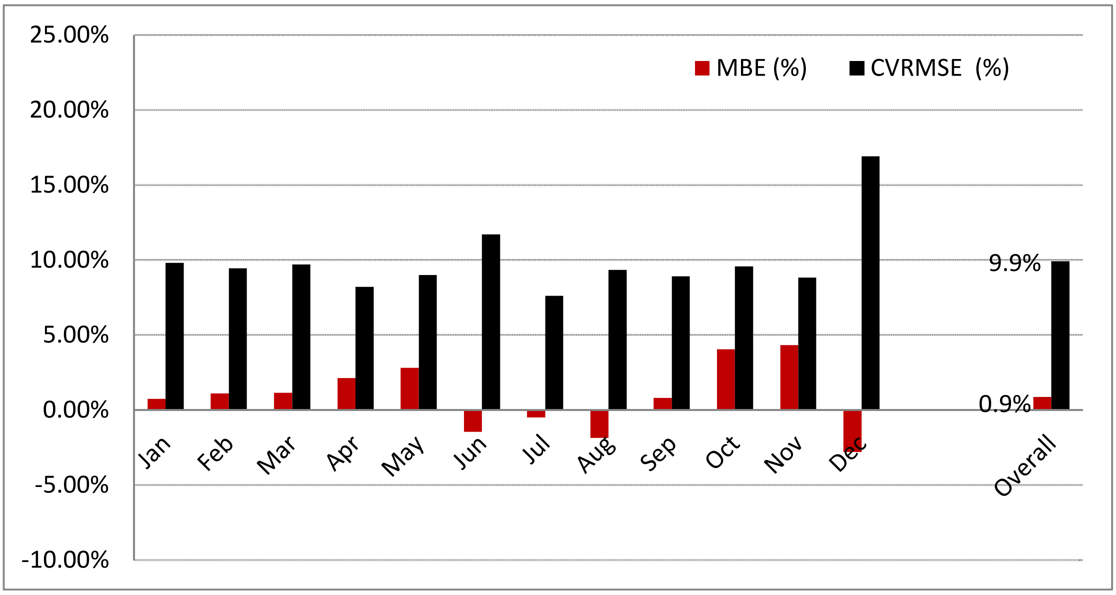


Figure 43 MBE and CV(RMSE) analysis for building electrical consumption (hourly)

Quite clearly the building passes the calibration criteria set by the ASHREA guide 14 acceptance limits. CV(RMSE) results indicate larger accumulation of errors in June and December which reflects the more sporadic pattern of occupancy due to holiday seasons. Developing realistic occupancy template for simulation efforts is an undergoing research effort [127-131] although these tend to offer case-specific solutions. The facilities manager also takes a very proactive role in managing this building and therefore the set points within the space are regularly updated in response to occupant's comments. This adds a greater probabilistic pattern to actual building performance as opposed to static template-driven nature of simulation results. Histograms of residual values as defined by equation 26 allow closer examination of results.

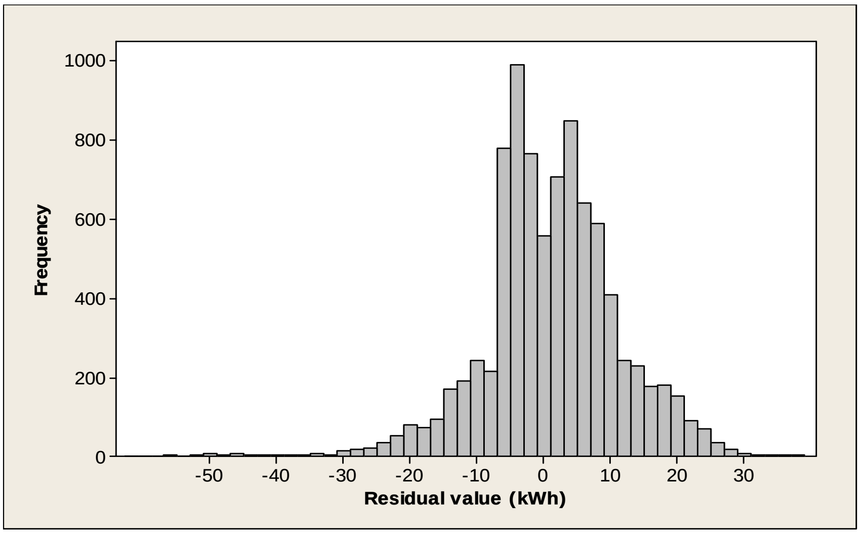


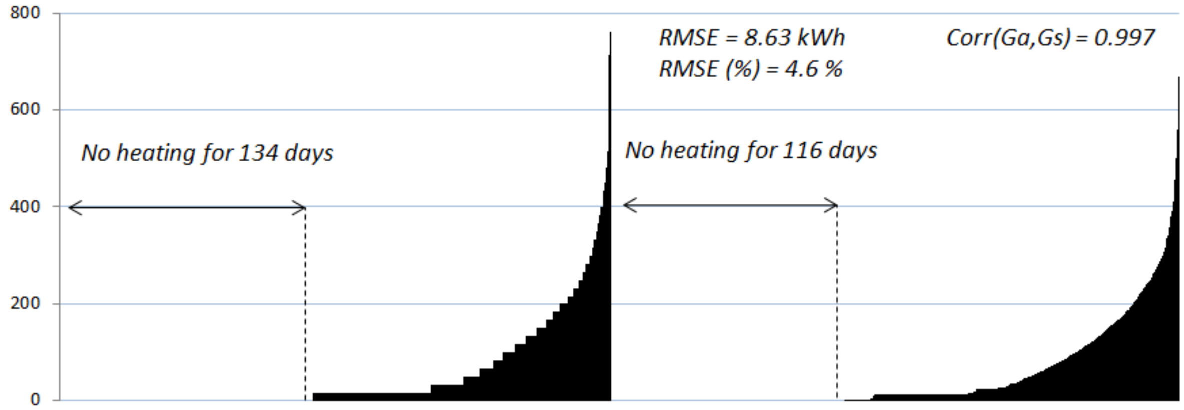
Figure 44 Histogram of residual for hourly electricity values (kWh)

Figure 44 illustrates a histogram of the full range of hourly model errors in kWh. The chart has characteristics of mostly normal (bi-modal) distribution centring on zero. 94% of errors have a magnitude falling within ±10% of daily peak electrical values (i.e. ±20kW). The incidents of negative error show a greater magnitude (indicating model over-prediction), yet the frequency of this instances are very low.

6.2.2 Gas

A close examination of the building's gas consumption demonstrates a well-managed energy regime as space heating only occurs on average during days with average daily outdoor temperature of 11.5°C or below. The heating system (for the year under examination) was also entirely shut down from mid-June to early October.

The measured and simulated gas consumption values, again another continuous quantitative data type, are arranged in ascending order in Figure 45:



Actual

i	8760	hrs
min	0.0	kWh
Max	731	kWh
Ave	41.4	kWh
∑	362,443	kWh
σ	62.6	kWh

Simulated

i	8760	hrs
min	0.0	kWh
Max	670	kWh
Ave	43.0	kWh
∑	376,426	kWh
σ	61.3	kWh

Figure 45 Measured and simulated building gas consumption in ascending order (kWh)

A building's heating-related gas consumption is a direct function of outdoor temperature. The weather data used in the simulation process was generated using the weather station located on the building's rooftop; the simulated and measured data therefore predictably bear a very close resemblance, with a correlation of 99.7%. The measured energy consumption has a stepped nature which is due to the fact that the three boilers serving the building cannot modulate infinitely, so there is repetition of specific part/full load capacities at times of similar heat demand, whereas the simulated results is a mathematical load calculation reflecting the infinitely variable weather data input values. Figure 46 outlines the MBE and CV(RMSE) calibration values. The largest errors belong to October season when the building was used at the weekends for organisational purposes.

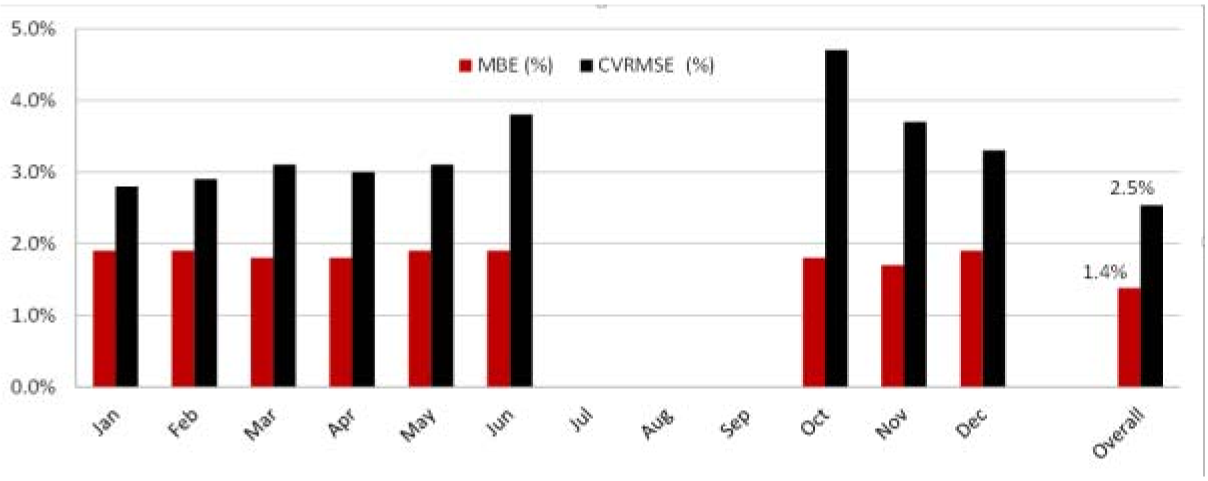


Figure 46 MBE and CV(RMSE) analysis for building gas consumption (hourly)

The MBE and CV(RMSE) values are however substantially lower than those of electrical calibration process and fall well within the respective ASHREA acceptance limits of ± 10% and ±30%.

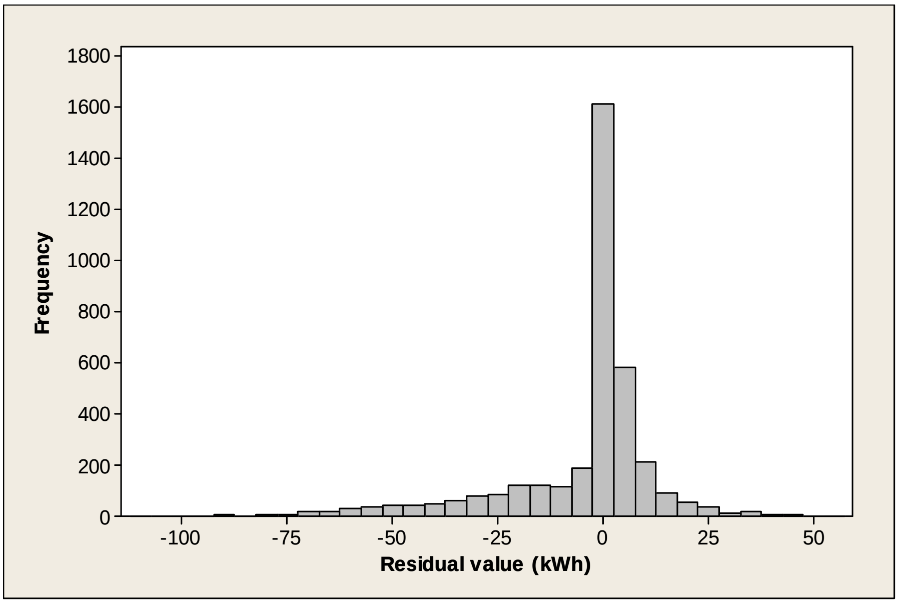
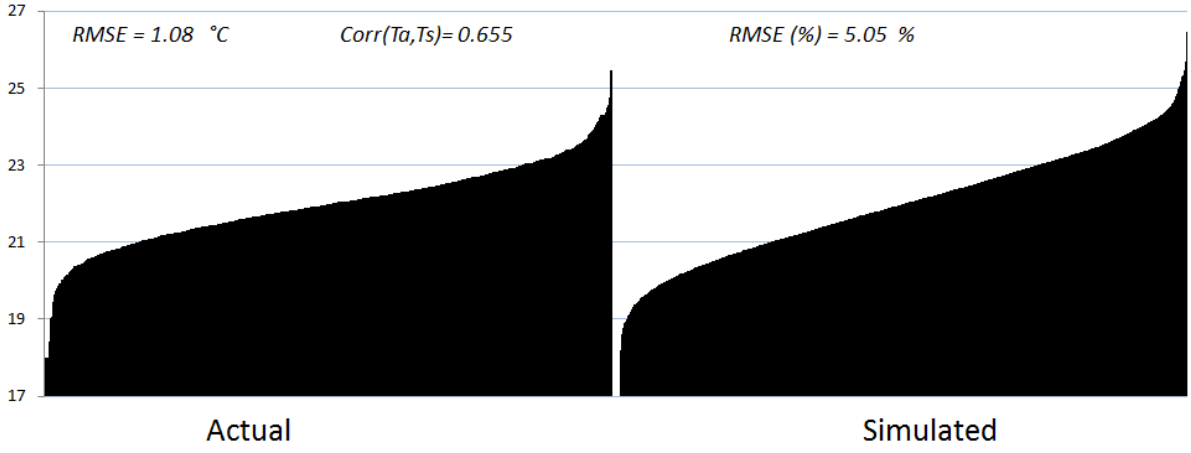


Figure 47 Histogram of residuals for hourly gas values (kWh)

Statistical analysis of residual value (produced using formula 21) shows that 91.1% of the errors fall within ±10% of daily peaks (Figure 47). The simulated model however displays a slight tendency to over-predict gas consumption (hence greater incidents of negative residual values). The instances of under and over prediction by the model are nearly similar, however the magnitude of over predicted values (negative residual bars) are bigger. The frequency of both over and under predicted values are however insignificant.

6.2.3 Space temperature

The sensor illustrated in 4.4.2, a multi-functioning set of sensors provided actual (measured) space air temperature logged at 5-minute intervals that enabled this part of the calibration. The sensor had a response time of less than a minute and accuracy of ± 0.5°C (at 22°C). Figure 48 demonstrates a comparative and statistical analysis of the measured and simulated space air temperatures.



	Actual	
i	8760	hrs
min	17.4	°C
Max	25.5	°C
Ave	22.0	°C
σ	1.1	°C

	Simulated	
i	8760	hrs
min	18.0	°C
Max	26.5	°C
Ave	22.0	°C
σ	1.4	°C

Figure 48 Annual hourly space operative temperature (°C)_ arranged in ascending order

Figure 49 outlines the RMBE and CV(RMSE) error checks for the calibration process. Both RMBE and CV(RMSE) errors are less than the acceptance value (96.2% of the values fall within ±1.5°C) and the results satisfy ASHRAE Guideline 14.

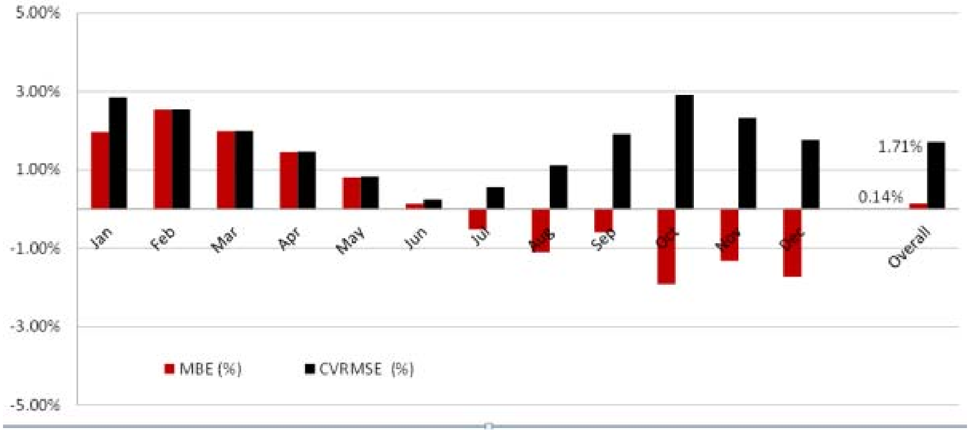


Figure 49 MBE and CV(RMSE) analysis of office temperature (hourly)

The histogram in Figure 50 has a bimodal spread with its centre at around -0.5°C, indicating that the EnergyPlus model generally tends to return marginally higher temperatures in the space. This could be a function of higher heating load returned by virtual model. Four atrium rooftops are also randomly opened by the building managers in response to the occupant complaints. The random nature of this boosted space ventilation couldn't be captured by the virtual model.

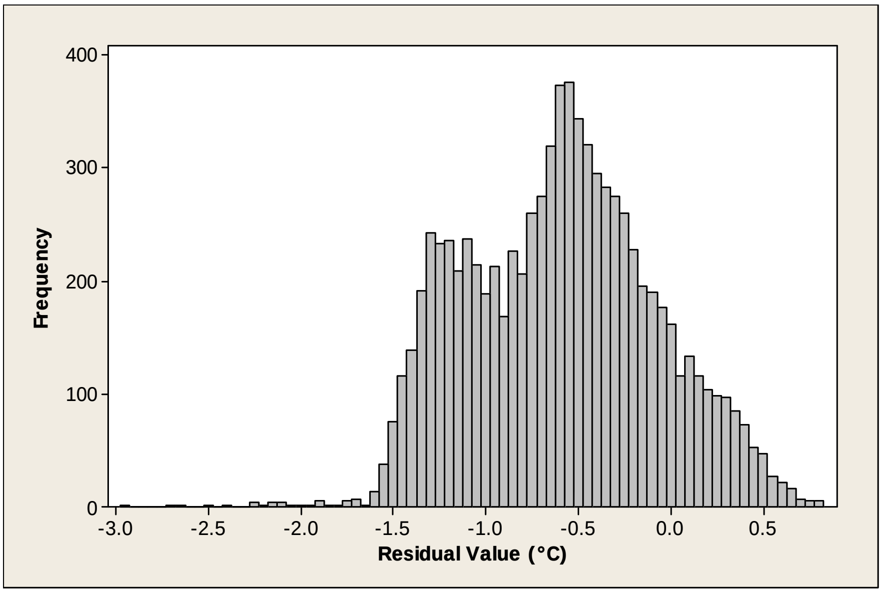


Figure 50 Histogram of hourly residual temperature values

The Energyplus model also maintains a constant level of accuracy with increasing space temperature (Figure 51).

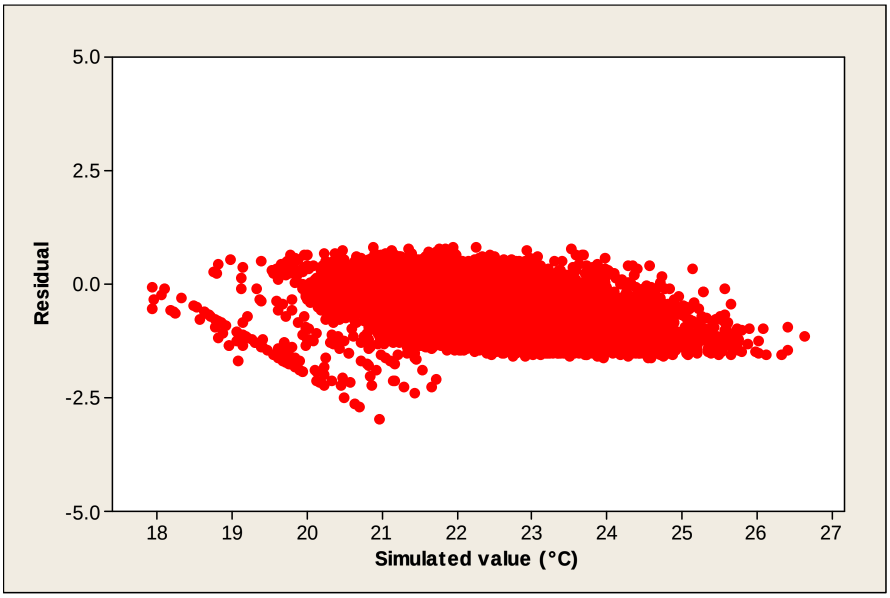


Figure 51 Scatterplot of residual versus simulated values (°C)

Underlying causes of discrepancies between measured and simulated values are vast and varied in nature [132-135]. Therefore all attempts dedicated to bringing virtual predictions closer to reality need to operate within an allowable error margin. Increasingly concepts such as BIM, model based supervisory controls, post occupancy energy audits and online building controls and optimisation require the creation, maintenance and updating of virtual building models [95]. As such, more exact calibration protocols are now required which should also allow for instances where measured data is limited or of a coarse nature.

6.2.4 Recommendation

Error analysis in the simulation of complex phenomena [136] conventionally defines error by subtracting reference value (observed) from the model forecast (simulated). This results in instances of negative error to correspond with the model under-predicting and instances of positive error with the model over predicting. This convention is not observed in ASHREA set of calibration formulae as the compound effect of squared errors guide the calibration exercise. Adhering to the convention however enables a more intuitive interpretation of errors where over-prediction produces positive error and vice versa. It is therefore suggested that the building energy analysis exercises can adhere to this convention.

6.3 Summary

This chapter examined the ability of the virtual model to predict the energy and environmental condition within the case-study building. Energyplus engine provided a very close evaluation of building performance when set against real building data. While it is perfectly acknowledged that benefits reaped by a detailed model calibration does not necessarily justify the depth of the work undertaken here, the following recommendation may serve as a guiding protocol for an state of the art calibration effort:

1- Calibration is conducted over an annual cycle using (preferably) hourly data
2- An explanation of the local (or justification of otherwise) is provided for the type of weather files used.
3- Calibration results (as those inferred by ASHREA Guide 14) are presented in monthly intervals allowing the assessment of seasonal change of model predictive capability.
4- Residual histograms or scatterplots could shed further lights on the tendency of the model to under/over predict.

Such a model therefore could be used as a valid platform for more meaningful comparative studies and building integrated technology evaluations.

Calibration acceptance criteria (i.e. ASHRAE Guide 14) could also be divided into several tiers to account for progressing levels of model accuracy and data granularity, as detailed building information may not always be readily available. Nonetheless insights offered by mathematical building models remain statistically much more significant than model error margins so long as they are accounted for.

Chapter 7 Adaptive comfort

7.1 Introduction

As noted previously, the calibrated model is used to examine the energy and environmental potentials of adaptive comfort as outlined by the EU EN15251 parameters. Freefloat zone temperatures are set against the adaptive comfort lower and upper bands within time-series line charts. Lower and upper adaptive comfort data trends are constructed for EU EN15251 building category definitions II and III (reflecting moderate and normal occupant expectations). The results outlined in the following section show significant heating load reduction for the base model when adaptive comfort is implemented, while passive house standard quite predictably eliminates the heating load altogether. However the boundaries of space operative temperatures obtained using adaptive method are a major departure from Fanger's thermal comfort indices and also Predicted Mean Vote models stipulated by BS EN ISO 7730:2005. It is worth noting that since the space target temperature is guided by a band, it becomes necessary to define the heating and cooling seasons (in order to avoid instances of heating load in summer). Using EN15251 heating season was specified as instances where outdoor running mean temperature is below 10°C (i.e. $\bar{T}_{ao}$<10°C). Similarly a running mean temperature of above 15°C ($\bar{T}_{ao}$>15°C) defines the beginning of cooling season [104].

Figure 52 to Figure 57 report the results reflecting category II and Figure 58 to Figure 63 summarise the results for category III buildings. The expression $'t_{T_{operative\,\epsilon\,(T^{-},T^{+})}}'$ denotes instances of time (t) where the internal space operative temperature ($T_{operative}$) falls within the adaptive comfort band (T^{-}, T^{+}), as outlined by formulas 22 and 23 (sub-section 4.5.1) .This figure is informed by the free-float simulation (with HVAC disabled). A second simulation (with HVAC enabled) informs the values reported by expressions Q_h and Q_c which stand respectively for the heating or cooling loads. Q_h and Q_c are the energy input required to satisfy adaptive comfort building category II or III (see 4.5.1 for full details). In order to enable a comparative carbon study between adaptive comfort and conventional control lower and upper comfort bands are constructed using historical and future weather files sourced from UKCIP09. These findings are elaborated on the following sections.

7.2 Y=2

Y=2 reflects a normal level of occupant expectation. Within Figure 52, all instances of zone operative temperature that fall outside adaptive band indicate heating load.

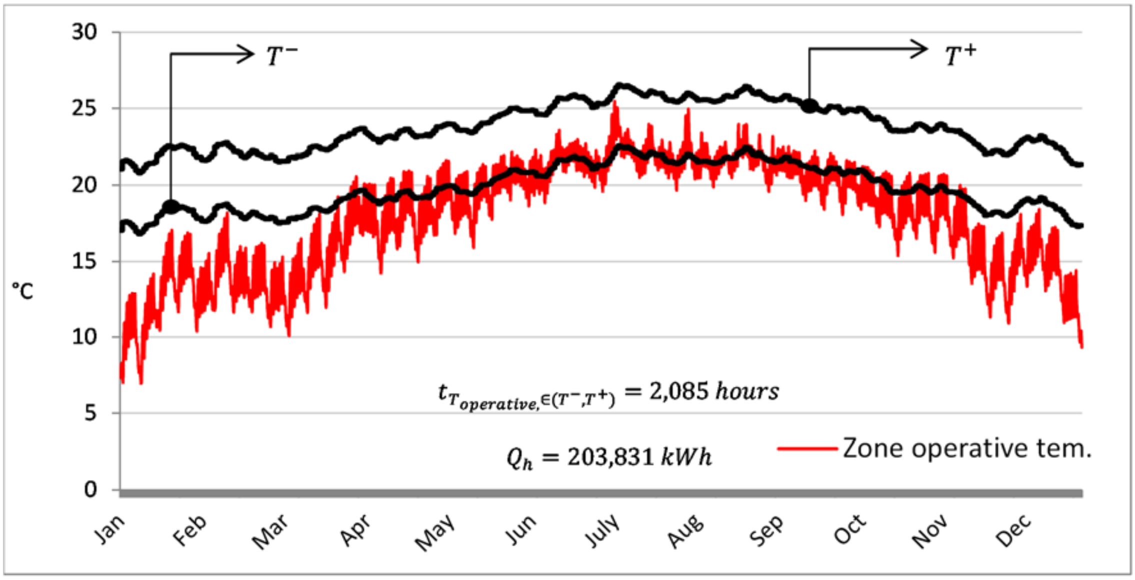


Figure 52 Base-model (current weather files)

While static zone temperature control results in a load of 332MWh, a 39% reduction is experienced by adaptive temperature implementation in the base model building using current weather files (Figure 52).

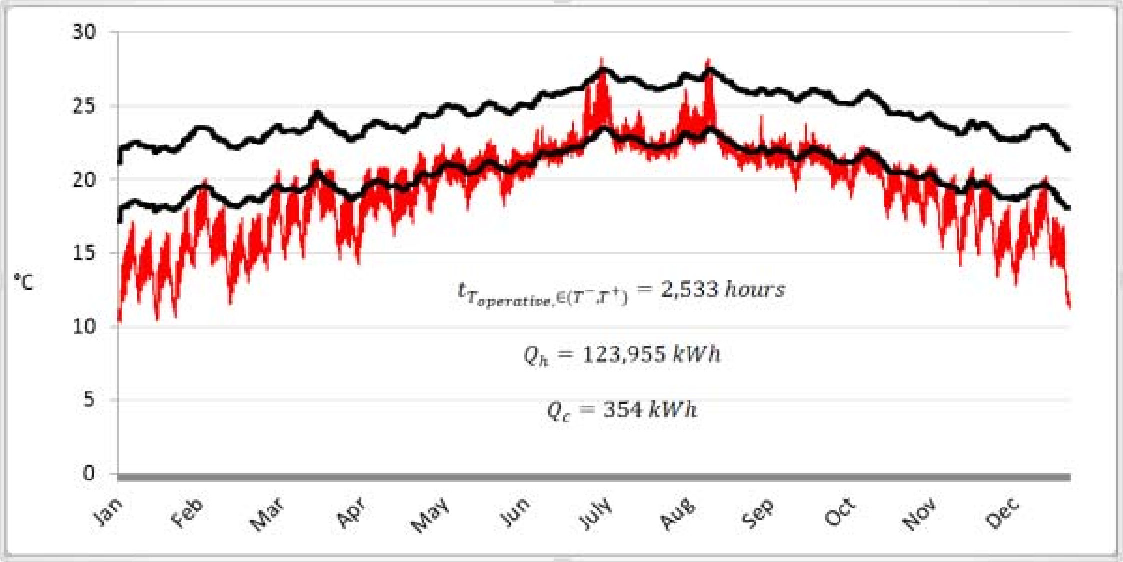


Figure 53 Base-model (2040 weather files)

Similarly (and set against a benchmark of current weather files and static control regimes) heating loads are further reduced by 62% and 70% when the base model is run using 2040 and 2080 weather files (Figure 53 and Figure 54 respectively).

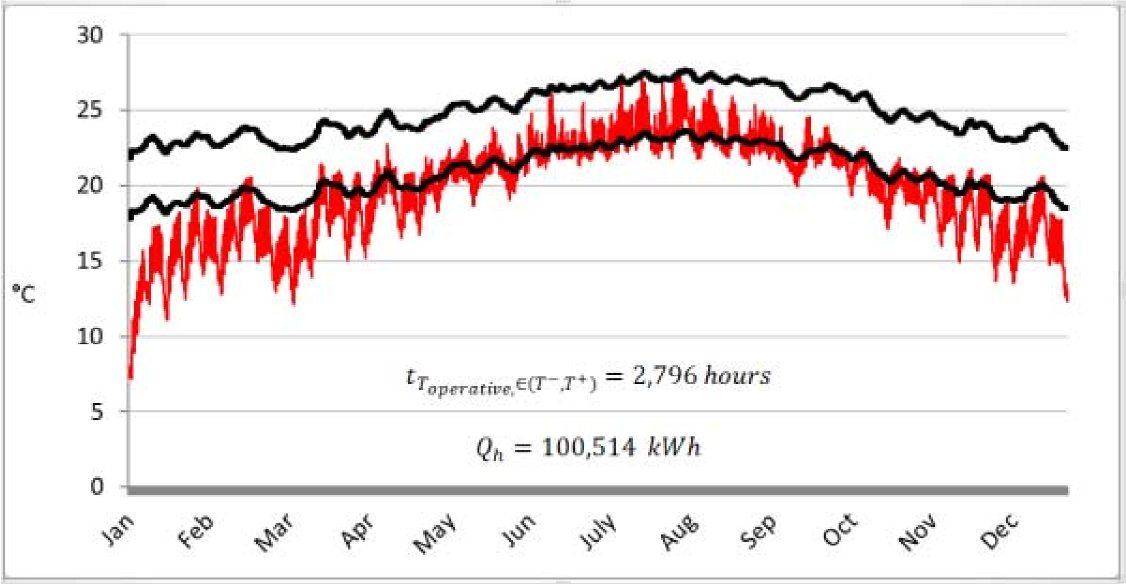


Figure 54 Base-model (2080 weather files)

However a dramatic change is observed in freefloat building zone temperature when the building fabric is improved to passive house standards (Figure 55). Regardless of which weather files are used within the virtual model, the passive house standard, quite predictably, manages to completely eliminate the heating load in the target building.

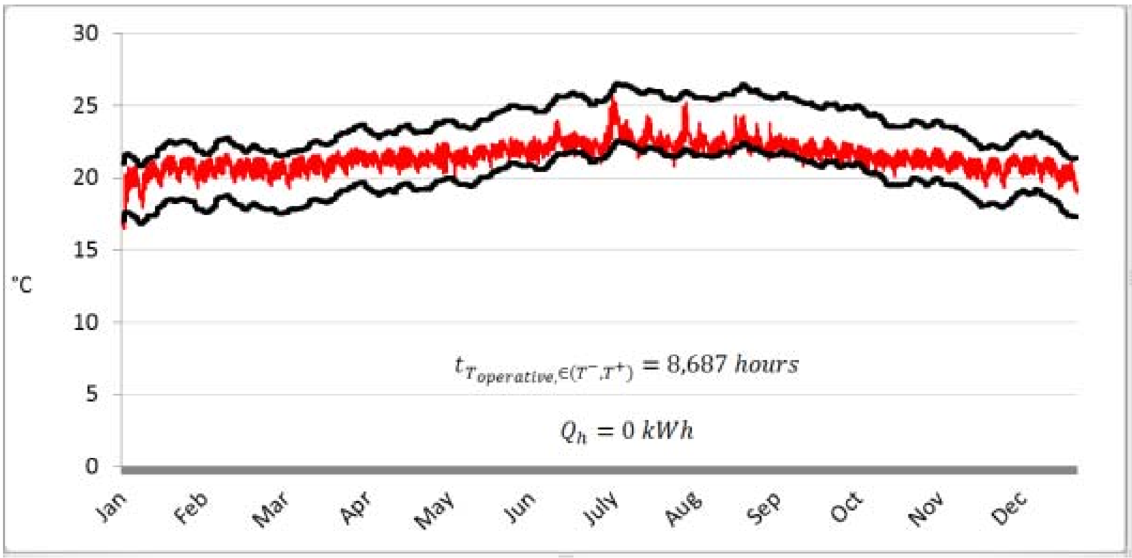


Figure 55 Passive house (current weather files)

Given that each figure contains adaptive comfort temperature bands and freefloat building zone temperature resulting from a unique weather file, both sets of temperatures tend to fluctuate in synchrony. As a result, and as evident from Figure 55 to Figure 57 the highly insulated passive house fabric when combined with high IT-driven internal loads lead to high winter-times temperatures that fall within adaptive comfort bands and eliminate heating loads.

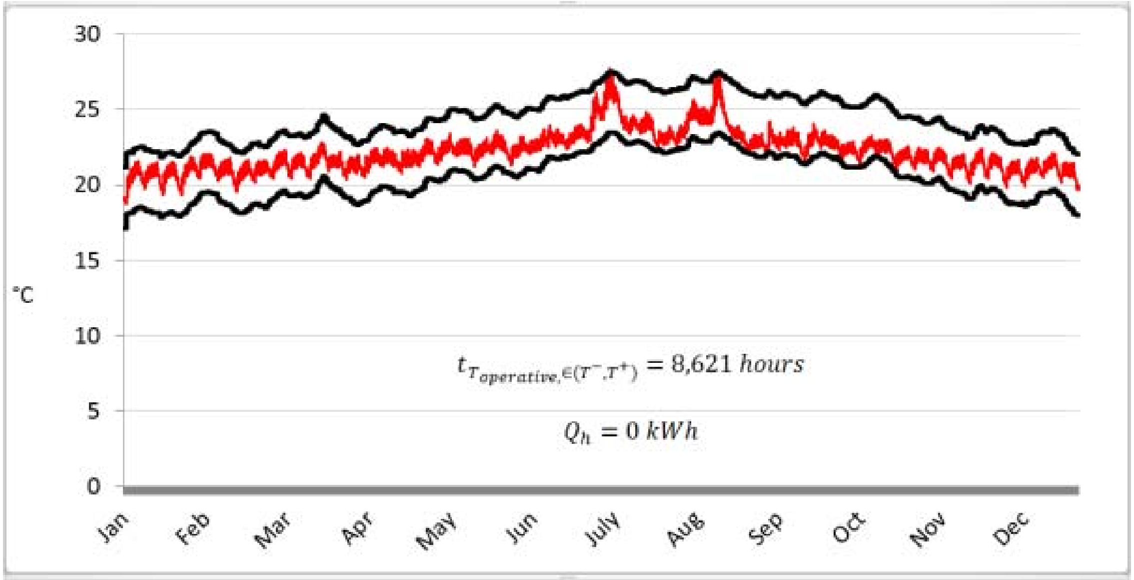


Figure 56 Passive house (2040 weather files)

Although the Northern European location of the building means that the servicing strategy and energy footprint of the building is dominated predominantly by heating loads, nonetheless the super-insulated building fabric and high internal gains do not lead to any instances of summer time overheating. This is firstly due to the adaptive comfort concept that allows higher summer time temperatures as well as the ability of the super-insulated fabric to minimise conductive solar heat gain through the opaque fabric (Figure 55 to Figure 57).

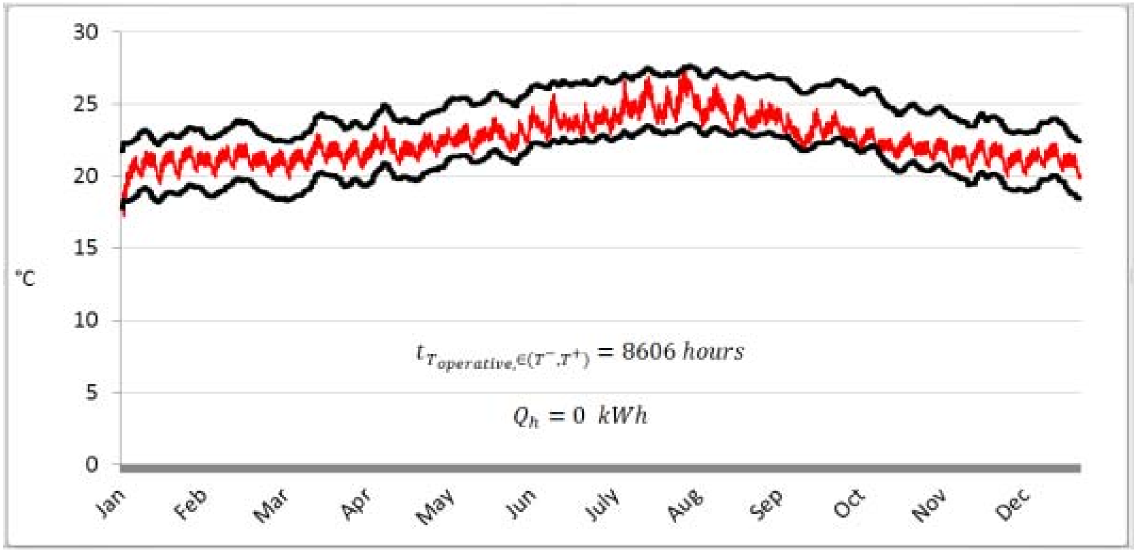


Figure 57 Passive house (2080 weather files)

7.2.1 *Category II implications*

Within Figure 52 to Figure 57 a category II buildings Y value of 2 are assigned, reflecting a ‘normal’ occupant expectation in a new building as outlined by EN 15251. The static values outlined in table A.2 of this document defines a range of 20°C to 26°C for an open plan office hosting sedentary work. Controlling the building using this strategy dramatically reduces the heating loads. Using UKCP09 baseline weather files and the current space conditioning regime (with static target temperatures), the building model returns an annual heating demand of 332 MWh. However if the conventional static target temperature controls are replaced with the adaptive comfort bands constructed using the same UKCP09 baseline weather files, the base model building experiences a heating demand reduction of 39% (Figure 52).

In free float condition (with no plant heating input) the base model building (simulated using baseline weather files) stays within adaptive comfort bands for 2085 hours. This corresponds to 32% of the operational time, which is defined as 8am to 5pm. When using 2040 and 2080 weather files, the base model building will stay within adaptive comfort bands for 36% and 43% of the occupied hours, offering heating energy reductions of 37% and 31% respectively (Figure 59 and Figure 60). Quite clearly for a heating dominated region (as with this study), the warming of the climate results in smaller heating loads and therefore smaller reductions in building heat demand. Climate warming also means that adaptive comfort criteria are met more frequently over the warmer future weather patterns. Note that each energy reduction figure is calculated for the virtual building model using a ‘single’ weather file, but under two different control strategies; first that of conventional static target temperatures and later adaptive comfort target temperature bands.

The passive house building model returns the most significant results as the space operative temperature stays within comfort bands for the entire annual working hours for all 3 sets of weather files. Figure 61 to Figure 63 illustrate this; where zone operative temperature stays predominantly within lower and upper adaptive comfort bands. No heating loads results from passive house model simulations for any of the weather files examined. Figure 53 (base model simulated with 2040 weather files) is the only simulation where 359 kW of cooling is required to cope with 12 hours of summertime temperatures exceeding the adaptive comfort upper limits. Note that where summertime (i.e. cooling season) temperatures fall below the lower limit of adaptive comfort no heating load is allowed.

7.3 Y=3

Y=3 constitutes a less rigid operating regime and therefore the level of energy saving potentials are higher. Once more when set against a bench mark of static zone temperature control, the base model heating load reduces by 69% as a result of incorporating the adaptive comfort zone controls (Figure 58).

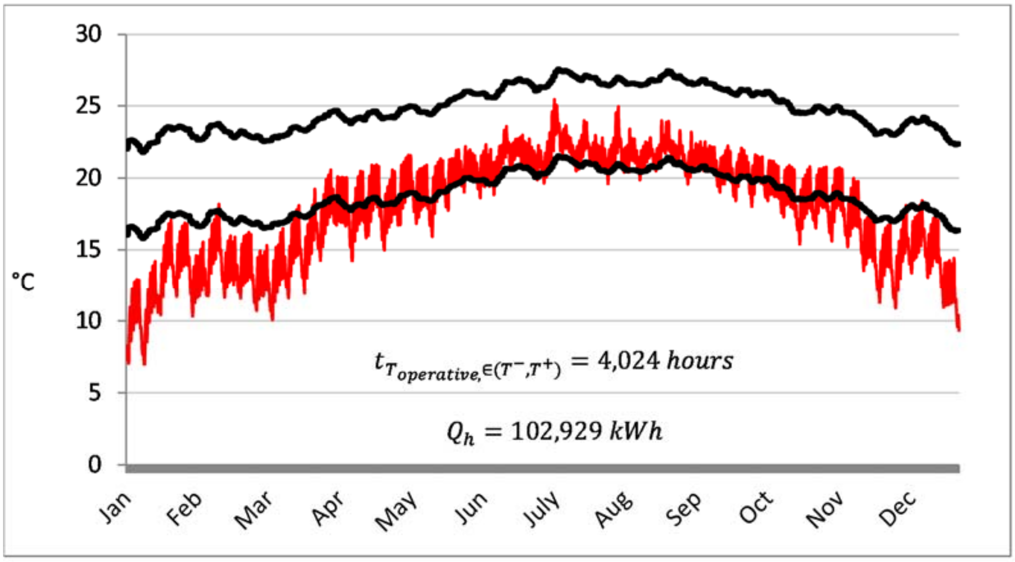


Figure 58 Base-model (current weather files)

Heating load energy reduction is improved to 81.2% and 82% for future weather files 2040 and 2080 as defined by UKCP09 (Figure 60 and Figure 61).

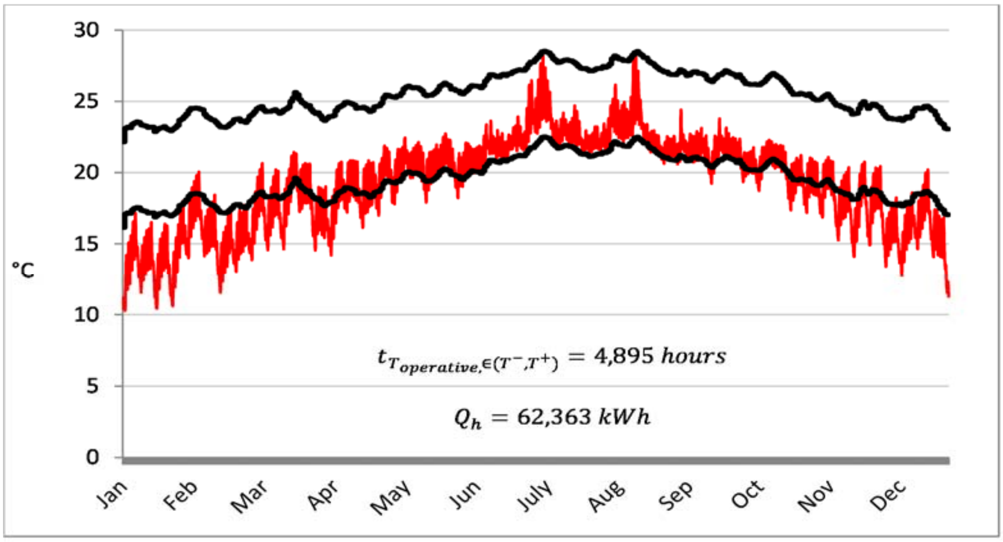


Figure 59 Base model (2040 weather files)

The passive house model simulated using Y=3 results are identical to Y=2 in that the zone operative temperature rest entirely within comfort bands for all three weather files. In this respect passive house design achieves its objective of eliminating heating load.

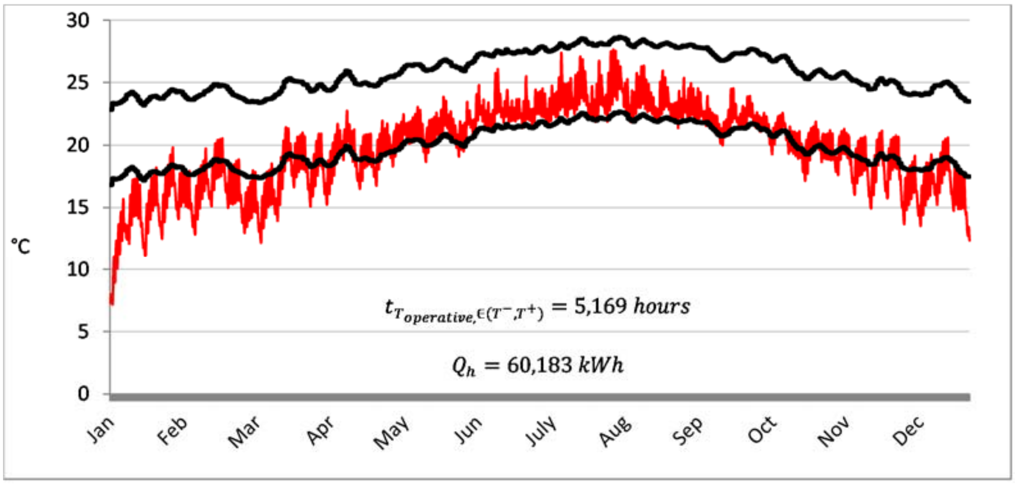


Figure 60 Base model (2080 weather files)

Given that no instances of heating load occurs within any of the simulation results for the passive house mode (Figure 61 to Figure 63) internal zone temperature falling outside the comfort band defined by Y=3 is zero for both sets of future weather files.

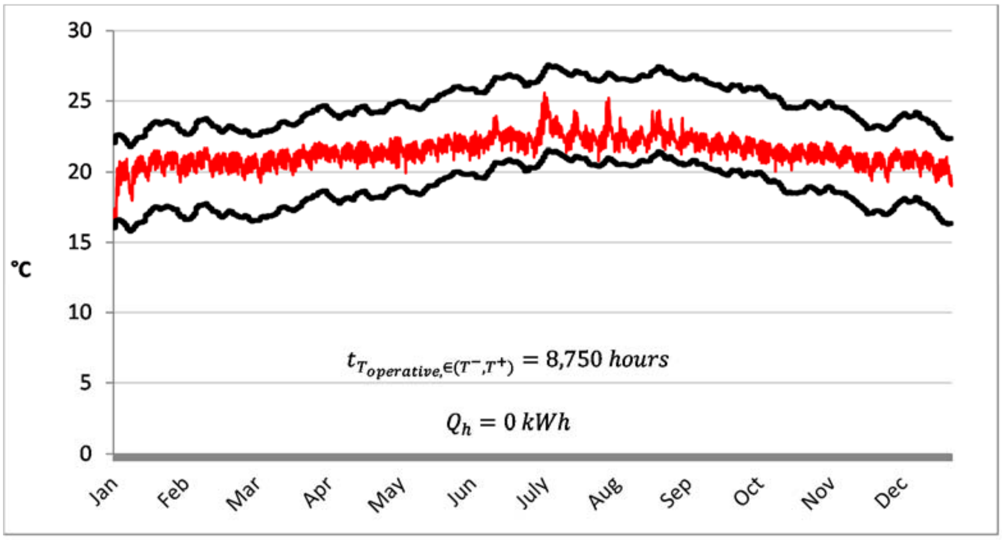


Figure 61 Passive house (current weather files)

However using the current weather files there are only 10 instances of time when freefloat zone temperature falls outside the adaptive comfort. These instances are however outside office working hours (Figure 61).

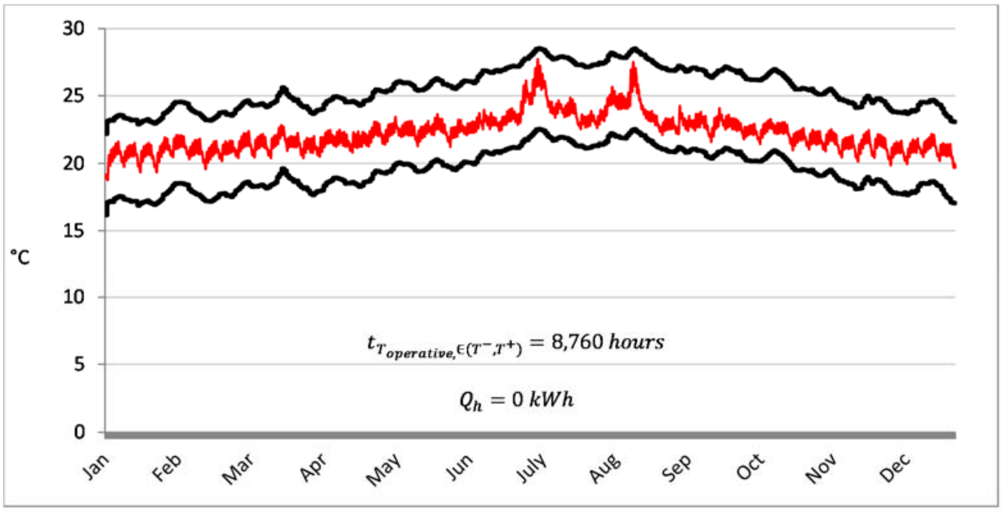


Figure 62 Passive house (2040 weather files)

Comfort bands constructed using a value of 2 for Y (within formulas 22 and 23) represent a closer control of indoor environmental temperatures when compared to Y=3 bands. As a result simulations conducted with Y=2 yield smaller energy savings (the comfort implications of II and III categories are discussed later).

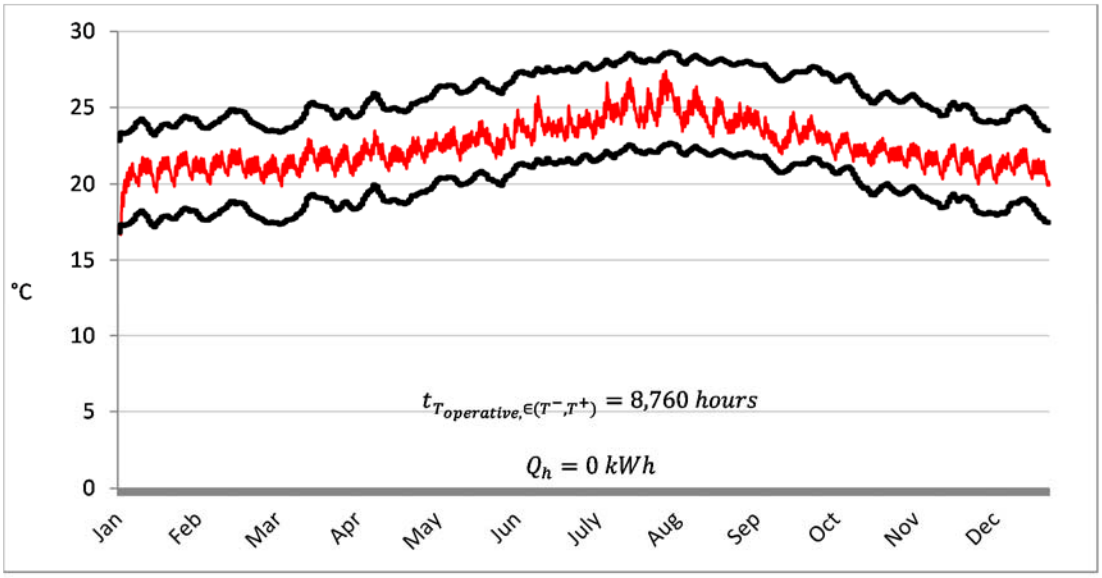


Figure 63 Passive house (2040 weather files)

7.3.1 *Category III implications*

Controlling the base model building to a Y value of 3 offers energy reductions of 69, 68 and 59% for baseline, 2040 and 2080 weather files respectively. These represent energy saving improvements of 30, 31 and 28% over Y=2 values. However the human comfort dimension of space control does not comply with the best practise standards set by CIBSE Guide A as using current weather files a minimum temperature of 16.5°C occurs with the average of the heating season being 17.7°C (table 6).

Satisfactory wintertime zone temperature within the free-float passive house simulation is aided by the high internal IT and equipment gains. Summertime free-float temperatures are moderated by the cumulative effect of natural ventilation, substantial exposed thermal mass and night purge strategies (reflecting the actual operational nature of the building). However in locations where the immediate surrounding renders natural ventilation impractical (e.g. due to traffic noise, pollution or security) summertime gains will build to a much greater magnitude. If coupled with a warmer local climate, such as those found in southern Europe, the combined effects will entirely change the economics of building fabric and core design, as well as energy statistics presented here. While generic conclusions cannot be drawn from a single study, the combination of adaptive comfort, passive house fabric design and passive methods of summertime cooling offers the potential to reduce a commercial building energy demands in the North East of England, even when the warming effect of climate is taken into account.

7.4 EN EU 15251 considerations

7.4.1 Energy

To allow for a meaningful overall comparison of operational carbon cost, the equivalent CO_2 contents of 0.18521 kg/kWh and 0.46002 kg/kWh representing gas and electricity are used to generate graphs 65 and 66.These values are published by the UK Department of Energy and Climate Change for 'used' energy in 2012 [137]. These two figures show the equivalent operational carbon results for the series of trials discussed in the previous section. In the target building where IT-related electrical demand is the dominant cause of carbon footprint, adaptive comfort's carbon reduction potential is less tangible to see (Figure 64).

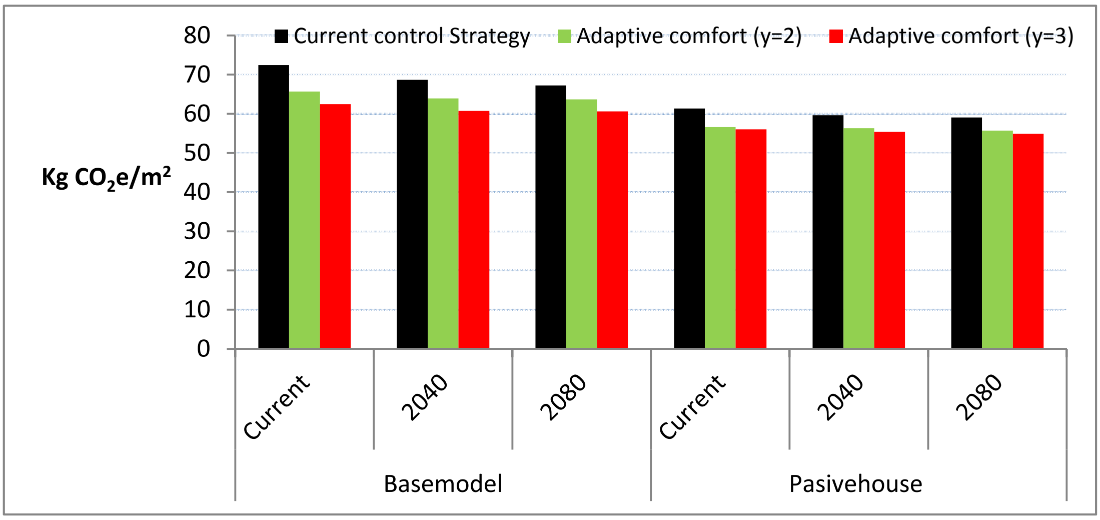


Figure 64 Total equivalent carbon emission in the office space under various control regimes and weather files

If however the effect on the building's heating-related carbon footprint is examined in isolation, adaptive comfort's impact on carbon reduction becomes more visible (Figure 65). Within a heating dominated climate similar to Britain, adaptive comfort therefore offers its carbon reduction potential mostly in the form of heating demand reduction. This reduction in heating demand also has implications for primary plant design by removing the need to over-size heating plants. Conventional HVAC design practice is guided by accounting for 'worst case scenario', inevitably over-estimating plant duties in turn leading to plant oversizing. Informing the plant design in the context of adaptive comfort can therefore eliminate oversizing and reduces the initial building capital costs.

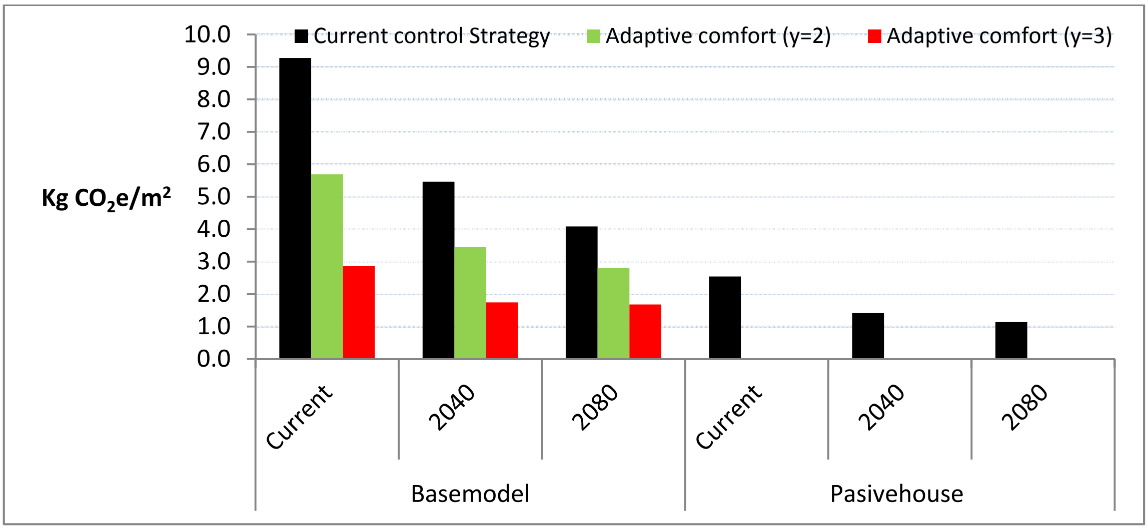


Figure 65 Equivalent carbon emission in the office space (heating only) under various control regimes and weather files

7.4.2 Comfort

Adaptive comfort has primarily been deemed suitable for naturally ventilated as well as mixed mode buildings [68, 69], although the standard is being developed to encompass all building types. The comfort analysis in this section is however undertaken with no reference to building type (i.e. base line or passive house design) as the adaptive comfort bands are purely a function of the weather data under examination. Table A.2 of 15251 (2007) recommends the following operative temperatures for the heating (min) and cooling (Max) seasons:

- min 21°C – Max 25.5°C (building category I)
- min 20°C – Max 26°C (building category II)
- min 19°C – Max 27°C (building category III)

In contrast, summary statistics for lower and upper bands developed in this study using three sets of weather files are set out in table 6.

		Heating season		Cooling season	
		min	Ave	Max	Ave
Y=2	1970	17.5	18.7	26.5	24.8
	2040	17.9	19.4	27.5	25.5
	2080	18.2	19.8	27.7	25.9
Y=3	1970	16.5	17.7	27.5	25.8
	2040	16.9	18.4	28.5	26.5
	2080	17.2	18.8	28.7	26.9

Table 6 Adaptive comfort zone temperatures for baseline and future weather files

Controlling the environment using the less stringent Y=3 value leads to average space temperature of 17.7°C (with a minimum of 16.5°C) for the baseline weather file. Hence on average the heating season's space temperature is 1.5°C lower than that stipulated by table A.2 of EN15251. Similarly future weather files produce heating season average temperatures which are 0.6°C and 0.2°C lower than the recommended value of 19°C. The magnitude of this deviation stays the same for bands constructed using Y=2 as the recommended value and summary statistics increase by 1 unit. Summertime temperatures however fall within the recommendations for all scenarios. Recall from formulae 22 and 23 that following a week of freezing temperatures (i.e. $\bar{T}_{ao} = 0$) the lower band zone temperature ($T^{-}_{operative}$) would be just below 17°C. Such wintertime climatic condition is quite probable in the region studied here.

		Simulated [1] (%)	Recommended [2] (%)
Y=2	1970	16.5	10
	2040	13.1	10
	2080	12.1	10
Y=3	1970	22.1	15
	2040	19.5	15
	2080	17.1	15
[1] Averaged over the heating season			
[2] static figures outlined in EN 15251 (2007)			

Table 7 Simulated versus recommended PPD values for historic and future weather files

EN15251 stipulates that category II and III buildings will have PPD values of less than 10% and 15% respectively. This index is a mathematical model of human thermal physiology calibrated against the warmth sensation reported by people during experiments in climate controlled spaces [10]. Current best practice standard (as stipulated by CIBSE Guide A) states that good design attempts to achieve a PPD of no more than 10%. Using Fanger's PPD method within EnergyPlus, PPD figures for 1970, 2040 and 2080 years were constructed and averaged for the heating season [100]. These values are outlined in table 7. Quite clearly hourly operative adaptive comfort temperatures derived from formulae 22 and 23 produced lower temperatures and PPD figures than the static recommended values outlined in the EN15251 standard. This is partly due to the cold nature of the region that is under study. Also PPD index has not always been found to agree with the sensations reported in by people in field studies of thermal comfort [138, 139].The comfort related observations made here could therefore be summarised as below:

1. Adaptive temperature bands (particularly those constructed using Y=3 value) represent a major departure from CIBSE Guide A recommended bands (21-23°C for winter and 22-24°C for summer in an open plan office) [10]. In this respect adaptive comfort (as stipulated by EN15251) is not compatible with PMV-PPD model (as defined by CIBSE Guide A).
2. We observe that, when using UKCIP09 weather files for the North East of England, the best practice environmental condition stipulated in CIBSE Guide A are only achieved by EN 15251 building category I. Types II and III buildings produce minimum and maximum temperatures that are in disagreement with CIBSE Guide A recommendations.
3. Similarly when using UKCIP09 weather files for the North East of England, the static recommended values within EN15251 are achieved by EN 15251 building category I for all instances. Types II and III buildings only comply with these recommendations in cooling season.

A possible solution for bridging the gap between the mutually exclusive nature of adaptive comfort and PMV-PPD could be arrived at using extensive field studies:

1. If field trials prove lower band adaptive comfort values to be unacceptable to the occupants, a minimum threshold value (derived from static recommended figures within EN 15251) could replace all instances when weather-derived adaptive comfort figures fall far short of these recommendations.
2. If field trials find wide censuses on comfort from the occupants, PMV-PPD models should be replaced in favour of adaptive comfort values.

It is critical to remember that adaptive comfort is deemed for free-floating building whereas PMV-PPD model was derived (and is targeted at) air-conditioned buildings[67]. A critic of the analysis applied here therefore might be that treating adaptive comfort results using PMV-PPD values are not suitable.

1- This enables a direct comparison between the two proposed methods.
2- It offers another sphere of discussion on how and why a combination of thermal and environmental guidelines are viewed suitable in an air-conditioned space but deemed unsuitable (or inapplicable) for a naturally ventilated or mixed mode space.

EN 15251 specifies (but does not require) how different building categories for different indoor environments could be selected. This is left to national calculation methods and project specification. Similarly this standard needs to be expressed differently in different climatic conditions, as adaptive comfort temperatures as low as 17°C and as high as 30°C were found to be acceptable in different countries [22].

During the audit conducted in Chapter 5, 97% of the occupants were happy to work in slightly colder wintertime environments if substantial energy savings were to be achieved (but only 40% were prepared to experience higher summertime temperatures). Other research work has produced evidence that the green image of a building has a positive impact on building occupant's perception [140, 141] and energy reduction attempts leads to a greater tolerance of wider environmental conditions domestically [4]. Equally (and if communicated clearly) energy saving measures (such as those stipulated by EN15251) might make the occupants of an office more accepting of sub-optimal indoor temperatures as ultimately the human thermo-regulatory system is capable of an infinitely greater degree of adaption to the environment than building controls are of regulating the environment. This further illustrates that a range of field trials over a wide geographical and climatic condition is required to gauge the occupant acceptance in a systematic and methodical way. This could pave the way for wider implementation of adaptive comfort standards in commercial buildings.

7.5 EN EU 15251 and Passive House

Passive house design - when combined with adaptive comfort - entirely remove the heating load requirement for the target office building in this study. The increased wall insulation required for passive house model claims an additional 1.24% of the gross internal office space. From a practical point of view building to passive house standard is also beyond the construction capability in many parts of the world. There are also concerns that super-insulated buildings with high internal gains run the risk of over-heating which in turn makes energy intensive refrigerant-based cooling necessary. To have a complete picture therefore a lifecycle analysis is required that takes the additional embedded carbon of the passive house building fabric into account. Principally the reason why passive house model satisfies adaptive comfort in its free-float condition is heavy-weight design within a supper insulated shell. Both the base and passive house model of the target building incorporate 3500 tonnes of high density concrete and brickwork within the insulated envelope. This 'exposed' internal masonry offers a total thermal capacitance of about 3.4 GJ. Additionally this thermal mass is 'close-coupled' with the heating and cooling systems as ventilation air enters the building via integrated floor concrete ducts. This strategy has gained wide architectural audience and following several field studies is also recommended by professional bodies in the UK [82, 83]. High thermal anchorage, when combined with solar control glazing (the building glazing G value is 0.38), brise-soleil and natural ventilation works effectively for the building under study to avoid summertime overheating. A more comprehensive approach needs to investigate the imbedded carbon dynamics too.

7.6 Limitations, recommendations and further studies

The purpose of this work has been to investigate the effects of adaptive comfort as a control strategy in an audited office building. The selection of future weather files necessitated scaling down to 99 percentile years from a collection of 3000 annual forecasts, leading to the collapse of the distribution of possibilities which is intrinsic to the uncertain nature of long term weather predictions. Each building model simulated in this work contained a detailed HVAC and operational description and with a total of 131 separate spaces over 5 floors, preparation and simulation of each scenario exceeded 120 minutes.

Performing this work across the full range of climate projections therefore would have been beyond the available resources. Further the results of this work could not have been presented in a clear manner, or completed within reasonable time horizons, had such downsizing of the entire range of future weather possibilities not been undertaken. We reiterate that there is yet no established framework for carrying out climate change risk assessment on building stock.

In order to account for the measurement error within the calibration exercise, authors have also made the assumption that the gas and electricity meter's accuracy within target building complies with SI 684 (1983) and IEC 62053 respectively as extensive attempts to obtain meter compound error margins from manufacturers failed to produce any results.

7.7 Summary

Adaptive comfort demonstrated the potential to substantially reduce energy consumption in buildings constructed to recent UK building regulations (Part L 2006) and passive house standards. The climate warming trend particularly makes this standard more relevant since adaptive comfort permits higher summer time temperatures. Wintertime values derived here were lower than reference best practice standards used but do not violate World Health Organisation or Health and Safety act minimum value of 16°C [105, 142].

Therefore any attempt to introduce the concept of adaptive comfort in (particularly air-conditioned) buildings needs to be mindful of the occupant acceptance issue; by briefing the building users on the link between fluctuating external dry bulb and internal operative temperatures. To this effect a series of field studies of adaptive comfort in real air-conditioned buildings across a diverse geographic and climatic area can provide invaluable insight. Such studies could also examine how financial incentives, involving the occupant in the management of their environment (i.e. deploying voting mechanisms), energy feedback interfaces and regulatory forces might impact on the success of adaptive comfort implementation. The HVAC control engineering needed to deliver space conditioning as a function of the outdoors weekly running mean temperature are already available and therefore the implementation of this standard to buildings is within the reach of modern engineering practices. Such control regimes presents no problem to heating plants (particularly with variable volume primary circuits) but refrigerant-based cooling systems require greater attention as flow temperature and pressures are more critical. This partly explains why EN 15251 primarily targets naturally ventilated and mixed mode systems.

Another potentially radical outcome resulting from adaptive comfort standards in air-conditioned buildings is the design of HVAC systems. In the UK, CIBSE method of plant duty calculation recommends the design to satisfy test reference year (TRY) weather files. These files set out several different levels of extreme weather years that a particular site has historically endured. Although this prepares the building to cope with the worst case scenario, it could also result in the cooling (or heating) plants operating regularly at part load (causing efficiency penalties). As adaptive comfort is informed by external temperatures, the duties imposed on HVAC plants will not be affected as greatly by the extremities of the weather, which in turn brings about a plant working load that is closer to steady state (moving in the same direction as outdoor temperatures). It will have favourable consequences for plant controllability, reduced wear and tear, prediction and management of thermo-electrical loads and micro-generation technology incorporation.

This chapter examined adaptive comfort in the context of a modern office building. The predominantly older stock of existing office buildings in the UK would benefit even to a greater extend from this standard as lower levels of fabric insulation and loose air-tightness requires more energy input to achieve close environmental control in these buildings. The following considerations could further facilitate a wider adaption of adaptive comfort in buildings:

1- Adaptive comfort needs to be fine-tuned in different countries to better reflect the prevailing local situations.
2- Where possible, a more relaxed cultural and corporate induced clothing norm can further facilitate the acceptance of this standard.

Seeking to create single buildings that are very efficient is of little value to the building design community and wider public; and in among ways to reduce building emissions scalably and affordably, EN 15251 offers a workable and implementable solution. With its comfort-related weaknesses addressed, this standard offers energy reduction potentials that can be replicated across markets, sectors and even globally.

Chapter 8 The Control implication of Adaptive Comfort

8.1 Introduction

In this concluding chapter of this work we examine historic and current perspectives of building control technologies at plant and management levels to identify best candidates for automation of a building controlled using adaptive comfort guidelines as set by EN 15251. Building control techniques that have moved beyond proof of concept and into the real-world application are examined in greater detail. New concepts such as occupancy-based controls and web-based demand-side controls are also introduced and discussed, with a focus on the transformational effects of wireless sensor networks, web-based diagnostics and occupant sampling tools.

Increasingly concepts such as smart cities, soft infrastructure, wearable technologies and Internet of Things are dictating the dynamics of the next generation of building controls; as it will no longer be efficient to control buildings as free standing islands in isolation from other civic activities, namely power generation, storage and distribution and city transport. An industrial survey conducted in section 6.10 implies that HVAC industry has a tendency to continue with the conventional control techniques, which leaves the digital technology innovators to pioneer the move towards intelligent buildings and ultimately cities.

The review of current research also shows a rift between the scientific work conducted in building controls and the HVAC industry practices. Techniques such as Artificial Neural Network and Reinforcement Learning have seldom moved from research community labs to be taken up by application designers in HVAC and BAS industries. The industrial survey conducted here further endorses this realisation.

8.2 Managing energy and environment

Holistic control of buildings is a multi-dimensional task. It requires control mechanisms that can provide acceptable levels of comfort for the occupants, while minimising the energy use and most importantly perform robustly under a variety of fluctuating conditions. The conflicting nature of energy conservation and the delivery (or sustaining) of human comfort also makes optimisation techniques necessary in order to guide the system to the best possible compromise [143].

The science of human comfort in buildings is mainly dominated by its thermal aspect, although the perception of comfort has further dimensions (i.e. satisfaction with auditory and visual environment, privacy, etc. [10]). Metrics of thermal comfort in buildings continue to be shaped by the work of Ole Fanger. His work is also widely adapted in publications and building design guidelines [10] i.e. ISO 7730. In his original paper [11] he defined thermal comfort as a thermally neutral state in which the occupant doesn't know if they prefer a higher or lower ambient temperature level. However, he stipulates that there will be a dissatisfied minority of 5% even in the best thermal environment. This has encouraged a great deal of research into attempting to optimise human comfort and energy consumption [12]. It was noted in section 2.6 that Fanger's 'static' definition of thermal comfort was recently taken into a dynamic, weather dependant realm by the theory of adaptive comfort.

Building performance is widely reported in terms of annual energy footprint per unit area (kWhm^{-2} per year)[10]. Recent updates of EU rules (also implemented in UK building regulations) asks for the examination of buildings in terms of their carbon footprints (kg CO2/(m^{2}.year)[144]. Energy conservation at its simplest can therefore be defined as minimising CO2 emissions. Occupant satisfaction however is more convoluted to define and achieve.

Despite expecting our buildings to perform better continually, building design remains dominated by static control parameters, whereby at early stages of design (and with little knowledge of the building in operation) a number of control parameter sets are decided by the architect and engineers [145]. These initial assumptions seldom remain adequate, particularly given the fast pace of change currently. Emerging technologies, in particular wireless sensor networks, improved data storage capabilities and intelligent controls hold the promise of resolving this issue. Intelligent controls have the potential to address disadvantages of conventional methods by collecting information from sensors to learn and predict what a building might require rather than relying on pre-determined set-points and standard assumptions [146].

Within the overview of building control techniques presented in this chapter, first we examine the historic and current methods of control, and seek to report if the building design community is closer to the adaption of full building automation systems as standard. Later a survey of building control design professionals reports on the level of uptake of technologies considered as most promising within the literature reviewed. Research into the most promising future methods seeking to integrate human comfort and pervasive sensing are identified together with an outline of their strengths and weaknesses.

8.2.1 Historical background

Little has been written on the history of control methods used in buildings, and the available materials are inconsistent. The progress of building control has also been heavily influenced by attempts to refine control methods in maritime and aviation applications. This is despite the broad segregation of controls into positional and process. Positional tends to belong to defence systems, where controls seek stability despite very rapid rates of change, whereas process has evolved in petro-chemical and HVAC industries and within systems which are for the most part very slow, with moderately fast activities being the exception.

The development of controls have been defined in stages by Stuart Bennett [147]. A degree of overlap between successive generations is inevitable; with the more recent developments meriting finer examination.

First generation – Early control (to 1900) dealt with temperature, pressure, liquid level and the speed of rotary machines. The steam engine governor, electric relay, thermostat and spring-biased solenoids were significant developments of this era.

Second generation – Pre-classical (1900-1935) characterised by the design of feedback controller systems for voltage, current and frequency regulation. Ship and aircraft steering and auto-stabilisation directed much of these efforts. Negative feedback, and work on fixed-parameter modulating controllers and pneumatic control systems were major outcomes.

Third generation – classical period (1935-1950), heavily influenced by refining different weaponries. The collaboration of mechanical, electrical and electronic engineers led to the recognition of non-linear, stochastic and sampled data systems. Optimum start control systems began to take shape; as did central station supervisory and 'moving-parameter' modulating controls and monitoring systems.

Fourth generation –beginning of modern controls (post war). High levels of scientific progress resulted from the need to control ballistic objects. The advent of digital computer and solid-state devices. The beginning of 'state-space' approach, followed by full DDC; self-tuning and multi-variable optimal controllers. Computers allowed data collection online for optimisation and supervisory control.

Fifth generation – (1970's onwards) begins with the commercial availability of computerised energy management systems, increasing role of microprocessor and application-specific DDC. Open Protocols are introduced; and the popularity of internet and wireless sensor networks begin to shape horizons. Adaptive and intelligent controls using predictive models and artificial intelligence (AI) are more recent examples of this era.

The first three generations of controls had applications beyond building controls and only the fifth generation began to be fully implemented into the building environment control. Future generations of controls are predicted (on a micro level) to be most influenced by digital innovation and mobile communication devices. AI in buildings exploits online information to move closer to real time (and optimised) performance. Moreover HVAC controls will merge closely with other aspects of building operation, most notably occupancy detection. On a macro level the concept of smart cities is set to make 'soft infrastructure' an inevitability, where information from individual buildings will form a web-linked mega-network that enables smart grid to oversee the generation and storage of power optimally on regional and national scopes, giving full realisation to demand side management and renewable integration [148-151].

8.3 Control strategies

Buildings experience a variety of internal and external disturbances, and the manifestation of these disturbances are most pronounced in the thermal domain. The primary role of building control has therefore been to regulate the thermal environment [152].

All control methods essentially attempt to lessen the dependence on human judgement and intervention, and to achieve (or optimise) one or a number of objectives according to certain criteria [153]. Every building contains one or a number of internal spaces with diverse degrees of service requirements. At any given time there are various control mechanisms acting at several different levels within any building (i.e. supervisory and local loop levels). As more building elements are now automated, control systems increasingly perform a supervisory role to enable the integration of different tasks. For instance complex buildings with designated energy centres (particularly with thermal or electrical energy storage) could perform sub-optimally unless a centralised control approach is taken. Such central approach is only possible through computational methods (at times a hybrid of several methods acting as various autonomy levels). The following two sections provide an overview of controls at filed (loop) or management (supervisory) levels.

8.3.1 Control at field level

Designing effective control entails breaking the overall process into smaller sub-systems each delivering a part of the process. Salsbury, T.I [154] divides the HVAC controls into three main subsystems:

1- Central plants (i.e. boilers, chillers and cooling towers) that produce cooling or heating.
2- Air Handling Units comprising many components configured to deliver constant or variable air volume (CAV or VAV) to the space.
3- Terminal units, for instance VAV dampers or a thermostatic valve.

Terminal units are mostly controlled by a local-loop operating either a modulating or switched mechanism. Central plants (as well as modulating terminals) predominantly employ PID control, with derivative action often disabled (as it responds aggressively to small changes). Historically the low-cost nature of the building industry meant that control systems were set up with a minimum number of sensors; with data collected and fed-back at long intervals. This of course would not present a major problem because of the sluggish nature of response in buildings. Nonetheless this approach does not lend itself to more advanced controls or diagnostics. One other problem arising from inadequate sensor deployment is that a badly performing loop in a building is difficult to detect and re-tune as other loops might compensate (i.e. a malfunctioning AHU damper could be compensated by central plant adjusting the air temperature or central fan speed). In reality problems such as temperature offsets, oscillatory and sub-optimal control performances are generally tolerated in buildings because of the non-critical nature of space conditioning (compared to chemical processes, aviation or defence applications).

Seen from a high level of abstraction, building (and HVAC) control is a function of varying weather conditions and dynamic loads. The research community has made considerable effort to address the nonlinear and time variant nature of HVAC plants, in particular the issue of efficiency penalties at lower plant loads. Mathematical modelling of plants are the main test-bed for HVAC control strategies although since theoretical modelling carries major limitation, further work has also been done on empirical model fitting to assist dynamic model analysis, though results of such studies tend to be problem-specific [155-158]. Developments in modular simulation programmes have addressed problem-specificity; although most programs describe the plant components in steady-state or quasi-steady-state modes [159, 160]. This makes them suitable and computationally efficient for low frequency dynamic analysis but unsuitable for high frequency disturbances which are essential in solving control problems.

The non-linear dynamics and time-varying characteristics of HVAC controls set it far apart from other process control types [156]. An added layer of complexity is the global system optimisation. This is to say that apart from the changing behaviour of HVAC plants with load variation, at any given load there are numerous opportunities for optimisation of the system. For instance increasing cooling tower fan speed means more power consumption by fans, but it reduces condenser load by delivering cooler inlet water to the condenser, similarly higher chilled water temperature means lower evaporator energy use but higher pumping duties as the building cooling demand will require greater chilled water flow [161]. These situations are further complicated when several primary plants (chillers/boilers or CHP systems) are to be sequentially controlled to run at optimum points. Therefore ultimately ‘global’ optimisation is required which makes computational interventions necessary. Such global optimisation would only materialise through an integrated control at management level.

8.3.2 Controls at management level

Up until the 70's the human operator would supervise all aspects of a building's operational needs. Although fuel efficiency has always been important particularly for commerce, still few organisations had any form of energy monitoring (or targets) and ultimately 1973's oil crisis gave birth to energy management as a separate discipline; with 1979's oil crisis making energy management imperative for both the commerce and governments[162].

The 80's and 90's were the key periods in the development of building energy management systems (broadly termed BEMS). Evolving from early, cumbersome and expensive systems, it was ultimately the falling cost of computer technology and on-board HVAC electronics that created the leaner and advanced systems that are available today. The increasing building complexity has progressively brought more controllable elements under a single 'automation' system too [163]. In addition to HVAC plants, modern buildings can incorporate active facades (i.e. smart glass, shading systems, automated windows etc.) and/or local generation (i.e. solar collectors, fuel cells, CHP etc.). Advanced building materials, aided by the science of human-computer interaction is promising to turn building envelopes into dynamic and energy efficient climate moderators, as well as enabling it to interact with the building occupant [164]. Human comfort (conventionally a static system target) is now used in research as a dynamic system input to inform HVAC operation [165, 166]. Similar to other disturbances effecting building management human comfort is time-varying and the rate of change in the perception of comfort in a building is different from the rate of change of external factors [22].

In future, it is possible that building automation and communication networks will integrate a broad range of functions including access and security, fire systems, transport (i.e. lifts) and renewable supervision. Modern standards (such as BS EN ISO 50001:2011) also increasingly call for integrated building automation systems [167]; a demand that is supported by research pointing to notable operational advantages when automation and integration strategies are in place[153, 168, 169]. Falling costs of sensing technology, data processing and storage capacity will also mean that control devices will be able to execute substantially more complex control algorithms. An additional benefit will be that intelligent buildings can perform functions geared more towards analysis and diagnostics than mere controls [154].

8.4 Control types

For brevity, and in order to maintain relevance, coverage of only the control methods that are still deployed is provided. These includes classic controls (earlier classified into the third generation) and computational controls which spread over fourth and fifth generations. This overview however does not attempt to be an exhaustive survey on the topic and any omission of related works is purely unintentional.

8.5 Classic controls

8.5.1 Binary

Binary (on/off) control has traditionally been used widely for small systems in buildings, in particular for temperature control via thermostats. Quite clearly this method only suits applications where no output modulation is sought. Characterised by two switching points and a deadband in between; this mechanism is prone to hysteresis and overshoots [170]. In its basic form, binary temperature control also produces a deviation from the set point that requires more sophisticated controls to rectify. One solution could be to use a switching algorithm such as pulse-width-modulation to generate a pulse train. This approach can be taken further to include both pulse width and pulse frequency modulation which is easier to set up for the practitioners [171].

8.5.2 PID

P, PI and PID are used for modulating continuous controls; therefore clearly only applicable to plants whose output is capable of modulating. Although developed as early as 1910 for ship and aeroplane automation, remarkably still 90% of industrial controls continue to use them [172]. PID actions relate to present (P), past (I) and future(D) [173]. Proportional (P) controller simply corrects the error by multiplying the deviation from the set point by a constant that is proportional to the magnitude of error. P controllers suffer from sustained offsets (persistent error between the set-point and prevailing value) that can only be rectified by the introduction of integral (I) action. Integral further adjusts the control signal by including the integral of error with respect to time, so as long as an error exists, the integral controller will continue to adjust the signal. Adding integral action clears the offset, but it could slow the system down and also reduce stability. Differential (D) action is therefore added to further complement PI in that it corrects the low frequency errors accumulated by integrator action. Differentiator acts on rapidly changing error values and ignores the slow changing values (i.e. it acts on the 'rate of change of error', hence only rapid errors activate it). Derivative controls are however hardly used for the control of building plants. It's worth noting that P controllers are also used in isolation with either I or D components (PI or PD controls).

For PID controls to perform optimally; various settings and constants (i.e. gains) need to be selected judiciously. This presents a problem given the nonlinearity of all HVAC systems; whereby the system can be set up to work to perfection in one part of the operational range (i.e. full load) but responds badly at others (i.e. part load).Ziegler-Nichols (Z-N) technique is the classical tuning approach though it suffers long testing time and limited performance. The wide (and continuing) application of PID has sustained the development of many PID tuning techniques and associated soft and hardware packages [169]. Several auto-tuning techniques have been proposed; for instance relay-auto-tuning [174], open loop step tests [175] or a combination of these [176]. A number of building automation companies offer products that incorporate these ideas [154]. PID has a wide scope of application at all levels of controls, from supervisory down to local loop level [177].

Academic research into PID has however entered a state of diminishing returns and the trend has now moved in to the integration of PID with computational control methods to improve stability and response time [178-180]. A single example is PID with Adaptive algorithms (covered later).

8.6 Computational controls

Research remains active in proposing replacements for classic controls, including some hybrid solutions which still retain elements of the classical methods. Building control industry has on the other hand become used to the strengths (and understands the weaknesses) of PID and considers it an adequately tried and tested method. This partly accounts for the reluctance to take up new proposed control methods. The robustness of some of the alternative techniques can however be difficult to guarantee, and some require additional parameter specification that increases the set-up time. Additionally some methods are computationally demanding for the typically low cost building controls design [181]. Nonetheless the level of supervision required within modern buildings, the non-linearity problems and global optimisation makes the adaption of more advanced methods increasingly inevitable. The following techniques outline some of the major alternative schemes.

8.6.1 Supervisory method

Supervisory control was developed for industrial automation in late 1990s, and because of its potentials it provided a blue map for scientific research into its wider application [182].

Over the past two decades, the collection of large volumes of on-line operational data, together with growing integration of BAS software has enabled the development of supervisory (and optimal) control strategies. In its most comprehensive form, this approach can find the optimal solution (operational mode/setpoints) for a system equipped with energy storage (thermal and electrical) while also taking into account the carbon and monetary costs of electricity and gas [95]. It is important to note that supervisory method encompasses a variety of techniques often involving training methods (Such as artificial neural networks, fuzzy logic or genetic algorithms). Supervisory controls are sub-categorised into the following forms:

8.6.1.1 Model-free method

Supervisory control systems could either utilise a model of the targeted system (i.e. model based) or be model-free; where expert systems and on-line learning techniques are applied to guide the system to its optimal point, or enable the process to function optimally. Although each version can take several forms, supervisory control essentially suits complex control problems whereby operating points need to be updated constantly to find the optimum point under changing conditions.

Model free supervisory control (also referred to as expert system) utilises knowledge harvested from online data streams to determine the optimum settings for system operation; therefore in essence it attempts to mimic the behaviour of a human operator and as a result, it can even work with ‘incomplete’ data sets (although an accuracy penalty ensues). One particular example of model-free supervisory controls is reinforcement learning (RL) technique; where the control system tries to improve its behaviour as a result of previous actions. Although reinforcement learning requires no prior knowledge of the system, at times the learning process could be unacceptably long, making them impossible to implement in practice [183].

8.6.1.2 Model-based method

Model-based supervisory control takes the optimisation to a more advanced level by both selecting the set-point and ‘predicting’ the optimum time for a set-point change. An illustration of this could be a dynamic model of both space and chilled ceiling plant that was successfully developed within Hong Kong Polytechnic University. A supervisory algorithm was used to self-tune the set points every 10 minutes to achieve both comfort condition and energy efficiency [184]. Quite clearly this method is suited to more complex systems where updating operating points can yield higher efficiencies, notably central chiller plants. This was illustrated in a study where simplified models of major central chiller components were used as performance indicators using genetic algorithm. The virtual system achieved cooling energy reduction of 0.73% to 2.55% [185]. Essential to the success of model-based supervisory method is system models with simplified structures, high prediction accuracy, easy calibration and low computational costs [95].

A further demonstration of capability is a study of an optimal model defined by several operational constraints developed to control room heating. The model is then solved by an optimisation technique in real time, using dynamic programing and on-line simulation. The system included a weather predictor that forecast temperature and solar irradiance data between 12 to 24 hours in advance. This approach was put to test in a ‘solar room’, where high thermal capacity concrete floors were deployed to absorb and store solar energy. An underfloor heating system complemented solar heat. The results showed savings of 10 to 27% in energy cost and the capability of the supervisory system to arrive at global optimums [186].

Supervisory control could also be a hybrid of model-free and model based techniques, as well as building on other approaches such as performance map data, artificial-neural-network (ANN) or empirical-relationship. A detailed breakdown of these methods is provided by S. Wang & Z. Ma [95]. Their work concludes that hybrid supervisory control methods suite practical applications best, as detailed model-based methods are not computationally efficient. Model-based controls in their most comprehensive form can accommodate various performance optimisation techniques aimed to satisfy several objective functions. This is mostly realised by the unification of building simulation packages (e.g. Energyplus or TRNSYS) with generally an independently developed software-based algorithm (e.g. in Matlab or Genopt)[112]. At present, leading scientific efforts seek to perform multi-objective optimisation task which seeks a solution that lies in the trade-off between a number of conflicting design objectives (i.e. human comfort and energy consumption).

8.6.2 Reinforcement Learning (RL)

Initial control policies generated to oversee the operation of a complex building could prove suboptimal as the building moves through different phases of its life. RL tools provide a solution by assisting self-calibration of control parameters and in more advanced forms have been applied in conjunction with ANN or Fuzzy logics [187]. There are three main categories of RL method, namely Dynamic Programing (DP), Monte-Carlo and Temporal Difference (TD) [188]. TD in particular can learn from the environment on a step by step base and hence doesn't need a model of the environment [189].

RL however suffers from a long training process. The learning parameters, the dimensionality of the state and action space all combine to hinder the ability of RL controller to find the right policies [183]. RL continues to feature more widely in neuro (and computer) sciences as opposed to applications in building controls [190]. The most recent efforts are limited to employing RL to tune a supervisory control for a building energy system with respect to comfort [189, 191], and to develop optimal controls for passive and active building thermal storage inventories [192-195]. RL however remains distinctly under-reported in building control literature.

8.6.3 Fuzzy logic (FL) controls

FL resembles human thought process in that it is capable of dealing with partial truth (whereas conventional binary variable sets are either true or false).

Consequently FL is capable of working with uncertainties in multivariant control systems more effectively. Except for some early attempts [196] FL controls are rarely used on their own for building control applications. Most successful applications entail the integration of FL with PID, ANN or other adaptive techniques [197]. FL has the same scope of application as PID where visual and thermal comforts as well as natural ventilation management were reported to improve through its application [198-201]. In situations where comfort expectations of building occupants change as a function of time, FL control can be coupled with pervasive sensing so that a building learns to adapt to new preferences or new occupants. Reports show notable results when FL was applied to control energy and comfort in buildings [202, 203].

Hybrid methods where FL is combined with other techniques have also been examined successfully. Figure 66 is a comparison in performance improvement when first FL is used to schedule the PID controller gain coefficient (i.e. F-PID) , and later genetic algorithm (GA) is introduced as a means to optimise the efficiency of a dynamic energy system (i.e. GA-F-PID) [197]. The latter achieves the best stability control with practically no oscillation or overshoot.

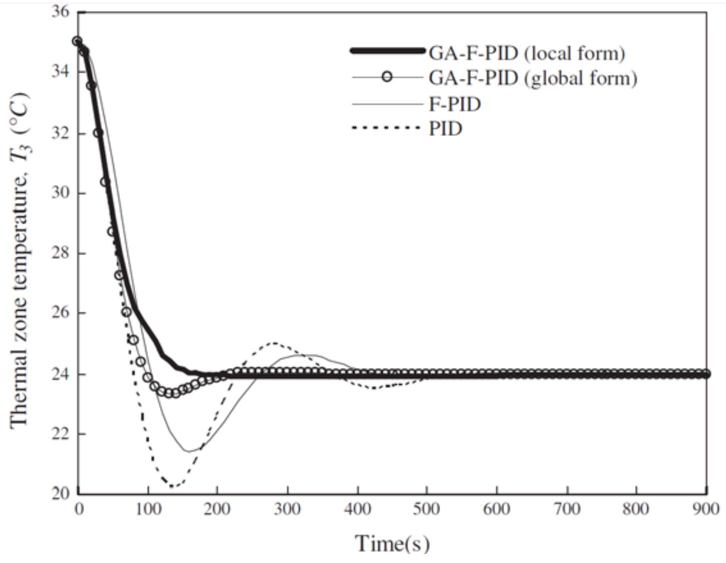


Figure 66 Comparison of transient thermal zone temperature response for PID, F-PID, and global and local form GA–F-PID controllers

FL is widely used in industrial automation and HVAC controls [204] and the fusion of FL with generic algorithm allows successful control of more demanding HVAC applications such as VAV and VRV air-conditioning systems [205, 206].

8.6.4 Robust controls

HVAC plants are selected for the maximum load they need to serve, although for most of their working life they will be operating at part loads; leading (often) to efficiency penalties and control problems. Robust control aims to address this problem by algorithms that deliver disturbance attenuation and stable operation across the full operational range [155, 207]. $H-\infty$ optimisation synthesis has proven successful in constructing robust controllers where a reference signal is asymptotically tracked [208], however this technique require plant and space uncertainty definition to form fixed (or variable) parameters and also contain high-order mathematics, that can make them difficult to implement from a numerical point of view. This method therefore is suited to the supervisory levels of control, where system nonlinearity and model uncertainties are to be addressed. For instance when combining demand-controlled ventilation with an AHU economiser, a transitional instability ensues at the point of switching between the two modes that was overcome with the robust method [209, 210].

8.6.5 Artificial neural networks (ANN)

ANN are the mathematical representation of biological neurons. Borrowing from massively connected biological networks, this method can be deployed when partial analytical knowledge of the system model exists[211]. The learning ability of ANN has been used to chart the relationship between input and output data aiming for initially the prediction (of behaviour) and ultimately optimised control of systems. Examples of recent simulation-based attempts include the adaption of ANN to control a double skin façade [212], hybrid ground source heat pump operation [213] and building energy and comfort optimisation [214-216]. Within all these attempts the ANN carries out a prediction that is used to decide the next control action. ANN ability to construct relationship between multiple input and multiple output systems lends itself in particular to efficient energy management of complex AHUs at supervisory level [217-219] . Additionally hybridisation of ANN with other expert systems shows better HVAC control performance as compared to more conventional ANN approaches [220].

Although the building control applications industry has adapted some of the simpler approaches to automation and optimal scheduling, more complex approaches such as ANN remain at research stage because of the difficulties in guaranteeing convergence and robustness. Despite this reluctance, recent research work has reported improvements greater than 50% in the efficiency of HVAC systems, when ANN are used to develop 'predictive controls' for thermal management and comfort [221].

8.6.6 Agent-based controls

Agents (in the form of electronic devices) have been deployed and stationed strategically mostly in process automation and electronic engineering allowing flexibility and robustness. These are interacting, automatous and flexible components that have found widespread applications in extremely complex systems [222-224]. As large, dynamic and the multi-faceted nature of buildings mean that vast amounts of information are unfolding within and beyond the envelope all the time, building scientists have deployed agents-orientated methods to perform a variety of different tasks (coordination, switching, simulation and reporting) to enable comfort and energy management. Building-specific applications include developing agent-based management systems with PSW; a method interestingly inspired by collective movements observed in birds and fish [225, 226] in order to optimise complex non-linear control problems. One such (simulation based) study reports energy and comfort improvements over different operating scenarios [227]. Similar works found agent-based controls able to deal with energy shortage while maintaining comfort levels, as well as managing to optimise HVAC performance that included a VAV system [228, 229]. An additional feature of these systems is their open architecture that could enable retro-fitting into existing BAS to facilitate greater functionalities [230]. Autonomous agent based controls however understandably steer the system towards a more decentralised decision making model that makes it more difficult to predict the overall system behaviour. The current area of active research is now on merging and integrating agents' interplay to produce desirable 'system-wide' behaviour. With the exception of a few industrial process (and manufacturing line) control prototype demonstrations, real world performance of agent based systems, either in real buildings or even controlled laboratory condition is not yet available.

Increasingly however attractive features of a number of techniques outlined above are fused together to create hybrid systems to guarantee robustness, efficiency and adaptability. For instance on-line Reinforcement Learning (RL) was used in a study to 'tune' a supervisory controller. Essentially RL uses prior knowledge of the system generated by off-line fuzzy rule simulation and using the training process it also begins to correct erroneous off-line information [191]. This technique was reported to offer a much quicker training process of only a year to enable controlling a complex low-energy building system. HVAC&R applications continue to be dominated by PID, yet the need to address energy and comfort simultaneously has boosted research into optimal and adaptive measures using computational methods set out earlier.

8.7 Lighting controls

Lighting consumes between 20-45% of electricity demand in commercial buildings [231] (20% of UK electricity production is consumed by lighting [232]). Lighting control radically differs to that of HVAC, yet a brief coverage is provided in recognition of the ability of full building automation to unite HVAC and lighting controls.

Modern lighting control systems are a network of devices that includes luminaires, sensors and control inputs, connected either wirelessly or otherwise [108]. Society of Light and Lighting lists DALI and DMX 512 as the two most common lighting and control systems. DALI is a collection of up to 64 circuits controlled via the ballasts; whereas DMX 512 is capable of controlling lights as well as other equipment (as required in the entertainment industry). Leading designers predict that light emitting diodes (LEDs) and improved controls will provide the majority of light sources by 2030 [232-234]. Controls will primarily take the shape of dimming or off-switching in instances of no-occupancy using PIR, wearable devices, low cost sound sensors, and in rare instances biometric systems and closed-circuit television [235-240].

The success of artificial lighting design and control is inextricably intertwined with the daylight characteristic of each space [241, 242]. Local climate, topography, building and glazing type will all affect the success of daylight control, with daylight linked systems performing best in heavily glazed buildings with large fenestration on the equator side of the building [243, 244].

Broadly speaking, photoelectric lighting controls are divided into

1- On-off mode mostly equipped with differential switching, time delay or solar reset to reduce the number of switching operations [245]
2- Dimming action (or top up controls) that vary the lamp output to compensate the deficit luminance level from daylight.

The later will not be able to dim the light infinitely; also the dimming mechanism (mostly ballast frequency control) itself consumes energy. Therefore in well daylit spaces simple on/off controls may yield better savings [246]. A year-long field experiment in a south-facing office in Canada (Ottawa) found that simple on/off control system achieved greater lighting energy savings than continuous dimming controls [247].

Overall it is difficult to find united opinion on the potential savings of daylight-linked lighting controls, with scientific literature reporting a wide range of saving potentials which can be as little as 20% and as high as 92% [247-249]. Parallel to this however are post occupancy research showing that anticipated daylight-linked lighting energy savings are seldom realised in real buildings [247, 250] and some literature even going further to claim that there is no relationship between daylight availability and lighting energy reduction [251-255]; counting, among other reasons, the complex physiological reaction of the occupants to automated controls.

International Energy Agency in a recent publication [256] states that the key to obtaining the highest levels of building efficiency is integration of artificial lighting with occupancy and daylight information as well as active façade and ultimately HVAC systems. However little real world experience (or even research work) exists on such integration attempts, in particular full integration with activated façade control [257]. No clear evidence was found in scientific literature to report on efficiency benefits from integrating a daylight-linked lighting system with associated HVAC system in a building.

8.8 New concepts

In the next 4 sub-sections a review of recent development in building controls is offered.

8.8.1 WSN, web service and diagnostics

WSNs provide low powered energy efficient solutions for making extensive yet non-invasive networks within commercial and domestic buildings. These enable low cost and at the same time detailed monitoring of the indoor environment [22, 145]. WSNs have improved significantly in terms of bandwidth, reliability and cost effectiveness and are now widely adapted in areas such as aviation, agriculture, security and defence. However building application of such technologies has remained limited. This technology shows great promise for mapping and controlling energy flow in buildings, and in recognition of their potential, the industry has moved towards the standardisation of communication protocols [258].Transmission and interference challenges associated with WSNs are for the most part solved and further standardisation is underway to support greater adaption of them in the industry [259].

The network demand of WSNs could be imbedded with various internet protocols. Open Protocol web services emerged in commerce in 90s (with BACnet and LON as forerunners) and with its increasing popularity, www has now completely dominated BAS systems. Software development will therefore ultimately take BAS into its next chapter. It is expected that beyond HVAC, WSN will allow other information such as weather and occupant/operator data and process information to be integrated into the automation system [260].

In addition to mapping energy, WSN can offer their potential to occupancy detection, light and noise surveys and temperature profiling. A recent study successfully deployed WSN to demonstrate a surprising 10K temperature profile across air intakes of data racks within a data centre [261]. Real world data monitoring of this nature can enable better design and configuration of HVAC services and building layout. Buildings with very stringent indoor climate control can particularly be great beneficiaries of pervasive WSN deployment. Two separate studies for instance conducted continuous monitoring of the indoor air quality in both an art museum and a greenhouse to obtain a more exact climate control in these spaces [262, 263]. WSN, together with web services has the potential to transform the BAS domain from an information island to a real-time and interactive web-based service. BAS in itself will feature more fault detection and isolation thanks to web-enabled data collection and analysis trends [264, 265]. This is a particularly important development for both energy efficiency and critical mission engineering. Recent research demonstrated the ability of online diagnostic test (ODT) where abrupt changes in HVAC process were successfully detected, even when occurring simultaneously [266, 267]. However multiple stage faults, in particular when they happen simultaneously are more challenging to detect [268]. Similarly the identification of slow degradation and gradual faults are still a science problem [266].

Over the past few years the operating cost of buildings has risen dramatically (and continues to rise as a product of high fuel prices). This trend, together with the rapid evolution of smart systems, will justify higher capital costs for technologies that can bring about lower operating costs through optimisation, diagnostics and commissioning [269-271]. Industry leaders anticipate that the synergy between WSN and Web service will allow auto-tuning and self-commissioning to become the norm [87, 260].

8.8.2 Control strategies using elements of human comfort

Broadly speaking, heat balance and adaptive comfort are the two main thermal comfort categories [67]. Heat balance theory (fundamentally defined by the work of Fanger[7]) lead to the development of control models which defined static target temperatures to facilitate human comfort. Increasingly however researchers and practitioners have cast doubt over the validity of applying fixed temperature set points to working environments. These works are primarily driven by the adaptive principle; the concept that if a climatic change produces discomfort, people react to restore their comfort [31, 33, 50]. These efforts have collectively informed European (and hence British) as well as American standards [62, 63, 272]. BS EN ISO 15251 (2007) subsequently defines an ‘allowable’ indoor operative temperature band, taking the form of lower and upper values that could be defined daily or even hourly. These adaptive temperature bands are derived from external daily running mean temperature (θ_m) and are defined for 4 different building categories depending on operational sensitivity and occupant expectations [273].

Computational methods have enabled a whole raft of comfort based control studies and where thermal comfort informs the controls, Predicted Mean Vote (PMV) is used as the satisfaction index [22, 274]. This method measures human comfort perception on a seven-point ASHRAE thermal sensation scale (-3 to +3) that correspond to cold, fresh, slightly fresh, neutral, warm, hot, very hot votes and is originally a derivative of Ole Fanger's work [7, 11]. The determination of PMV has to take into account 2 personal (clothing, activity level) and 4 environmental factors (mean radiant and air temperature, humidity and air speed)[7]. Therefore in the most comprehensive form, controls use both comfort and energy as indices to optimise building operation. To that end P. Bermejo et al. designed an adaptive algorithm that used a fuzzy logic system; this enabled the control system to use 'on-line' learning to adjust a radiator's actuator. The system would learn the preference of an occupant in order to choose the most appropriate target temperature in the space; and in doing so minimised the number of direct adjustments made by the occupant. A similar study took the optimisation to a greater level by including air quality and energy indices in addition to PMV to set appropriate control set point of an HVAC system [257]. To achieve this, a multi-objective optimisation controller was designed to determine optimal indoor air condition in real time (giving equal weighting to thermal comfort – indoor air quality and load reduction). Sensors would pass environmental conditions to a central controller; the readings were then compared to baseline values to send the correction signal to HVAC plant. This experiment reports a 17.5% reduction in cooling value at the same time as maintaining CO_2 concentration below 1000ppm.

Computer-based optimisation and artificial intelligence techniques are required for the global optimisation of comfort and energy. Reinforcement Learning (RL) is one such technique where fruitful results have been reposted by many [191, 192, 275, 276]. Dalamagkidis and his team used RL to find the balance between energy and comfort although the learning process took 4 years and even after this period, the system would still make mistakes (i.e. calling for cooling in winter)[189, 277]. Other researchers shortened the training process to one season by using template fuzzy rule and off-line knowledge of the plant [191] . Comfort driven controls continue to attract research efforts, and the prevalence of digital technology, agent and online data and PC-based sampling tools is directing current and further work in this area [165, 166, 278].

Later years of the last decade saw a parallel study to occupancy-driven controls; the concept of control-orientated occupant's behaviour [279]. Occupants operate control devices (windows, shades, fans etc.) to bring about desirable conditions with significant impact on building operational behaviour. Extensive empirical studies on occupant manipulation of their visual, thermal and acoustic environment has been conducted, leading in instances to stochastic algorithms, dynamic or otherwise, that describes this relationship [280-282]. In recognition of this a strong sense of conviction exists that regardless of the great promises of system automation, the occupants should ultimately remain capable of overruling to assure acceptability and avoid conflict [283-286].

8.8.3 Control strategies using occupancy detection

Buildings, particularly those intermittently occupied can benefit greatly from using occupancy data to inform controls. Demand or occupancy driven HVAC controls are now deployed in very simple forms in buildings (i.e. a pre-set CO2 concentration value triggers the ventilation boost). Research conducted in this area shows notable energy saving potentials, although downsides such as insufficient ventilation and high CO_2 concentration remain to be solved [287, 288]. At the heart of this problem lies inadequate detection of occupant density despite the much improved levels of detection accuracy compared to earlier years. Occupant detection technologies that are currently deployed in buildings are divided into individualised and non-individualised systems, based on whether the individual in the sensing area is detected, tracked and identified or not [289]. PIR sensors are the most widely adapted but cannot detect the stationary occupant and are not able to identify or track a subject. To overcome this limitation, PIR sensors are coupled with other sensor types. A combination of PIR, acoustic and CO2 sensors were adapted by two research groups; where between three machine learning techniques that were applied, hidden Markov model proved the best, achieving an average detection accuracy of 73% [290, 291]. Occupancy detection relying on CO2 level alone could be misleading as carbon dioxide could be a function of several different parameters. A combination of PIR, CO2 and a video camera coupled with historical data helped to boost detection to 80% when deployed in an office [292]. A variety of techniques have also been developed for individualised occupancy detection; whereby the identity and coordinate of the occupant is determined by the sensing system [289]. Individualised detection enables a more refined regulation of HVAC system, and is most effective in open plan offices, but issues concerning privacy impede wider exploration. A study undertaken in Southern California University looked at radio frequency identification (RFID) technology to determine the real time occupancy level in order to control the HVAC systems [289]. This work required the building occupants to wear an active RFID tag throughout the study. System performance varied between different areas, and different mobility levels, with an average detection rate of 88% for stationary and 62% for mobile occupants at zone levels (the study involved 13 specified thermal zones). However the overall detection rate across all zones was 100%. In other words the system was able to tell the total number of people at all times, and where exactly they were most of the time.

Using 'instantaneous' occupant detection rates to adjust lighting and ventilation level have been reported to improve energy efficiency [287, 289, 293-295]. Although using more convoluted methods to 'predict' short term occupancy (i.e. occupancy information within a Model Predictive Control (MPC)) hasn't improved these results any further [296]. More recent attempts includes the use of Wi-Fi, digital calendars and also mobile phones to detect occupancy [297].

The most promising work on occupancy detection however are now led by digital and communication industries and social media platform owners. It has led to research that aims to use mobiles phones, electronic calendars and Wi-Fi infrastructure to headcount and in turn inform building operations[298, 299], Although major privacy issues remain to be resolved.

8.9 Industrial survey

The participants' knowledge of the recent work of the research community was quite limited, in particular regarding the computational methods covered in section 6.6. They were also in disagreement with the scientific community on the potentials of these techniques. Figure 67 illustrates the methods participants are already familiar with (black bars), and methods that they anticipate as major contributors to the future development of building controls (red bars):

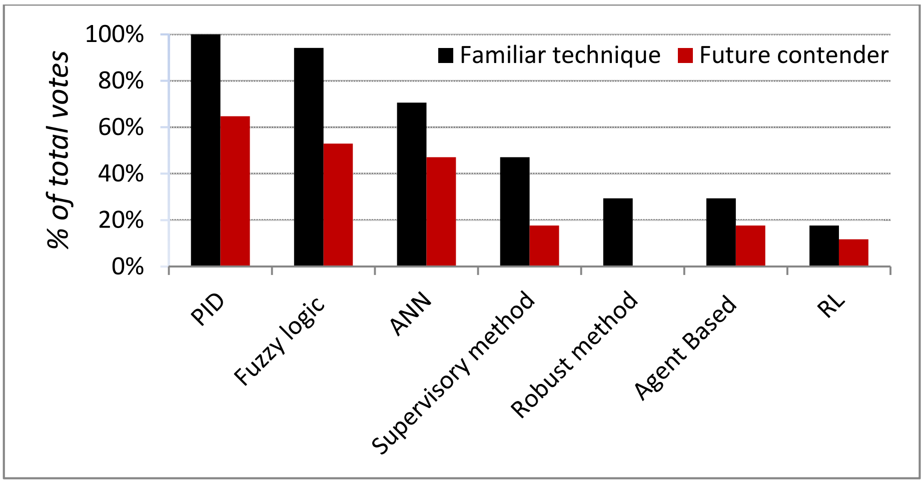


Figure 67 Industry views on current and future development of building controls

Quite clearly the participants have expressed very strong views on the potential of PID method. Individual comments regarded PID could be summarised as:

1. PID is an aging yet constant and trusted engine behind commercial expansion and economic growth of control service providers and still constitutes the backbone of most systems installed today. It will be integral to the future of HVAC controls as well.
2. PID is seldom set up properly in practice.
3. Difficulties in integrating the new proposed methods into legacy applications leave the commercial sector reliant and contented with more conventional technologies. Also some of the more recent control developments are viewed as disruptive technologies for some service providers; who see an expensive and challenging business and manufacturing restructuring to accommodate new techniques.

The views on fuzzy logic and ANN collectively indicated that the participants were familiar with these techniques, However supervisory, robust, agent based and RL techniques became progressively less familiar and quite understandably were all voted as less significant as future building control contenders. An overall theme also emerged in most (but not all) participant views that techniques other than PID are more suitable for process controls than HVAC&R and building applications. Few attributed ANN with the ability to interpret complex data and offer an alternative. Several contributors felt that some of the computational control strategies (RL, ANN and robust methods) will be only adapted in isolation, limited capacity or be abandoned in preference for emerging digital technologies.

When invited to express views on the ability of control strategies to accommodate adaptive comfort in a building, 21 out of 27 participants indicated that such time-variant space control is already possible via cloud computing, the internet of all things and software intervention to analysis historical data. Similar participants also referred to these as the main drivers of future controls. In conclusion the practitioners within building automation and controls industry have not moved as rapidly as the science community in adapting advanced control methods, and this gap could only perhaps be bridged if the two communities worked more closely together. The recognition of this has prompted major funding bodies to seek measures by which the uptake of research outcomes are enhanced .Scientific community also needs to play a more persuasive role if its efforts in developing laboratory-based theoretical measures are to be rewarded and deployed in real buildings.

Despite the rift between the convictions of scientific community and industry practitioners, particular technologies and concepts continue to offer great potentials. The main drivers for these are the ever increasing pace of innovations in IT, web-based services and cyber space. Table 8 summarises these technologies, taking a historical perspective and also reflecting the views of both the scientific and commercial sectors.

Control level	*Classical periods*	→	*Modern buildings*	→	*Future trends*
Management level	- *1950 + 60s: Human Operator.* - *1970s: Initial computer-based management systems introduced, functionality limited to monitoring only.*	→	- *1990s: Open Protocol introduced (BACnet – LON …)* - *2000s: www begins to dominate BAS systems* - *2000s: Inter-operability + standardisation of protocols*	→	- *Single software platform for all controls, domestic too (smart homes).* - *Controls approaching real time* - *Buildings digitally connected (soft infrastructure).* - *FDD and optimisation enabled via computational controls.* - *Mobile Devices provide interface.*
Automation level	- *1970s: Micro-chip analogue electronic control.*	→	- *1980s: Microprocessor panels (high density I/O)* - *1980s: Application-specific DDCs*	→	- *Full systems integration.* - *Self-commissioning and auto-tuning will be the norm.* - *Demand-side controls.* - *Comfort-orientated voting.*
Field level: - *Room controls* - *Actuators + valves* - *Primary plants* - *Lighting system*	- *Local loop Pneumatic control systems (1950s).* - *PID (1950s onwards).* - *Manual operation.*	→	- *PID continues.* - *1990s: Fuzzy logic.* - *2000s: Rapid expansion of wireless.* - *2000s: computational controls (governing 'uncertain systems') stay within R&D.* - *Schedule driven, PIR and daylight-linked.* - *2000s: Fire and safety systems merge with lighting.*	→	- *PID (self-tuning).* - *Local generation and storage, demand side energy management and HVACs with embedded AI enabled by computational methods.* - *HVAC fully integrated with lighting, security, etc.*

Table 8 Current and future trends in building controls

8.10 Discussions

The development of holistic, fully integrated controls has been a common practice in aircraft or robotics industries. Fully integrated building automation however has to overcome greater challenges mostly centring around the time domain gap of various subsystems that can range from sub-seconds (in communication systems) to years (i.e. geothermal heat source behaviour) [300]. It is imperative to note that a software-based visual display providing feedback from HVAC, lighting, fire and security, etc. does not constitutes a fully integrated building control system. Instead such a system would enable the controllable subsystems of the building to interact with the aim of deriving improved efficiency. The case for the benefits of full integration remains inconclusive and the proponents have mostly offered simulation-based evidence to support fully integrated controls [301-307]. In addition historically the fragmented nature of building industry has meant that simulation, control and optimisation tools which are independently developed remain incompatible despite a recent trend towards more integrated systems (as in BIM). Much of the innovation will therefore need to happen at the interface between different disciplines to allow fuller integration; which is fundamentally a software development issue. One such effort (though still in preliminary stages) is the BIM development that promises to enable virtual models developed and utilised by all involved at the design stage to also facilitate commissioning, fault detection and diagnoses and ultimately supervisory control as the model is eventually integrated into the building lifecycle [308].

PID (with occasional higher level heuristic supervisory control) continues to dominate the HVAC&R systems that are installed today. Model-based predictive (and optimal) controls have shown notable results primarily due to energy saving potentials even when performing with incomplete knowledge of the system. The most promising results for the integration of HVAC&R with aspects of occupancy or other building subsystems (i.e. lighting) is offered by model-based predictive and supervisory methods .Some of the more advanced forms of building computational controls (i.e. ANN, RL or agent-based) continue to remain in demonstration stage (with little efforts from the scientific community to involve the industry in development and deployment of new control concepts). The lack of real world deployment and absence of long-term performance data for these concepts partly account for the reluctance of the risk-averse building control industry to adapt them. The industrial survey reported earlier suggests a focus on developing traditional controls for individual systems rather than fully integrated controls (note that existing BAS systems similarly control individual systems independently, and not in a fully integrated manner).

The exact details of the next generation of controls might still be unclear, but the direction of travel could be expressed with a great degree of confidence. Digital technologies and cyber space are now the foremost incubators for innovation at a rate that outperforms any other field of science, with most observers pointing to the law of accelerating returns; where each breakthrough helps foster further innovations. It is therefore interesting that building control and automation will be influenced more by digital science, than the marginal gains derived from improving conventional techniques. Given that people are also more likely to implement energy conservation practices in response to consumption feedback [309, 310]; online sampling and feedback tools are favoured to become an integral part of future automation systems.

8.11 Control implications of adaptive comfort

It was noted that this chapter sought to investigate technologies that can provide solutions for the control of HVAC plants and zone temperature to operate under a time-variant adaptive comfort regime. A weather compensated heating system is a basic example where outdoor temperature is used to proactively adjust the heat supply (flow temperature) to reflect the changing outdoor conditions. To verify this further a total of 65 building automation and control engineers were contacted to provide feedback on the ability of current building automation technology to accommodate dynamic time-variant space control in buildings. All of 27 respondents indicated that electronic sensing and software intervention can enable adaptive comfort to be readily implemented. Similarly scientific literature concerning pervasive sensing using low cost WSN, model based and hybrid supervisory control (or similar web-enabled, data-rich techniques) points to the ability of BAS systems to accommodate high frequency updating of target temperatures and set points [184, 260, 308]. There are examples of measured and forecast weather parameters informing room temperature controls [186]. Technological capabilities therefore exist to construct daily (even hourly) adaptive target temperatures using local weather data to control a building's climate.

8.12 Summary

An implicit conviction exists within scientific community on the advantages of full integration of all building subsystems. The literature suggests that the tools to deliver this already exists and it would not require any fundamental change to the building systems that are installed today. This concept is also actively encouraged by several organisations with international reach (i.e. IEA) yet the case for such integration and its benefits stays inconclusive and simulation-based. Real building demonstration of a fully integrated building management/automation system is still missing. However the expert views collected in this chapter centred on a firm consensus that a dynamic, time-variant plant control aimed at providing space conditioning according to EN EU 15251 is within the reach of the existing control solutions readily available from the HVAC&R controls application industry.

It is also clear from the review here that beyond the conventional HVAC&R, future controls will supervise more renewables, local generation and most probably forms of energy storage too. Controls solutions will also be most influenced by cheap, multi-functional sensors, occupant interactive control mechanism, and the widespread deployment of sub-meters that produce a vast quantity of fine-grained data. Aided by high performance computing, online analysis, digitally integrated controls will be able to perform ‘near’ real-time multi-objective calculations and present decision makers with best operational choices. The internet of things, where virtual representation of physical objects is seamlessly integrated using internet has come to define newly coined concepts such as smart grids, smart homes and smart cities [304, 305, 311]. Digital innovation therefore appear to show greater potential to change the future of building controls, where the IT industry is leading the way and BAS industry adapting the innovations.

Chapter 9 Conclusion and future work

The work presented here outlined a detailed examination of the energy and human comfort performance of a newly built office building in the North East of England. Against the actual field study result, an examination of the potentials of EN 15251 (2007) was also undertaken by using current and future weather files. This examination also compared current building design practices in the UK (Building Regulation part L) with the more arduous passive house standard. Below is a summary of the main findings reflecting the original objectives of this study which are further elaborated in the following sections:

1- Using ASHRAE Guide 14 indices, the EnergyPlus model was calibrated to achieve Mean Bias Error (MBE) values within ±5% and Cumulative Variation of Root Mean Square Error (CV(RMSE)) values below 10%. The calibrated EnergyPlus model was found to be able to predict hourly annual space air temperatures with an accuracy of ±1.5°C for 99.5% and an accuracy of ±1°C for 93.2% of time.

2- When implementing a time-variant, weather dependant adaptive control regime in the calibrated model, significant heating load reduction for the base model is achieved, while passive house standard quite predictably eliminates the heating load completely. However the boundaries of space operative temperatures obtained using adaptive method are a major departure from Fanger's thermal comfort indices and also Predicted Mean Vote models stipulated by BS EN ISO 7730:2007.

3- 60 participants based at similar workstations across three different levels of the case-study building were interviewed to engage their views of the environmental performance of their working environment. No significant relationship was found between either the age or the gender of the occupant and their rating of the working environment.

4- Out of a total of 65 building automation and controls specialist contacted as a part of an industrial survey, 27 respondents based on 5 European countries and the US offered their views. 21 stated that software intervention and integrated design will be able to allow a time-variant building zone management to be implemented without fundamental changes to the nature of HVAC systems installed today. The literature produced by the scientific community also supports this view but more specifically calls for further integration of all building subsystems to enable more optimal controls. This concept is also actively encouraged by several organisations with international reach (i.e. IEA). Real building demonstration of a fully integrated building management/automation system implementing zone controls similar to that stipulated by adaptive comfort is however still missing.

9.1 Adaptive comfort potentials

Promoting end-user efficiency is regarded as one of the most effective carbon reduction measured and to that end adaptive comfort - particularly if combined with a more relaxed organisational dressing code – can achieve significant energy reduction. For buildings built to current UK design guidelines, under current and future weather conditions, Y=2 (category II building type) reduced heating related loads by about a third and Y=3 (Category III building type) reduced heating load by more than a half. Also, as outlined in chapter 6, the technology already exists to incorporate this energy saving measure widely and affordably. Also as the simulation results indicated, the current practice building design will benefit more from adaptive standards than passive house design. This therefore demonstrates that the implementation of this measure in existing building is more effective than taking building fabric design to the more arduous passive house levels .However some of the adaptive comfort wintertime temperatures (outlined in sub-section 7.4.2) fell short of the current practice guides stipulated by CIBSE. These discrepancies merit greater attention in particular through field studies which will allow an examination of the extent to which office workers might ‘accept’ lower temperatures implemented to reduce carbon or in return for various incentives. An independent UK government report concluded that UK households are now 4°C warmer in wintertime than 50 years ago [312]. Although this trend is broadly viewed as progress, there might be a case for managing occupants’ expectations towards lower wintertime temperature levels with a view to conserve energy. This also resonates with current social marketing efforts aimed at reducing energy consumption in over-heated homes [313, 314]. Clearly a complete knowledge of occupant health, consent, activity and clothing level should inform such efforts. A demonstration of absolute wintertime boundary is –for instance- World Health Organization's standard for warmth which stipulates that to protect those with respiratory problems or allergies, a minimum of 16C should never be exceeded [142].

9.2 Passive house and high performance fabric design

The ability of the passive house model to retain fairly constant zone temperature without HVAC plant intervention highlighted the benefits of highly insulated fabric design (section 5.3). Static target temperature control strategy imposes equivalent carbon emissions of 2.5, 1.4 and 1.1 $KgCo_2/m^2$ for current, 2040 and 2080 years, while these loads are eliminated completely by the introduction of adaptive comfort control measures. Although heating related energy reductions are experienced within the passive house model, the level of benefit that current practice fabric design (i.e. part L 2013) derives from this standard is far more pronounced. Passive house design therefore doesn't constitute a strong complementary technology when coupled with adaptive comfort space control regime. New commercial buildings (depending on their built quality) are expected to last beyond 60 and potentially up to several hundred years. Domestic properties follow the same pattern. It is often argued that it makes for a much better economic and engineering case to design high performing fabrics to eliminate mechanical interventions as far as possible, and where such interventions are unavoidable low carbon technologies bespoke to the development could be deployed to service the building. However in the modern, electricity dominated office building examined in this work passive house design doesn't create major carbon-saving advantages for the UK climate, particularly in the context of the rising temperatures (as noted in sub-section 7.4.1). At the time of the construction of the target building the prevailing building statutory requirement was set by Part L 2006. In order to exceed the prevailing standards, King's Gate was built with the composite fabric thermal property improved by a further 27% and the infiltration by 34%. These improvements bring King's Gate thermal performance in line with the requirements of part L 2010. However when the fabric of this building (referred to as the base model) was improved to achieve Passive House standards, the simulation results reported very minor heating-related carbon savings. Therefore within the context of the UK climate (and for commercial buildings with high internal gains) greater energy efficiencies will be harnessed if resources were directed to renewable energy and micro-generation, rather than taking the fabric thermal insulation performance to that beyond the current part L (2010) specifications.

9.3 The role of controls

As outlined in Chapter 8, an industrial survey of 65 control engineers were conducted to engage their expertise on the ability of current HVAC control systems to deliver a time-variant zone temperature as outlined by BS EN 15251: 2007. Of 27 responses, 21 stated that the deployment of adaptive comfort is within the capability of the current generation of BEM and BMSs without major changes to the nature of either air or water based HVAC systems installed today (sub-section 8.9). The industrial survey also highlighted the raft between the work of the research community and industrial uptake of the outcomes of such research to ultimately inform the next generation of HVAC controls (in that valid research work which has moved beyond the proof of concept stage fails to be deployed by the industry practitioners). Although this raft is fully acknowledged by the research reviewed in Chapter 8, addressing this issue is far beyond this work.

9.4 Recommendation for future work

At European level, approximately 80% of a building's total lifecycle energy usage occurs during its operational stage. Operational efficiency improvement therefore targets the greatest source of lifecycle building carbon footprint. The increasing automation of buildings which is celebrated as an inevitable product of the age of smart buildings (and ultimately cities) needs to take into account the need to inform and also educate the building occupant simultaneously. Therefore the best attempts for integration and automation of building systems seeks also to facilitate a two-way dialogue with the occupants.

Future changes to building controls and automation ought (and is highly likely) to come from the widespread deployment of WSN and feedback systems. The development of low-cost readily deployable environmental sensors capable of logging all aspects of human comfort is still in progress and will assist invaluable longitudinal data collections. Historically a rigid set of guidelines informed the design of a building. Feedback systems (such as web-enabled occupant sampling tools) could assist participatory control strategies, where the building is constantly adjusted to address the occupants' most recent requirements. This will serve to de-centralise design codes, providing a unique occupant-adapted space conditioning solution that could also incorporate climate adaptive standard (as outlined with EN15251). In that sense such a strategy forms a hybrid control technique where zone set-point is constantly adjusted by external operative temperature (i.e. EN 15251) and the vote of the occupants (i.e. web-enabled sampling/voting tools). The data rich nature of such a hybrid control strategy could provide further insight into the mechanisms by which the best performing buildings in any given vicinity achieve their energy and comfort targets. The web-based feedback system from the occupant could also be used as an educational tool firstly to aid the occupant better understand the working of complex HVAC systems (further addressing the proposition that automation can ultimately deskill the workforce [315]). Secondly this embeds a greater degree of tolerance of zone temperature to achieve better energy results (perhaps also incorporating various incentives). To this end the deployment of a voting system in an office building which is conditioned using adaptive comfort is invaluable (and a natural progress of the work carried out here). This would also remove the currently distorted nature of environmental building performance that is dominated by the feedbacks of discontent minority. A trial of this proposal within a pilot building can enable the collection of long-term (and fine-grained) comfort data, paving the way for studies that seek to provide insight into the possible links between environmental comfort, human behaviour, financial incentives and building performance. Although web-enabled occupant feedback is a recent possibility, the few initial trials are reporting promising results [316, 317].

Two further potential benefits of this is first the collection of a data repository that could further refine neutral temperature preferences that are deemed to be a close function of climatic and cultural environment (as accumulated by ASHRAE [37]), and second to move towards consensus-based building management systems, where the ability to control the environment in complex buildings of the future is handed back (or partly shared) with the occupant, a countermovement to the increasingly disenfranchising nature of fully automated commercial buildings. Such a filed study could be designed to evaluate peak-shifting, renewable feasibility and building integration into smart grid, smart cities and digital infrastructure[7].

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[7] Digital infrastructure is defined as web-enabled services that enable exchange and storage of data which at management level seeks to improve system efficiency.

Acknowledgements

The author would like to thank Engineering and Physical Sciences Research Council (EPSRC) whose support enabled the undertaking of this work (EPSRC grant reference EP/I000755/1).

Appendix

A CHP Quality Index

Department of Energy and Climate Change, in a policy cascade from European commission directorates, defines Good quality CHP as

Existing Schemes the ones who achieve

Quality Index (QI) ≥ 100

Power generation efficiency ≥ 20%

New and upgrades the ones who achieve

Quality Index (QI) ≥ 105

Power generation efficiency ≥ 20%

The general definition of Quality Index is

$$\boldsymbol{QI} = \left(\boldsymbol{X} \times \boldsymbol{\eta_{power}}\right) + \left(\boldsymbol{Y} \times \boldsymbol{\eta_{heat}}\right) \qquad [27]$$

Where:

$$\boldsymbol{\eta_{power}} = \frac{\boldsymbol{CHP_{total\ power\ output}}}{\boldsymbol{CHP_{total\ fuel\ input}}} \qquad [28]$$

and:

$$\eta_{heat} = \frac{\boldsymbol{CHP_{quantity\ of\ heat\ output}}}{\boldsymbol{CHP_{total\ fuel\ input}}} \qquad [29]$$

X and *Y* coefficients are defined for various types of fuel; Natural Gas, oil, coal and also alternative fuels such as by-product gases, waste gas or heat, wood fuels, etc. Respective *X* and *Y* values of 230 and 125 are recommended by DECC CHP Guidance Note 10[8] for the unit studied here.

For ALFAGY N50 (50kWe- 82kWt), following DECCs recommendation, the index formula will be:

$$\boldsymbol{QI} = \left(\boldsymbol{230} \times \boldsymbol{\eta_{power}}\right) + \left(\boldsymbol{125} \times \boldsymbol{\eta_{heat}}\right)$$

---

[8] Available at https://www.chpqa.com/guidance_notes/GUIDANCE_NOTE_10.pdf

Hence (and form manufacturer's literature):

$$\boldsymbol{QI} = (\mathbf{230} \times \mathbf{0.33}) + (\mathbf{125} \times \mathbf{0.55}) = \mathbf{145}$$

B Temperature data

Table 9: Field measurements of indoor air quality at three different levels within King's Gate.

		Air- Temperature (◦C)		Air movement (m/s)		Humidity (%RH)		Pass benchmark?
	Space	M[1]	B[2,4]	M	B[3]	M	B	
1st Trial (Nov)	Level 1	23-23.5	21-23	0.05	0-0.15	55	40-70	Yes
	Level 3	22.9-23	21-23	0.05	0-0.15	50	40-70	Yes
	Level 5	23.7-24	21-23	0.10	0-0.15	58	40-70	Yes
2nd Trial (Dec)	Level 1	21.5-22	21-23	0.1-0.12	0-0.15	56	40-70	Yes
	Level 3	22.9-24	21-23	0.05	0-0.15	54	40-70	Yes
	Level 5	23.7-24.2	21-23	0.13	0-0.15	60	40-70	Yes
3rd Trial (Jul)	Level 1	22.9 - 23.6	22-24	0.1-0.13	0-0.15	56	40-70	Yes
	Level 3	23.5 - 24	22-24	0.08	0-0.15	55	40-70	Yes
	Level 5	24.2 - 24.8	22-24	0.05-0.13	0-0.15	57	40-70	Yes[6]

Table 9 Raw field measurements

Footnotes:

1- Measured values.

2- Benchmark values.

3- Air movement can never be studied in isolation from operative temperature, turbulence intensity and relative humidity. Figures presented here are general guidelines from CIBSE Guide A, section 1.3.

4- All recommended values are extracts from CIBSE Guide A. Temperature ranges refer to winter time design targets.

5- The measured values represented here are each a collection of 20 sample reading at 20 workstations concerned that then has been averaged into a single unified value (i.e. each measured humidity value is the average of 20 sample readings at the specific trial referred to which was then expressed as a single figure)

6- CIBSE Guide A allows the temperature of the space to exceed 25°C for non-air-conditioned spaces (which includes King's Gate). Also 28°C may be exceeded in such buildings for no more than 1% of the operational time (25-30 hours).

Note 1: Operative temperature

Operative temperature is defined as

$$\theta_c = H\theta_{ai} + (1 - H)\theta_r \qquad [30]$$

Where θ_c is the operative temperature (°C), θ_{ai} is the indoor air temperature (°C), θ_r is the mean radiant temperature (°C), H is the ratio $\frac{h_c}{(h_c+h_r)}$; in which h_c and h_r are the surface heat transfer coefficient by convection and radiation respectively (W.m^{-2}.K^{-1}).

C Siemens sensor error margin

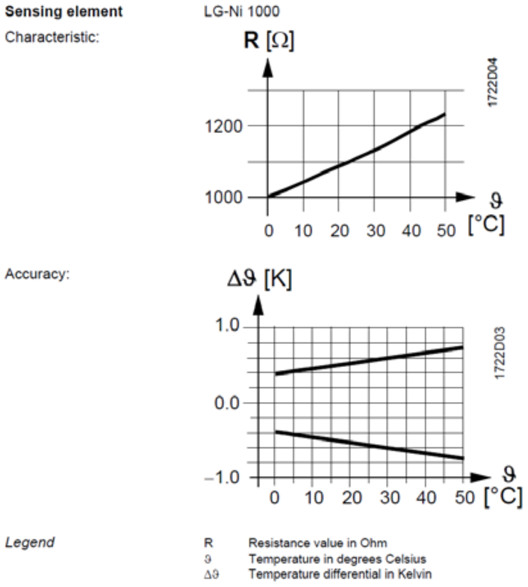


Figure 68 Reproduced from Siemens commercial literature

D Lighting data

Figure 69 TESTO 435 multifunction sensor

Audit instrument was a TESTO 435 multifunction sensor (Figure 69)

		Light level (Lux)		Light Uniformity		Pass benchmark?	
	Space	M[1,3]	B[2]	M	B	Light level	Uniformity[4]
Trial 1 (Aug 11)	Level 1	520	300-500	0.9	0.7	Yes	Yes
	Level 3	750	300-500	0.76	0.7	Yes	Yes
	Level 5	810	300-500	0.72	0.7	Yes	Yes
Trial 2 (Dec 11)	Level 1	465	300-500	0.85	0.7	Yes	Yes
	Level 3	495	300-500	0.78	0.7	Yes	Yes
	Level 5	561	300-500	0.71	0.7	Yes	Yes
Trial 3 (Jun 12)	Level 1	516	300-500	0.83	0.7	Yes	Yes
	Level 3	757	300-500	0.75	0.7	Yes	Yes
	Level 5	790	300-500	0.74	0.7	Yes	Yes

Table 10 Lighting data of field survey

Footnotes:

1- Measured values.
2- Benchmark values (CIBSE Guide A, section 1.3- also society of light and lighting handbook 2009).
3- A map of 10-12 individual values were averaged to arrive at a single figure for the whole space.
4- Uniformity is defined as the minimum/average illuminance ratio in a space. It should only be calculated for areas where work is undertaken (i.e. corridors and circulation spaces in an open plan office shouldn't be used in the calculation).

E Degree day analysis

Degree day analysis is a powerful yet simple way of analysing weather related energy consumption and is widely used by facility managers. This analysis establishes trends in energy performance of the target building and unusual departures from these trends are exposed when a degree day graph is set out. Full weather local weather data and metered energy from King's Gate enabled this analysis in details. The following graph is the analysis undertaken for a full year (2012).

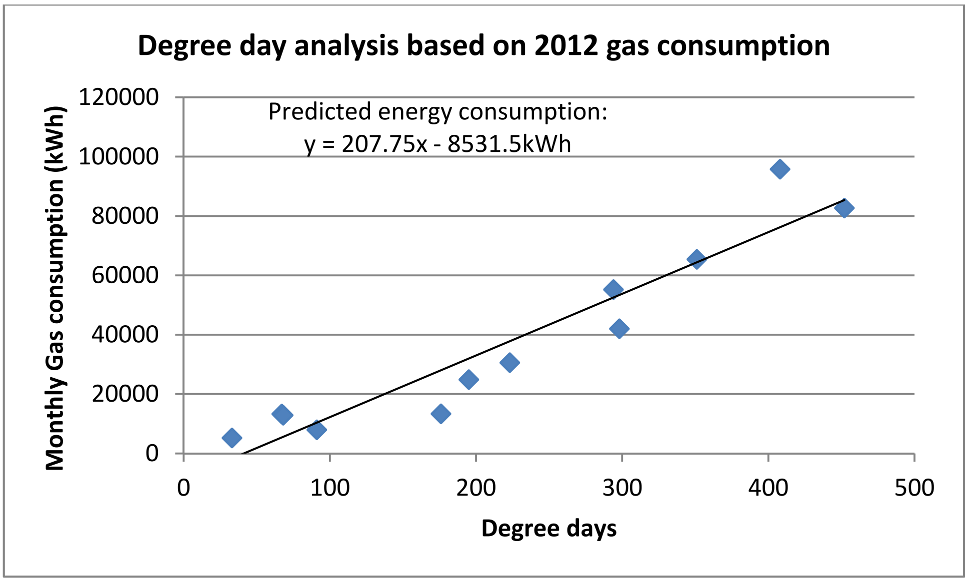


Figure 70 A linear relationship exist between degree days and gas consumption in King's Gate

Quite clearly the relationship between cold days requiring heating input to the building and cold days in weather files (i.e. accumulated degree days) are perfectly linear as demonstrated by Figure 70.

Full description of the steps taken to arrive at this chart is beyond the scope of this work however the methodology that informed this exercise is fully set out in CIBSE Guide J and CTG004 Technology guide[9].

F Occupancy questionnaire

Institution:

Building address:

Date: Time:

Dear participant:

The following is a set of questions designed to engage your views on the environment you work within. The results will help with future planning and improvements. The final report of this study will use summaries of the information provided and will not reveal the identities of any individuals. All notes will be destroyed at the end of the study.

---

[9] Degree days for Energy management- a practical introduction.

Please be assured that your participation is entirely voluntary. You may also ignore any question that you don't wish to answer. Are you happy to contribute to this study and allow your anonymised views to be included in the statistical analysis? Yes ☐ No ☐

Please tick/circle appropriate boxes.

1. *General*

1- Gender M ☐ F ☐

2- Age <30 ☐ 30-40 ☐ 40-50 ☐ 50-60 ☐ >60 ☐

3- Occupation:

  a. Administrative
  b. Management Team
  c. Technologist/Project management
  d. Pilot plant/logistics
  e. Other: ________________________________

4- Full-time ☐ Part time ☐

5- How long do you normally spend in the building in an average day?

Hours	≤1	1-2	3-4	5-6	7-8	≥8

6- If applicable, was your previous work environment a cellular or an open plan space?

2 *Air quality and temperature*

1- Is your working area comfortable in summer?

Too Cold	1	2	3	4 (comfortable)	5	6	7	Very Hot

2- Is your working area comfortable in winter?

Too Cold	1	2	3	4 (comfortable)	5	6	7	Very Hot

3- Do you have any control over temperature in your working are?

No control	1	2	3	4	5	6	7	Full control

4- How do you rate the air movement in your working area?

Quite still	1	2	3	4 good air circulation	5	6	7	Too much circulation and draft

5- Does air movement/ventilation have a negative effect on your work performance?

No negative effect	1	2	3	4	5	6	7	Significant negative effect

6- Does the air feel stale or fresh?

Stale	1	2	3	4	5	6	7	Fresh

7- Is direct sunshine a problem?

Serious problem	1	2	3	4	5	6	7	Not a problem at all

8- Is clothing policy flexible enough to allow for seasonal changes?

Not flexible at all	1	2	3	4	5	6	7	Very flexible

9- How do you rate the heating system in your working area?

Not effective at all	1	2	3	4	5	6	7	Satisfactory and effective

10- How do you rate the cooling system in your working area?

Not effective at all	1	2	3	4	5	6	7	Satisfactory and effective

11- What improvements (if any) would you make to improve air quality?

a. Heating

b. Cooling

c. Ventilation

3 *Acoustic*

1- What are the main sources of sound you can hear during the course of a working day?

2- For a very important piece of work, would you need to move away from your desk to isolate yourself or can you conduct it from your workstation?

3- Is there significant noise distraction from outside the office[10]?

Not at all	1	2	3	4	5	6	7	Very significant distraction

4- Is there significant noise distraction from other colleagues/workstations?

Not at all	1	2	3	4	5	6	7	Very significant distraction

5- Is there significant noise distraction from office equipments[11]?

Not at all	1	2	3	4	5	6	7	Very significant distraction

6- Is there significant noise distraction from building services[12]?

Not at all	1	2	3	4	5	6	7	Very significant distraction

7- How do you rate your working area from a noise point of view?

---

[10] Traffic noise, railway/metro, emergency services, road works...

[11] Photocopiers, fax machines, PC towers, etc.

[12] Supply air ducts, extract fans, etc.

Not satisfactory at all	1	2	3	4	5	6	7	Very Satisfactory

8- Do you have suggestions for improving your office from an acoustic point of view?

4 *Lighting*

1- Can you see the sky directly from where you sit? Yes ☐ No ☐

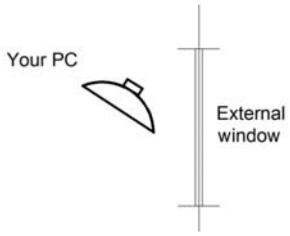
2- What is the rough distance between you and the nearest window? ___________ meters

3- Could you please draw a diagram of your workstation arrangement in relation to the closest window?

As illustrated below, a very simple drawing is sufficient

4- Can you assign some rough percentages to the proportion of your work that is;

Screen based[13] ______ %
Workstation based[14] ______ %
Away from your desk[15] _______ %



5- Do you prefer electric lighting or daylight when you are working?

Electric Lighting ☐ Daylight ☐ No preference ☐

6- Do you have control over electric light on your desk

No control	1	2	3	4	5	6	7	Full control

7- Do you have any glare problems[16] when using your computer?

No glare problem	1	2	3	4	5	6	7	Serious glare problem

---

[13] You would be sitting at your desk and working on your PC.
[14] You would be sitting at your desk but are not using your computer (i.e. writing, on the phone, etc)
[15] Meetings, laboratory work, library research, away from the office or on the road, etc.
[16] Disruptive reflection from windows/electric lights on your PC screen.

8- Is the glare caused by daylight or electric lights?

Electric Lighting ☐ Daylight ☐

9- Are there any blinds/shutters to control the amount of daylight? Yes ☐ No ☐

10- Are the blinds/shutters effective in blocking out the natural light?

Not effective at all	1	2	3	4	5	6	7	Very effective

11- How often do you adjust the blinds/ shutters (daily, weekly, rarely)?

12- Are you satisfied with the quality of daylight at your desk?

Not satisfied at all	1	2	3	4	5	6	7	Very satisfied

13- Are you satisfied with the quality of electric light on your desk?

Not satisfied at all	1	2	3	4	5	6	7	Very satisfied

14- Are you satisfied with the access that you have to outside views from your window?

Not satisfied at all	1	2	3	4	5	6	7	Very satisfied

15- Could you think of ways that can improve the lighting in your office?

5 *Privacy*

1- Are you happy with the degree of enclosure from other workstations (by screens/ furnishings)?

2- Would you like removable and re-adjustable modular screens around your workstation which would afford you a greater degree of privacy?

3- Are you happy with the distance between you and others you work with?

Too little distance	1	2	3	4 Just right	5	6	7	Too far a distance

4- How would you rate the overall personal space around your workstation?

Not satisfactory	1	2	3	4	5	6	7	Very satisfactory

6 *Other*

1- How do you rate general cleanliness and maintenance within your working area?

Not clean at all	1	2	3	4	5	6	7	Very clean

2- How do you rate the quality of the furnishing and office equipments?

Not good at all	1	2	3	4	5	6	7	Very good

3- How easy is it to move around the space (and to other floors)?

Very difficult	1	2	3	4	5	6	7	Very easy

4- From a security point of view, how safe do you think the building and its surroundings are?

Very unsafe	1	2	3	4	5	6	7	Very safe

5- Please rate the following in order of importance

Visual Privacy[17] Acoustic privacy[18] Daylight availability Access to outside views

(Most important) 1st

2nd

3rd

---

[17] The extent to which your computer screen and workstation can be viewed by others.

[18] The extent to which your conversations could be heard by others.

(Least important) 4th

5- What are 3 things that you like about your working area?

1.

2.

3.

6- On conclusion, is there any element that affects your comfort in the office and was not mentioned here? (Please also note any views you wish to express).

G BAS Questionnaire

Dear participant:

The anonymised information provided here will be used to form statistics in scientific literature.

Please feel free to ignore any question that you don't wish to answer.

Clicking in checkboxes will activate the tick/untick function.

Control technologies

1. Please tick all control methods that you have heard of:

PID ☐ **Supervisory method** ☐ **Fuzzy logic method** ☐

Robust method ☐ **Artificial Neural Networks** ☐ **Agent Based controls** ☐

Reinforcement learning ☐

2. Which one of these do you believe will contribute significantly to future development of building controls?

PID ☐ **Supervisory method** ☐ **Fuzzy logic method** ☐

Robust method ☐ **Artificial Neural Networks** ☐ **Agent Based controls** ☐

Reinforcement learning ☐

3. In your view, what are the top 3 technologies/realities that will change the face of building automation and controls in future?

    1.

    2.

    3.

4. Do you have any views on the potential of any of the following methods?

PID:

Supervisory method:

Fuzzy logic method:

Robust method:

Artificial Neural Networks:

Agent Based controls:

Reinforcement learning:

5. Adaptive comfort is defined as controlling space temperature in a building using a set of two temperature bands (lower and upper limit) which are derived from external air temperature and are therefore time-variant. This standard stipulates that the building environment needs to fall within this band (see Figure 71). This therefore results in zone temperature fluctuating (however moderately) all the time, offering energy saving potentials.

    Deriving from your own experience, does the current generation of building environment control methods have the capacity to accommodate such time variant standards to be used for the control of HVAC systems?

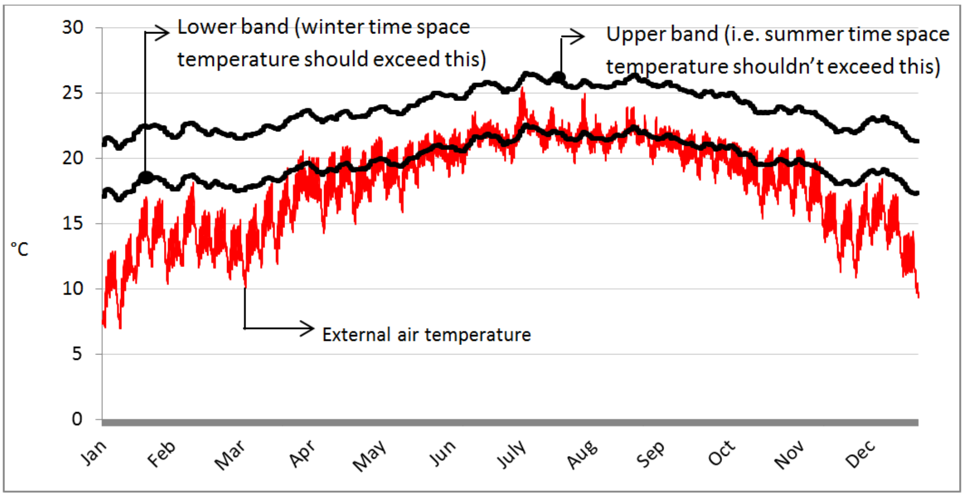


Figure 71 Illustration of lower and upper band adaptive comfort temperatures

Would you like to make any further comments?

I Renewable Integration feasibility

The consistency of electrical load within the building allows the application of very specific electricity-based renewable technology solutions (i.e. electricity driven CHP or PV panels). However the absence of any summer-time cooling load would cause severe and highly undesirable summertime heat dumping in the case of a CHP unit.

As this work forms part of a tri-generation feasibility study, a guideline driven preliminary absorption chiller analysis is undertaken here to gauge the potentials of CHP deployment. This also adheres to broader views of carbon reduction studies that steers this work.

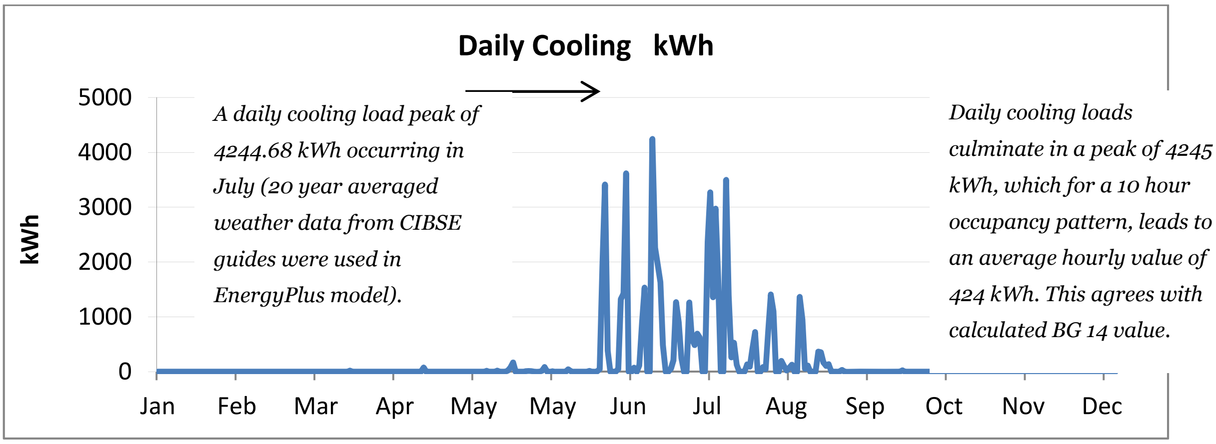
A. Empirical Calculation:

From BSRIA guide BG14/2003:

1. Interior zone general office summer-time cooling zone is 75W/m^2 [318].
2. Total office space at King's Gate is 5880m^2.
3. This suggests a summer time peak cooling load of 441 kW.

B. Model-based calculation

Simulated cooling results of the calibrated virtual model of King's Gate are illustrated on Figure 72. This illustrates daily cooling loads which closely agree with the Empirical calculation.

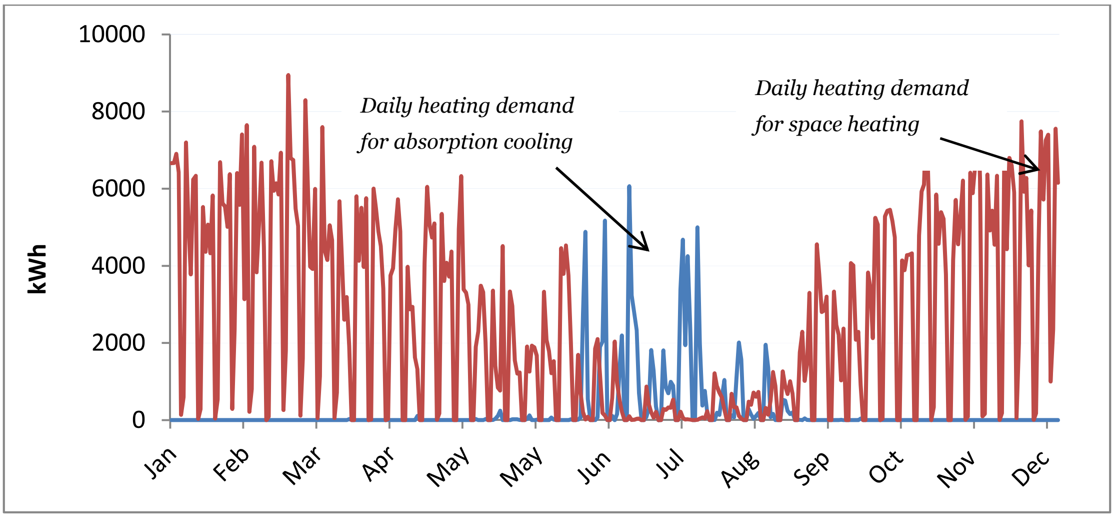


A daily cooling load peak of 4244.68 kWh occurring in July (20 year averaged weather data from CIBSE guides were used in EnergyPlus model).

Daily cooling loads culminate in a peak of 4245 kWh, which for a 10 hour occupancy pattern, leads to an average hourly value of 424 kWh. This agrees with calculated BG 14 value.

Figure 72 Daily cooling demand, King's Gate (EnergyPlus using local weather files of 2012)

Finally with a single effect Carrier 16LJ absorption chiller (COP of 0.7 from manufacturer) the BSRIA peak translates into 630 kW of heating requirements (441/0.7=630). Deploying an absorption chiller will therefore create a summertime heat requirement as illustrated in Figure 73.



Daily heating demand for absorption cooling

Daily heating demand for space heating

Figure 73 Daily cooling and heating demand; King's Gate's calibrated Energyplus model using 20 year averaged weather files.

Quite clearly a more consistent pattern of heat demand emerges for King's Gate when an absorption chiller is deployed. Hence working on the assumption that absorption chiller technology could replace the existing evaporative coolers, the integrated operational hour[19] heat demand generated using the calibrated virtual model described earlier is as follows:

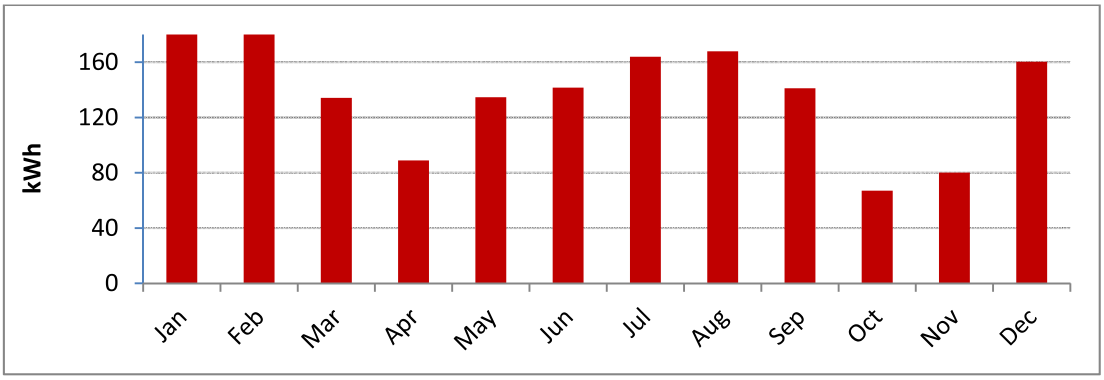


Figure 74 Hourly heat demand in King's Gate (calibrated EnergyPlus model)

Given that averaged weather files of 20 years were used in this calculation, this pattern of heat demand will be closely representative of the general pattern of tri-generation loads for the target building (this method is also recommended by CIBSE for building simulations). With a minimum hourly heat requirement of 67 kWh (October), the adaption of a small scale CHP engine within a tri-generation design becomes perfectly feasible. It should be noted that the values in Figure 74 are total heating demands concentrated to operational hours, calculated on the bases that the mechanical plants will be shut down outside this time bracket.

Sizing Strategy

An ideal demand pattern for CHP adaption would be as consistent a heating and electrical demand as possible with heat having a magnitude of 1.5 that of electricity. This principle is achieved in King's Gate if a proposed CHP scheme served the electrical base-load of 50kW in conjunction with a tri-generation based heat load.

King's Gate electrical load stays practically consistent all the way throughout the year, fluctuating around (and not departing much from) 50 kW (refer to Figure 12 and Figure 13). Therefore if an ALFAGY N50 (50kWe- 82kWt)[20] unit is specified to serve the building; the following two principle configurations can be examined:

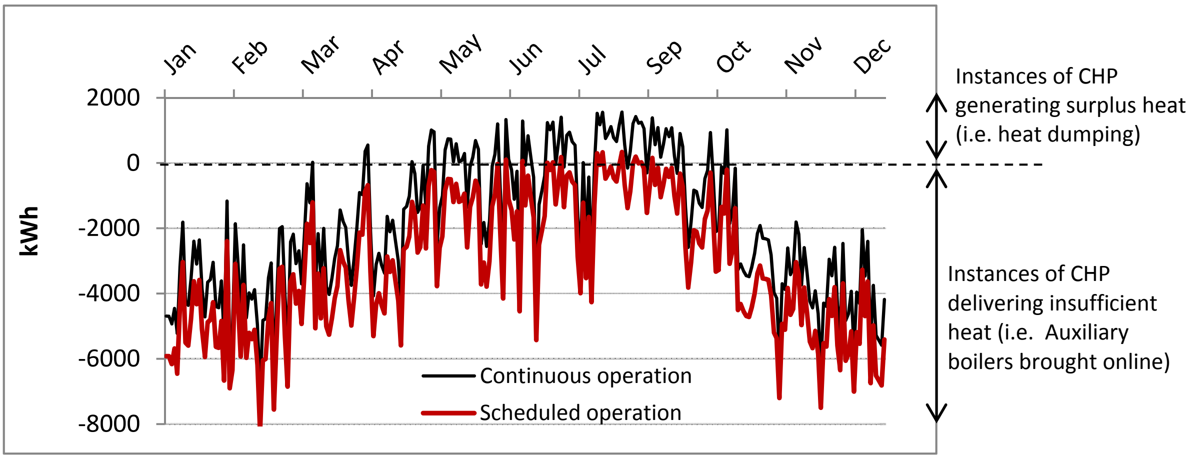
---

[19] 8am-9pm

[20] http://alfagy.com/micro-chp

1. Continuous operation: Unit running continuously round the clock. All electricity will be utilised but heat dumping would occur in 66 days (a total of 50,437 kWh).
2. Scheduled operation: (8am-5pm): Unit runs only during working hours. All electrical output will be utilised and heat dumping will occur on 11 days of the year (a total of 1,695 kWh).

The CHP unit has a Quality Index of 145 (see appendix A) and as such qualifies for DECCs CHP schemes. Within both operations the engine will be operating at the most engineering and fiscally efficient operating point (100% load). Figure 75 demonstrates heating residuals, arrived at by deducting the CHP heat generation from the building heat demand. Quite predictably the figure illustrates that instances of heat dumping are for the most part concentrated around summer months.



Instances of CHP generating surplus heat (i.e. heat dumping)

Instances of CHP delivering insufficient heat (i.e. Auxiliary boilers brought online)

Figure 75 Surplus CHP heat generation for King's Gate (20 year Averaged weather files)

Of all renewable technologies, CHP integration requires a much closer engineering examination. Quite clearly the building energy demand can accommodate a 50kWe unit which is operational during office hours. Renewable sources that produce heat or electricity alone can more easily be incorporated into services design of this building however broader examination of these is beyond the scope of this work.

J Energy conversion and storage

As the heated debate on the looming energy crises and the uncertain future of weather patterns sweeps across the globe, European policy makers continue to fall over themselves to prove their energy credentials. At the same time, the scientific community is, for the most part, divided into several camps. The environmentalists, who regard renewables as the only means of achieving UK's 60% emission reduction target by 2050[21] [1]; in fierce opposition to the nuclear camp, who regard nuclear energy as an indispensable part of the energy mix. Some scientists also seem to believe that fusion can (and will) contribute significantly to the large scale energy production during the second half of 21st century[319].

Amid this landscape of polarised views, what remains certain is UK's need to generate more of its own energy (75% of UK's primary energy needs is forecast to be imported by 2020[320]) and more importantly, to generate it responsibly and sustainably. It also necessitates the need to optimise the use of primary energy, of which buildings claim a share of 45% in this country [321].

J1 Conversion

Micro-generation

Concerns related to carbon cost of energy generation have resulted in a series of carbon reduction commitments and political acts globally, of which Climate Change Act 2008 is the most relevant, and the overarching document in the UK (Figure 76 outlines current UK targets). Micro-generation and renewable energy thereby come to play a pivotal role in building energy reduction.

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[21] Michael Meacher, former environmental minister. p. 18 of [1].

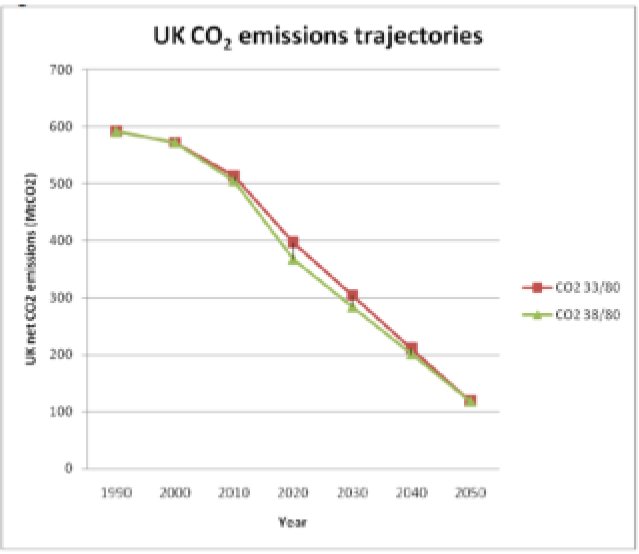

Figure 76 Climate Change Act 2008 (Table 2). The UK has a target of 80% CO2 emission reduction by 2050.

Micro-generation itself was a historic function of the collapse of New York City power supply in 1970s. This led to the idea of in-house power. These events, together with the free heat by-product of CHP engines brought about the idea of total energy systems. More recently, the gross inefficiency of the UK National Grid and greater commercial viability of CHP systems led the UK government to pursue a policy of 5 GWe by 2000 and 10 GWe of 'good quality[22]' CHP installation by 2010. 5 GWe was reached in 2002 and 10 GWe missed by about 20%, partly due to the global economic turndown[8]. The current target brings CHP installation under the overall policy of generating 15% of UK energy through renewables by 2020 (DECC).

The pursuit of micro generation and renewable technologies however require a major re-think in how generation, storage and consumption stages are designed and managed. Quite often CHP systems are installed where high levels of heat are dumped annually, which partly explains one of the covenants for good quality CHP which is the minimisation of annual heat losses.

Wind

The UK is the windiest country in Europe, capable of harvesting several times its energy needs from wind, although wind energy accounts for only 2.2% of its energy supply [322].

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[22] See Appendix A for good quality CHP

Wind turbine design initially borrowed heavily from accumulated aviation and wing design technology. This is despite major differences, mainly that wind turbines are subject to Coriolis Effect [23] and centrifugal forces, as well as frequently operating in deep stall condition [24] (which aeroplanes avoid at all costs). Improved transition and turbulence algorithms in recent years have separated the paths of aircraft wing and wind-turbine blade designs [323].

Current research attempts to improve blade design and its pitch control, reduce noise problems and material cost, avoid aviation interference and enable turbines to operate at a greater range of wind speeds [324]. Diffuser-Shrouded turbines (with an end flange) claim even to have achieved higher power coefficient that the Betz limit of 16/24 [325].

Despite its potentials however, the performance of some wind turbine installations, in particular small urban-scale units, has proven somewhat disappointing. This is mainly attributed to optimistic manufacturer' literature and inaccurate weather data. Scaling factors therefore are developed to account for wind data inaccuracies, urban terrain roughness and wind shadow effects [326]. These factors mean that in some instances the output of a turbine could be less than half the predicted figures. Wind-turbine industry is nonetheless expanding rapidly. In the UK, for instance the Carbon Trust has released figures suggesting that the UK is poised to grab a 10% share of the global offshore wind market; contributing £100bn to the UK's finances between 2010-50; as well as creating 230,000 jobs [6].

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[23] The deflection of the path of a moving object when viewed by a rotating observer. See http://www.britannica.com/EBchecked/topic/137646/Coriolis-force

[24] Stall is the separation of air stream at the back of rotor blades at higher angles of attack. Aircrafts avoid this situation as it leads to poor - or even loss of - control.

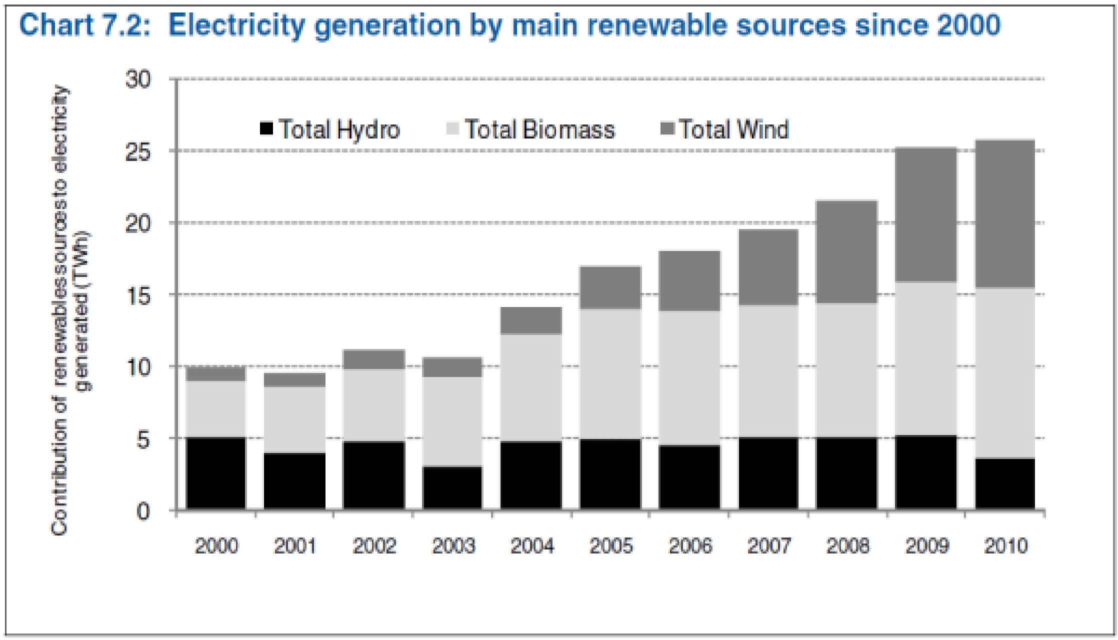

Figure 77 Wind has been the fastest growing renewable source in the UK, due to off-shore deployments (source: Digest of UK energy statistics 2011)

Photo-Voltaic

The relationship between higher illumination and improved material conductance goes back to early 19th century, although real world application of this knowledge emerged as late as 1960s, with the first silicon solar modules being integrated into earth-orbiting satellites [327].

Figure 78 Skylab 4 space station (1973) generated over 20kW of electricity by PV panels (photo reproduced from [23]).

Later in the 80s PVs were used to power consumer electronics (calculators/watches…), as well as providing power to undeveloped rural areas. It was only 70s energy crises that triggered significant efforts to develop commercial scale PV panels for buildings.

When integrated into buildings, PVs can reduce building loads considerably; in particular in warm and sunny climates (i.e. equatorial and subtropical regions), and most notably in applications where a commercial building energy profile nearly matches daily solar radiation availability. Although increasingly advanced technology and regulatory incentives have made PVs viable in mid-altitude regions as well [328].

Latest research is attempting to improve the efficiency of PV modules, reduce their production and running cost and expand their working life. On-going maintenance is required to remove accumulations of dust and other deposits, as well as to maintain cooling fan systems (PVs suffer efficiency penalties of up to 30% with rising temperature, hence the ventilation requirements). Interestingly current research in Italy observed that PV performance improved when submerged in water [329]. The improvement is explained by cleaner PV surface, reduced incident light reflection and the elimination of temperature drifts (surface temperature of exposed PVs can reach 70°C to 80°C in summer). Clearly this solution cannot be readily adapted in buildings within urban environments.

Quite often best renewable energy solutions are a combination of several complimentary technologies. For instance in one study a diesel generator and set of PV panels were sized holistically to meet a constant demand [330]; The PV panels enabled the diesel generator to operate near its optimal point (70-80% rated power) at all operating times.

The UK has however been behind the rest of the industrialised nations in both adapting, or the development of PV panels [331] with PV and solar heating currently accounting for only 1% of the renewable energy production. US, Japan and Germany have been the main driving forces behind PV's recent developments. More recently China has pledged significant contribution to a national solar plan.

Bio fuels

The prospect and opportunities of introducing vegetable oil and their derivatives to power internal combustion engines have attracted considerable research in recent years. It is interesting to note that the first diesel engine developed by Rudolf Diesel did actually run on vegetable oil, which has now made a comeback to capture scientific imaginations again.

Throughout their history, internal combustion engines have been optimised to run on petroleum products. Therefore modern diesel engines suffer various problems when run on vegetable oil [332]. These problems primarily emanate from the dissimilar bio-chemical properties of vegetable oil, namely:

1. Different injection, atomisation and combustion characteristics
2. High viscosity, leading to poor atomisation
3. Inefficient mixing with air, leading to heavy smoke emission
4. Higher cloud and pour points that cause problems in cold weather
5. Dilution with lube oil
6. Injection nozzle failure
7. High carbon deposits
8. Lack of standardisation. Wide variations exist in properties of bio-fuel from different sources

A recent publication [333] reports the following findings when a whole host of bio-fuels were benchmarked against diesel [25]:

1- Break power of engines running on pure or blends of plant oil varies in the range of -18% to +10% of diesel.
2- On average the density of plant oil is 12% higher than diesel whereas its calorific value is around 10% lower.
3- Cetane number (the fuel's readiness to ignite) is around 10-20% lower for most plant oils (compared to diesel).
4- Brake thermal efficiency (ratio of brake power output to embedded energy of the fuel) of pure plant oil is in the range of -10% to +3% of diesel.
5- Emissions of CO_2 are either similar or increase when engines run on pure plant oil.
6- Although there is little and conflicting long-term study of plant oil effect on engine durability, it is generally accepted that engines develop more problems when run on vegetable oil.

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[25] Results obtained for various fuels under the same operation conditions.

Research is underway to improve the properties of vegetable oil. These include modifying oil properties by blending them, adding oxygenates, emulsification, transesterification and winterfication. Other opportunities on the horizon include the pyrolysis of biomass. Writing in the journal Nature, a Cornell University professor of Biochemistry states that low temperature pyrolysis of plant biomass would double the carbon residue in the plant body. The charred plant can then be returned to the soil; acting as a carbon sink and also improving the soil fertility[334]. The exhaust gasses from this process can be used as fuel in internal combustion engines and gas turbines. Various combustion tests have demonstrated that they can be burnt in standard or modified equipment [335].

Biofuel remains the largest contributor to total renewable energy, accounting for 82.5% of total UK renewable generation in 2010 [336].

Alternative views

Despite the degree of respect that renewable technologies command in scientific and political circles, These are mostly spatially diffuse and intermittent sources, making them inefficient and inherently expensive [337]. This necessitates feed-in tariffs and other support mechanisms to make renewable more economically attractive. Some however voice concern over the weak economic merits of these technologies. Writing in a recent edition of CIBSE journal, Prof Colin McInnes argues that the adaption of fuels with greater energy density has been the propeller of economic prosperity. The Elizabethan era when wood was replaced with coal; and much later the use of oil and natural gas (and ultimately Uranium) all represent transitions to higher energy and lower carbon densities. The current 'green policy' imperatives are therefore taking us back to the use of diffuse energy sources that will require vast quantities of materials, land and subsidies. This will misallocate economic resources that could be used more productively elsewhere. He argues therefore that renewables cannot realise more energy at lower prices with less impact on the environment. Instead, next generation of nuclear power stations (i.e. uranium and later molten salt thorium reactors) together with advanced compact power stations which utilise supercritical carbon dioxide or energy dense, low carbon methane are the way to de-carbonising UK economy.

This viewpoint simply acts as an indication of the diversity of opinions that exists on how UK energy production should move towards later stages of 21st century.

J2 Storage

Energy might be produced at a time when there is no immediate demand for it. There is therefore the need to store the energy and also to minimise the losses between the production and the consumption stages. This philosophy is particularly true of renewable technologies whereby the key to unlocking their potential lies in successful energy storage facilities [338]. Electrical Energy storage technology (EES) has particularly invited greater interest because of the de-commissioning of old power stations, the more critical nature of power quality for the digital economy, and the widely fluctuating power demands over the diurnal cycle[339].

EES however covers many industries and applications. Extended range electrical vehicles, for instance, have recently spurred renewed research work in this area. Although a sharper focus is maintained here to explore stationary EES that relates more immediately to building technology. It must be born in mind that building energy storage design could involve a mixture of these technologies; for instance batteries and super-capacitors have complementary characteristics. Batteries are high energy density, low power density solutions. Conversely super-capacitors are high power density, low energy density solutions and the synergy between the two is therefore often used to engineer hybrid energy storage solutions in which super-capacitors provide periods of pulsed power that batteries are incapable of.

Electrochemical energy storage

Electrochemical storage devices work by introducing electricity to two separated cells which causes chemical reaction and upon reversing the chemical reaction, electricity is released back into the circuit again. Various forms of this technology were previously used for portable appliance batteries, power quality and back-up technologies. However their development and implementation have gathered great momentum in recent years in order to provide solutions to the hybrid or fully electric vehicle industry; as well as renewable energy system integration. The following passages cover the most prominent candidates and their applications.

Lead Acid (PbA)

Lead acid batteries have been in use in electrical power systems for more than a century. Their relatively low price, high unit voltage, wide operating temperature and stable performance makes them an attractive option in renewable technology system integration, in particular PVs [340]. Deep cycle Lead Acid batteries can discharge by as much as 80% which makes them a front-runner for distributed generation application [341] . They are however limited by their large foot-print as a result of low energy density, and also their life-span which is about 5 years. The lead content presents environmental problems too. Major research nonetheless is underway to improve their performance by introducing electronic regulators and control valves which prevents excessive charge and discharge of these battery types [342].

Nickel Cadmium (NiCd)

NiCd batteries rank alongside lead-acid batteries in terms of their maturity [343]. Their longer cycle life, higher energy density and low maintenance gives them a leading edge over lead-acid equivalents, although the toxicity of Cadmium presents major recycling issues [341]. NiCd batteries are capable of 100 complete and 500 partial discharges over a lifetime of 20 years. Current research work attempts to enhance their efficiency though better separation of electrochemical cells and integration of new material into each cell [344].

Figure 79 Golden Valley Scheme, Alaska. Capable of supplying 40 MW over 7 min, this scheme is rated the most powerful in the world (photo courtesy of Golden Valley Electric Association)

Nickel Metal Hydride (NiMh)

Essentially an alternative to NiCd batteries; Nickel metal hydride batteries have improved performance over NiCd (i.e. none-toxicity and a 25 to 30% higher energy density). In spite of fewer weaknesses compared to NiCd and PbA batteries, they remain more expensive and suffer severe self-discharge problems; making them inefficient as a long-term storage solution [341]. Self-discharge is known to be caused by decomposition of positive active material ((NiOOH), hydrogen gas evolution (the negative electrode), and also electrolyte deterioration. Current research therefore attempts to eradicate these problems[345]. Notwithstanding this, a combination of output power, reliability and cost has made them a favourite with Hybrid Electric Vehicle technology.

Lithium Ion (Li-ion)

A very successful technology, Li-ion batteries have, in less than 20 years, practically managed to displace other technologies in what is referred to as 3C sector (Cameras, Cellphones and Computers)[343] . The primary reason behind their success is their high power density (110-160 Wh/kg) and reasonable cycle life. The need to maintain them within a closely defined operational envelope dictates the use of sophisticated management systems, which together with expensive component material accounts for their high costs. The development of new anode, cathode and electrolyte technologies, plus new solid state ionics is hoped to take Li-ion batteries beyond their current limitation of consumer electronics onto auto-motive, power utility and marine sector[346].

Sodium-sulphur (NaS)

Details of this technology were first released by Ford Motor Company in 1966. Later, Tokyo Electric Power Company (TEPCO) and NGK Insulator Ltd were the primary contributors to the development of NaS batteries. NGK formally introduced Sodium-Sulphur to the world market in 2002; and despite global take-up, NaS is principally installed in Japan, spreading gradually in North America as time progresses[347].The principles of NaS operation relies on Sodium and Sulphur, both in liquid forms, to act as anode and cathode, with Beta-Alumina acting as both the separator and the electrolyte simultaneously. To maintain both electrodes in molten form, heat input is required to sustain an operating temperature of 300-350°C. This might give an impression of inefficiency, although given the battery's 100% coulombic efficiency (it suffers no self-discharge), an average of 85% DC conversion efficiency can be realised. This, together with a power density 3 times that of Lead Acid batteries, make NaS a promising technology. An 8MW, 58 MWh system installed at a Hitachi automotive plant in Japan is currently the world's largest battery in terms of Storage Capacity [343].

Flow batteries

Flow batteries; where two reservoirs of electrolyte facilitate the migration of electricity to and from the Cathode and Anode (depending on charge/discharge mode) are another prominent storage device. The energy and power density are respectively dictated by electrolyte volume and electrolyte reaction. The leading current technologies are

- Polysulphide Bromide (PSB)
- Vanadium Redox (VRB)
- Zinc Bromide (ZnBr)
- Cerium Zinc (CeZn) which is relatively new to the market.

Extensive research work has concentrated on increasing the power and energy density of flow batteries. High expectations are placed on mesoporous carbon for its increased specific and volumetric surface area as well as micro-reactor technology. In micro-reactors, chemical reaction happens on a chip, enabling high rates of mass transfer, easy control of power output and decreased maintenance because of small scale.

Future horizons

Li-ion, NaS and NiCd present the leading technologies in high power density batteries. Li-ion however retains the leading edge as it has a high energy density and storage efficiency close to 100%; although it requires increased power density for some applications. A 10m ×10m × 10m Lithium battery installation can store 400 MWh, equivalent of annual energy consumption of 83,000 UK households and comparable to a wind-farm; an indication of significant potentials of Li-ion technology [348].

The overall efficiency of batteries covered so far has been compared in a study by Rydh, C.J. and B.A. Sandén [349] and the results are summarised in Figure 80:

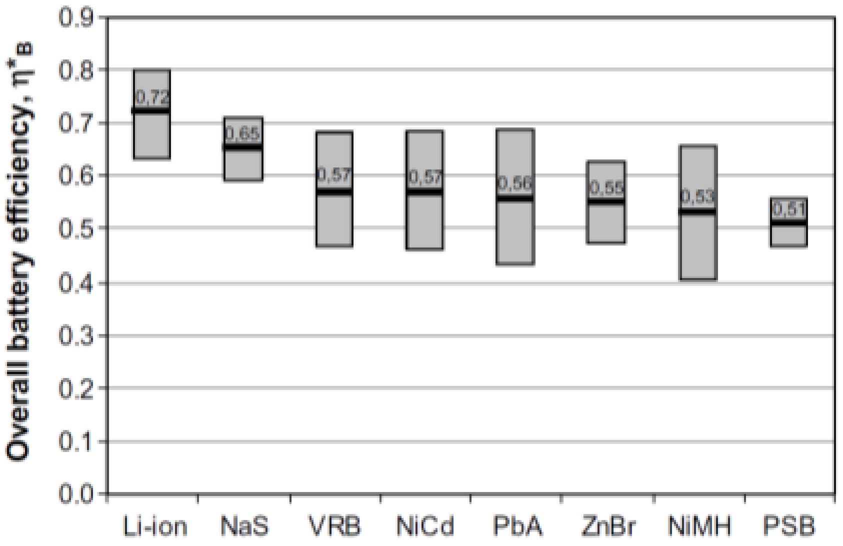

Figure 80 Analysis of battery efficiencies.

These figures take into account both the production and the transport of batteries and inverters.

Electrochemical supercapacitors

These are high power density storage technologies whereby the use of high surface area carbon electrodes and significant reduction in plate separation achieve high levels of capacitance. Supercapacitors have storage efficiencies of

>95% and can be cycled hundreds of thousands of times. As they represent the greatest life-time in terms of cycling ability, they are therefore used in portable appliances and automotive industries. Their disadvantage is susceptibility to self-discharge. Nonetheless they offer the best solution in high power-density energy storage and extensive research is currently focused on improving their performance.

Superconducting Magnetic Energy Storage (SMES)

The basis for these devices are the storage of electricity in the form of a magnetic field which is created by the flow of direct current in a superconductor. Since superconductors offer no resistance to the flow of electricity, energy loss in SMES is effectively zero. Losses are however associated with refrigeration and AC/DC conversion. Overall system efficiency of 98% can hence be achieved. Refrigeration is required to cool the device to below superconducting critical temperature; which is about 4.2K where liquid helium is used (low temperature SMES) and 20K when liquid nitrogen is used. Refrigeration and the high superconducting wire costs mean that SMES is currently only used to improve power quality. Most SMES devices cover the micro scale (1-10 MW). Although technical hurdles exist in further development of SMES, the development of 100 MW devices with efficiencies of 99% and a 40 year lifespan is a realistic goal by 2050. Such advancement will make SMES an integral part of power quality management.

Kinetic Energy Storage: Flywheels

Flywheels are basically rotating cylinders that are supported by magnetic bearings. High installation costs and frictional losses are the main disadvantages of flywheels [338] .To eliminate frictional losses high performance flywheels operate in a vacuum. Flywheels endure extremely high angular velocities that necessitate precision engineering. This contributes to the overall costs of these devices and results in high energy storage costs. As a result flywheels are less competitive compared to other forms of energy storage. Large arrays of flywheels have proved successful in frequency management, although they mainly retain the role of a power quality tool, in particular in Uninterruptable Power Supplies (UPS). Critical mission building design applications (i.e. data centres) are currently the only place where this technology is deployed.

The technologies that have been covered above all seek to improve energy efficiency of a building, ultimately seeking to sustain or improve human comfort in buildings. Extensive work has been done on how to optimise the management of energy and comfort simultaneously [67, 166, 350-355]. Primarily (but not inclusively) these works regard human comfort a constraint with cost, energy or carbon being the cost objective. Next we examine all aspects of human comfort with a greater emphasis on thermal (and particularly) adaptive comfort to provide a different perspective to the static comfort condition that until recently dominated the research work.

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