Impact of Climate Change on

Newly Detached Residential Buildings in the UK

Passive Mitigation and Adaptation Strategies

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Declaration of Authorship

I, Joseph Amoako-Attah, declare that this thesis titled, 'Impact of Climate Change on Newly Detached Residential Buildings in the UK – Passive Mitigation and Adaptation Strategies' and the work presented in it are my own. I confirm that:

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- Where I have consulted the published work of others, this is always clearly attributed.
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Abstract

Thesis title: Impact of Climate Change on Newly Detached Residential Buildings in the UK – Passive Mitigation and Adaptation Strategies

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The global increase in demand for dwelling energy and implications of changing climatic conditions on buildings require the built environment to build sustainable dwellings. The aim of this thesis is to apply passive mitigation and adaptation design strategies to newly detached residential buildings in the UK with the view to identify the key building envelop and systems parameters to secure the right balance of energy consumption and thermal comfort in dwellings. In addition, currently, acceptable robust validation process for validating space temperatures is required, as existing simulation software validation is geared toward energy consumption. The thesis further aims to apply an effective validation method to the validation of building simulation indoor temperatures.

This thesis comprised of six case studies. In the first study, Bland-Altman's method of comparison is used as a validation technique in validating space temperatures in building simulation application. This is a newly developed knowledge in civil and construction engineering research in validating thermal analysis simulation software. The relevance of this approach is due to the emergent understanding that the goodness of fit measures used in current building

simulation model validation are inadequate coupled with that fact that the current simulation software validation are geared toward energy consumption.

In the second study, global Monte Carlo sensitivity analysis is performed on two differing weather patterns of UKCIP02 and UKCP09 weather data sets to compare their impact on future thermal performance of dwellings when use in thermal analysis simulation. The investigation seeks to ascertain the influential weather parameters which affect future dwelling indoor temperatures. The case study when compared to literature affirms the mean radiant temperature and the dry bulb air temperature as the key parameters which influence operative temperatures in dwellings.

The third study, the extent of impact of climate change on key building performance parameters in a free running residential building is quantified. The key findings from this study were that the average percentage decrease for the annual energy consumption was predicted to be 2.80, 6.60 and 10.56 for 2020s, 2050s and 2080s time lines respectively. A similar declining trend in the case of annual natural gas consumption was 4.24, 9.98 and 16.1, and that for building emission rate and heating demand were 2.27, 5.49 and 8.72 and 7.82, 18.43 and 29.46 respectively. This decline is in consonance with the range of annual average temperature change predicted by the GCM based on the IPCC scenarios (IPCC, 2001) which generally shows an increase in temperature over stipulated timelines. The study further showed that future predicted temperature rise might necessitate the increasing use of cooling systems in residential buildings. The introduction of cooling to offset overheating risk, the trend of heating and cooling demand shows progressive increase variability with an average percentage increase of 0.53, 4.68 and 8.12 for 2020s, 2050s and 2080s timelines respectively. It is therefore observed that the introduction of cooling cancels out the energy gains related to heating due to future climatic variability.

The fourth, fifth and sixth case studies consider the integrated passive mitigation strategies of varying future climatic conditions, variable occupant behaviour, building orientation, adequate provision of thermal mass, advance glazing, appropriate ventilation and sufficient level of external shading which influence the potential thermal performance of dwellings and a methodology that combines thermal analysis modelling and simulation coupled with the application of CIBSE TM52 adaptive overheating criteria to investigate the thermal comfort and energy balance of dwellings and habitable conservatories.

In the fourth study, the impact of four standardized construction specifications on thermal comfort on detached dwellings in London, Birmingham and Glasgow are considered. The results revealed that the prime factor for the variation of indoor temperatures is the variability of climatic patterns. In addition, London is observed to experience more risk of thermal discomfort than Birmingham and Glasgow over the time period for the analysis. The total number of zones failing 2 or 3 CIBSE TM52 overheating criteria is more in London than in Birmingham and Glasgow. It was also observed that progressive increase in thermal mass of the standardized construction specifications decrease the indoor temperature swings but increase in future operative temperatures. The day ventilation scenario was seen not to be effective way of mitigating internal heat gains in London and Birmingham. The opposite was observed in Glasgow. Night ventilation coupled with shading offered the best mitigation strategy in reducing indoor temperatures in London and Birmingham.

In the fifth study, Monte Carlo sensitivity analysis is used to determine the impact of standard construction specifications and UKCP09 London weather files on thermal comfort in residential buildings. Consideration of London urban heat island effect in the CIBSE TM49 weather files leading to the generation of three different weather data sets for London is analysed. The key findings of the study indicated that in the uncertainty analysis (box and whiskers plots), the medians for the day ventilation scenarios are generally higher than those of the night ventilation and further higher than the night ventilation with shading scenarios. This shows that applying mitigation scenarios of night ventilation and shading have a significant impact on reducing internal operative temperatures. In addition, the sensitivity analysis shows glazing as the most dominant parameter in enhancing thermal comfort. The sensitivity of glazing to thermal comfort increases from Gatwick, with London Weather Centre having the highest sensitivity index. This could be attributed to the urban heat island effect of central London, leading to higher internal operative temperatures. The study thus shows that more consideration should be given to glazing and internal heat gains than floor and wall construction when seeking to improve the thermal comfort of dwellings.

Finally, the sixth study considers the use of passive solar design of conservatories as a viable solution of reducing energy consumption, enhancing thermal comfort and mitigating climate change. The results show that the judicious integration of the passive solar design strategies in conservatories with increasing conservatory size in elongated south facing orientation with an aspect ratio of at least 1.67 could progressively decrease annual energy consumption (by 5 kWh/m^2), building emission rate (by 2.0 $KgCO_2/m^2$) and annual gas consumption (by 7 kWh/m^2) when the conservatory is neither heated nor air-conditioned. Moreover, the CIBSE TM52 overheating analysis showed that the provision of optimum ventilation strategy depending on the period of the year coupled with the efficient design of awnings/overhangs and the provision of external adjustable shading on the east and west facades of the conservatory could significantly enhance the thermal comfort of conservatories.

The findings from these case studies indicate that thermal comfort in dwellings can be enhanced by analysis of future climatic patterns, improved building fabric and provision of passive design consideration of improved ventilation and shading. They also confirm that the utilization of appropriate mitigation strategies to enhance thermal comfort could contribute to the reduction of the environmental implications to the built environment and facilitate the drive towards the attainment of future sustainability requirements.

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List of Acronyms/Abbreviations

A1B	Medium emission scenario
A1F1	High emission scenario
A2	Medium-high emission scenario
ACH	Air changes per hour
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ANSI	American National Standards Institute
B1	Low emission scenario
B2	Medium-low emission scenario
BER	The Building Energy Rating
BIA	Bio-impedance analysis
BRE	Building Research Establishment
BRUKL	Building Regulations United Kingdom Part L
BS	British Standard
CEN	European Committee for Standardization
CDF	Computational Fluid Dynamics
CGCM2	Coupled Global Climate Model
CIBSE	Chartered Institution of Building Services Engineers
CLG	Communities and Local Government
CO_2	carbon-dioxide
CVRMSE	Coefficient Variation of the Root Mean Square Error
DA	Daylight Autonomy
DCLG	Department of Communities and Local Government
DEC	Display Energy Certificate
DECC	Department of Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DOE-2	Building Energy Use and Cost Analysis

DHEWRMT	Daily Hourly Exponentially Weighted Running Mean Temperature
DHW	Domestic Hot Water
DSY	Design Summer Year
DXA	Dual-energy X-ray Absorptiometry
E	Emissivity
EDSL	Environmental Design Solutions Limited
EN ISO	International Organization for Standardization, European Norm
EnergyPlus	Energy Simulation Software
EPC	Energy Performance Certificate
ESP-r	integrated energy modelling tool
EST APEE	Energy Saving Trust Advanced Practice Energy Efficiency Standard
EST BPEE	Energy Saving Trust Best Practice Energy Efficiency Standard
FEES	Fabric Energy Efficiency
FENSA	The Fenestration Self-Assessment Scheme
G-value	coefficient of solar energy transmittance of glass
GCM	General Circulation Models
GeSI	Global e-Sustainability Initiative
GtC/yr	Giga-tonne of Carbon per year
HadCM3	Hadley Centre Coupled Model, version 3
HVAC	Heating, Ventilation and Air Conditioning
IBM SPSS	International Business Machine Corporation Statistical Package for the Social Sciences
ICT	Information and communications technology
IPCC	Intergovernmental Panel on Climate Change
IPMVP	The International Performance Measurement and Verification Protocol
K	Unit of measurement of temperature, Kelvin
kWh/m^2	Kilowatt hours per square metre

MVHR	Mechanical Ventilation and Heat Recovery
$KgCO_2/m^2/yr$	Carbon dioxide emissions indicator
LHR	London Heathrow Airport
LWC	London Weather Centre
MOHC	Meteorological Office Hadley Centre
MBE	Mean Bias Error
NCM	National Calculation for Methodology
ODPM	Office of the Deputy Prime Minster
OECD	Economic Co-operation and Development
ONS	Office for National Statistics
PCC	Partial Correlation Coefficient
PPD	Predicted Percentage of Dissatisfied
ppm	parts per million
PMV	Predictive Mean Vote
RCM	Regional Climate Models
RMSE	Root Mean Square Error
SAP	Standard Assessment Procedure
SBEM	Simplified Energy Model
SE	Standard Error
SHGC	Solar Heat Gain Coefficient
SPA	Single Photon Absorptiometry
SRC	Standardized Regression Coefficient
SRES	Special Report on Emissions Scenarios
SXA	Single X-Ray Absorptiometry
T_{max}	daily maximum temperature (^oC)
T_{min}	daily minimum temperature (^oC)
T_{op}	average indoor operative temperature (^oC)
T_{rm}	exponentially weighted running mean temperature (^oC)
TAS	Thermal Analysis Simulation software

TM	Technical Memorandum
TRNSYS	Transient System Simulation tool
TRY	Test Reference Year
U-value	thermal transmittance
UDI	Useful Daylight Illuminance
UKCIP02	United Kingdom Climate Projections 2002
UKCP09	United Kingdom Climate Projections 2009
WCDH	Weighted Cooling Degree Hours
XML	Extensible Markup Language
ZCH	Zero Carbon Hub

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List of Publications arising from this thesis

The following publications have been produced and/or presented in advance of the thesis.

Articles in peer-reviewed journals

1. **Amoako-Attah, J., and B-Jahromi, A.** 'Impact of future climate change on UK building performance', *Advances in Environmental Research (AER): An International Journal of interdisciplinary research in environmental science, technology, and management, Techno-Press*. 2013, Vol. 2, No.3, pp. 203-227.

2. **Amoako-Attah, J., and B-Jahromi, A.** 'Impact of Standard Construction Specification on Thermal Comfort in UK Dwellings', *Advances in Environmental Research (AER): An International Journal of interdisciplinary research in environmental science, technology, and management, Techno-Press*. September 2014, Vol. 3, No.3, pp. 253-281

3. **Amoako-Attah, J., and B-Jahromi, A.** 'Method comparison analysis of dwellings' temperatures in the UK', *Proceedings of the Institution of Civil Engineers journal Engineering Sustainability.* 168 February 2015 Issue ES1 Pages 16-26.

4. **Amoako-Attah, J., and B-Jahromi, A.** "Impact of Conservatory as passive solar design of UK dwellings" Proceedings of the Institution of Civil Engineers journal Engineering Sustainability. Accepted for publication on August 12, 2015. doi:10.1680/ensu.14.00040 (in press).

Conference paper submissions

1. **Atkinson, L., Amoako-Attah, J., and B-Jahromi, A.** *'Government's influence on the implementation of BIM',* Paper ID 440, 2014 International Conference on Computing in Civil and Building Engineering, ICCCBE, June 2014, Orlando, Florida, USA.

2. **Amoako-Attah, J., and B-Jahromi, A.** *'Evaluating the Impact of Conservatory as a passive solar design on energy performance and internal temperatures of UK detached dwellings',* Paper assigned ID 37, 2014 14th International Conference on Construction Applications of Virtual Reality, 16-18 November, 2014, Sharjah, UAE.

CHAPTER 1: Introduction

This chapter introduces the research on the impact of climate change on newly detached residential buildings in the United Kingdom – passive mitigation and adaptation strategies. The chapter discussion includes the research background and context, the identified knowledge gap, statement of research focus, research questions and objectives which drive the six case studies in the work and the research structure and chapter layout.

1.1 Research Background and Context

The United Kingdom is currently confronted with a challenge to strategically attain its two major goals in its Energy policy of reducing carbon dioxide emissions to agreed standards and the provision of affordable energy to meet high expectations for sustainable energy. The 2008 Climate Change Act requires the UK to cut 34% of 1990 carbon dioxide emissions by 2020 and 80% cut by 2050 (DECC 2011a). The 26 million dwellings in Britain (ONS 2009) are responsible for a large proportion of carbon dioxide emissions. In 2010 the domestic energy consumption as compared to the total energy consumption in the country was 32% (DECC 2011).

In spite of the improvements in residential building construction, domestic energy consumption in the United Kingdom increased by 18% between 1970 and 2009, and more than 50% was used for space heating (ONS 2011). Vaughan (2011) advances that this is partly related to occupants increased use of space heating, appliances and lighting and also population growth and demographics where there is an increase in one-person households.

The impact of varying climate patterns and high thermal implications to various building occupants, geographic locations, building type and function will present a challenge in building sustainable buildings (Lomans and Giridharan 2012) and is a concept acknowledged by the scientific and political communities (Nicol et al. 2009). The anticipated growth of smart cities and the efficient functional advancement in ICT may drive a shift away from overdependence of office work and concentrate rather more on remote working from home (CIBSE TM55, 2014). This shift in working practise coupled with climate change will require having dwelling energy efficiency and the desired thermal comfort. The foreseen rise in future indoor temperatures by several degrees could lead to the increasing use of building cooling systems in the existing stock of free-running naturally ventilated dwellings in the UK, thus affecting the UK government set targets of reducing greenhouse gas emissions and mitigating climate change (Nicol et al, 2009).

Judicious making of informed long term strategic infrastructure investments decisions involve cost and sustainable environmental consideration in relation to building performance and occupancy comfort. Over the years, based on the knowledge to design and build with the view to reduce carbon dioxide emissions, professionals in the building industry have adapted two main approaches. Whilst one approach has been related to the reduction in the building energy demand through the appropriate selection of building elements and design, a converse approach has been the adaptation of renewable systems (Palme et al., 2013).

Although, these two approaches have led to the enhancement and improvements of building performance predictability, yet the future accuracy in real building performance cannot be ascertained due to the variability of climatic conditions (Palme et al., 2013). In general, the variability and impact of climate change to buildings and its components have been largely ignored (Crawley, 2008). Moreover, investigations ought to be pursued in the area of primary energy consumption and carbon emissions in relation to energy demands (Palme et al., 2013).

Furthermore, there is a global limited research on the impact of current climatic variability on buildings in areas such as heating and cooling demand, energy usage, equipment life and occupant comfort (Crawley, 2008). Buildings life time spans tallies with the projected trends of climatic variation (De Wilde and Coley 2012), an indication that the built environment should take cognisance of climatic variability in its design and build while considering the aim of improving building performance indicators and contribute to the overall global effort of greenhouse emission reduction.

Evidence exist that some work has been undertaken by professionals in the building industry to relate the variability of future climatic conditions to building performance. Whilst future weather information has been used in these studies, almost all of these studies were published prior to the advent of the UK Climate Projection 2009. The UK Climate Projection 2009 present the most advanced comprehensive future weather information for our century, thus resulting in a more accurate and reliable predictive building performance indicators using building simulation methods (Du et al., 2011). In addition, although currently extensive research have been done on the output of the UKCP09 in relation to building performance, the various analysis were based on the weather variables rather than varying building performance indicators (William et al., 2011).

Moreover, there are other related issues in modelling energy usage in buildings. Building materials and controls may be altered from the design specifications coupled with poor workmanship, model simplifications, poor management and maintenance practices (Demanuele et al. 2010). In addition, the type of building materials and external factors such as weather variations and building schedule are contributing factors (Turner and Frankel 2008). The challenge to accurately select modelling parameters to model energy performance in buildings is attributed to over-simplified modelling assumptions (Brounen 2011). These areas ought to be investigated in conjunction with the varying characteristics of occupants in energy simulation (Azar and Menassa 2010).

In addition, there is general lack of comprehensive studies of what encompass the inter-relationship between all the design variables associated with optimal year-round energy conservation and thermal comfort of conservatory form and performance metrics in the United Kingdom. In his work “Optimization of passive solar design strategies: A review” Sanja Stevanovic in 2013 provides an exhaustive review of about 80 simulation-based optimization of passive design strategies research publications since 2000 but no mention of conservatories as a passive design solution in UK is mentioned. Moreover, there is knowledge gap in the investigation of surface to volume ratio and aspect ratio of conservatories to facilitate optimum thermal performance design for current and future weather patterns variations.

This work seeks to address these issues and therefore employs integrated passive design strategies of varying future climatic conditions, variable occupant behaviour, building orientation, adequate provision of thermal mass, advance glazing, appropriate ventilation and sufficient level of external shading which influence the potential thermal performance of dwellings and a methodology that combines thermal analysis modelling and simulation to investigate the thermal comfort and energy balance of dwellings and habitable conservatories attached to detached dwellings in the UK using the CIBSE test reference year (TRY) and design summer year (DSY) emission scenarios for the current and future (2020's, 2050's and 2080's) climatic change projections.

The Zero Carbon Home in their March 2015 publication "Defining Overheating. Evidence Review" indicated the need to investigate the relevance of adaptive thermal algorithm to the domestic sector in the design of homes. The publication further indicated the need for a comprehensive methodology for the design of homes to assess annual and seasonal performance without adding considerable resource requirement to existing practices (ZCH 2015). The work therefore makes application of the CIBSE TM52 adaptive comfort criteria to assess overheating in the various case study buildings.

The work is further enhanced by incorporating Bland-Atman's method of comparison as a validation tool in building simulation. This serves as a knowledge contribution to the civil and construction engineering practice in the area of building simulation validation.

With the increase in population and demand for residential accommodation coupled with the cost of energy becoming more expensive, it is imperative to model and appropriately manage energy usage since this is necessary for the economic stability, growth and social wellbeing. Moreover, this field of research is highly relevant to issues involving climate change effects coupled with sustainable development and thus will not only contribute towards the achievement of the UK's broader energy consumption goals and the global quest for sustainable energy but also to building engineering practice.

1.2 Stated gap in knowledge

The scholarly features of this work are underpinned by the application of thermal analysis simulation software as an instrument to investigate and modestly contribute to the transformation of energy demand in the built environment. This study identifies the need for further research in the following areas:

1. Key finding 1 from literature review:
   The use of Bland-Altman's method of comparison as a validation technique in building simulation application.

2. Key finding 2 from literature review:

The impact of current and future climatic variability on buildings in area of thermal comfort based on CIBSE TM52 overheating criteria using the current CIBSE Design Summer Year (DSY) weather data set morphed from the UK Climate Projection 2009 weather information.

3 Key finding 3 from literature review:

The comparison of CIBSE TM48 and CIBSE TM49 weather data sets impact on thermal comfort of residential dwellings using deterministic, uncertainty and sensitivity analysis.

4 Key finding 4 from literature review:

A comparison of the impact of standard construction specifications in thermal comfort optimization in detached dwellings.

5 Key finding 5 from literature review:

Employing passive design techniques in conservatory to secure the right balance between energy performance and thermal comfort of dwellings due to the absence of modelling and simulation research/current publication into the use of conservatories as passive design solution in the UK.

1.3 Statement of Research Focus, Research Questions and Objectives

1.3.1 Aim/Focus

The main focus of this research is to evaluate and predict the impact of current and future variable climatic patterns on detached dwellings energy and thermal performance and further investigate how building total energy demand and thermal comfort will be improved through resilient building design using thermal analysis simulation software. The study further investigates the use of Bland-Altman's method of comparison as a technique for validation of building simulation.

1.3.2 Research Questions

The thesis aims to answer the following six questions in a form of six case studies;

Case study 1: How can internal operative temperature results from thermal analysis simulation be validated?

Case study 2: How does the impact of varying future climatic patterns of UKCIP02 and UKCP09 weather data sets compare when use in thermal analysis simulation to investigate thermal performance of dwellings?

Case study 3: How do the varying future climatic patterns affect the energy performance of dwellings?

Case study 4: How can passive mitigation and adaptation strategies be employed to optimize thermal comfort in dwellings?

Case study 5: What are the most influential building envelope and systems parameters which affect thermal comfort in dwellings?

Case study 6: How can passive design techniques be employed in conservatories to secure the right balance between energy performance and thermal comfort and further mitigate climate change?

1.3.3 Objectives

The essence of the six case studies is to investigate through modelling and simulation the impact of future climatic conditions on residential buildings and examine the variability in and quantify energy consumption, internal operative temperatures and carbon dioxide emission patterns under one umbrella with the view to apply passive design solutions as mitigation and adaptation strategies. The key objectives which drive the success of this work are as follows:

Case study 1: (Chapter 4) Explore the use of Bland-Altman's method of comparison as building simulation validation technique in analysing the statistical agreement between monitored dwelling temperatures and thermal analysis simulated operative temperatures of detached dwellings.

1a. Perform modelling and simulation on an identified detached dwelling.

1b. Conduct experiment to monitor and record the outdoor and a zone internal operative temperatures using approved efficient monitoring system.

1c. Establish a priori criteria for the bias and precision based on acceptable adaptive comfort standard.

1d. Evaluate the results using Bland-Altman’s method of comparison as a validation technique and ascertain its use as a new approach in civil and construction engineering research.

Case study 2: (Chapter 5) Investigate and quantify the variability of impact of climate on building thermal comfort considering the selected comparable CIBSE TM48 and CIBSE TM49 weather data set.

2a. Perform modelling and simulation on an identified detached dwelling.

2b. Based on identified input weather parameters from the simulation results develop an appropriate model for Monte Carlo uncertainty and sensitivity analysis to ascertain the most influential parameters which contribute to the internal operative temperature in dwellings.

2c. Perform Monte Carlo uncertainty and sensitivity analysis coupled with deterministic analysis consideration to identify the most influential weather parameters which contribute to thermal comfort.

2d. Compare the results with literature to affirm the key parameters which influence operative temperatures in dwellings.

2e. Analyse the variability of the selected comparable CIBSE TM48 and CIBSE TM49 weather data set on internal operative temperatures of dwelling.

Case study 3: (Chapter 6)	Evaluate and predict the impact on varying future climatic patterns on five building performance indicators.
	3a. Perform modelling and simulation of ten (10) newly built detached dwellings.
	3b. Improve the accuracy of the simulation through the appropriate selection of modelling parameters and assumptions.
	3c. Evaluate and predict the impact of future climatic variations on the ten (10) newly built detached dwellings.
	3d. Investigate the impact of future climate change on building performance indicators of total annual energy consumption, annual gas consumption, annual electricity grid consumption, building emissions rate and heating demand.
	3e. Perform heating and cooling demand analysis to ascertain the need of cooling demand in the United Kingdom with future prediction of increasing temperature.
Case study 4: (Chapter 7)	Examine the current and future thermal comfort implications of identified different standardized construction specifications which show a progressive increase in thermal mass and airtightness and incorporate passive design techniques as

mitigation and adaptation strategies for overheating in three cities in the United Kingdom.

4a. Perform series on modelling and simulation based on current and future weather data set on the identified different standardized construction specifications for the three identified locations of London, Birmingham and Glasgow.

4b. Explore the use of CIBSE TM52 criteria as an overheating assessment tool in naturally ventilated dwellings.

4c. Perform deterministic analysis to ascertain the effectiveness of the mitigation and adaptation strategies on thermal comfort.

Case study 5: (Chapter 8)	Investigate and quantify the variability of impact of climate change of three locations of Gatwick, Heathrow and London Weather Centre on building thermal comfort considering the identified four standardized construction specification with varying thermal mass and airtightness and passive design solutions using selected CIBSE TM49 weather data set. 5a. Perform modelling and simulation on an identified detached dwelling. 5b. Based on identified input mitigation and adaptation parameters from the simulation results develop an appropriate model for Monte Carlo uncertainty and sensitivity analysis to

ascertain the most influential parameters which contribute to the internal operative temperature in dwellings.

5c. Perform Monte Carlo uncertainty and sensitivity analysis coupled with deterministic analysis consideration to identify the most influential weather parameters which contribute to thermal comfort.

5d. Analyse the variability of the mitigation and adaptation strategies based on the four standardized construction specifications coupled with the passive design solutions to ascertain the key input parameters which influence thermal comforts.

5e. Compare the results with literature to affirm the key parameters which influence operative temperatures in dwellings.

Case study 6: (Chapter 9)	Investigate the possibility of using conservatory as a passive design solution.

6a. Perform modelling and simulation on an identified detached dwelling with varying sizes of conservatory.

6b. Explore the use of integrated passive design strategies to optimise solar radiation gains in the conservatory to secure the right balance of energy consumption and thermal comfort throughout the year.

6c. Explore the use of CIBSE TM52 criteria for adaptive thermal comfort criteria for both overheating and underheating assessment.

6d. Investigate the impact of integrating passive solar strategies in conservatory design on building performance indicators of total annual energy consumption, annual natural gas consumption and building emissions rate.

1.4 Research structure and chapter layout

The structure of the thesis as indicated below outlines the doctoral element of this work which seeks to answer the objective framework described at outset of this chapter. The work is organized into ten chapters.

Chapter 1: Introduction

The current chapter; the introduction, lays out the background, the stated gap in current knowledge, the research questions, the objectives of the study, the main structure of the thesis. It further touches on the relevance of the thesis topic insofar as it contributes to the UK's attainment of its energy policy goals.

Chapter 2: Literature review

This chapter offers a critical literature review of the main issues that underlie the objectives of the research. These include the impact of climate change on buildings, building modelling and simulation, building thermal performance, energy conservation and reduction of carbon dioxide emission, passive design solutions and validation of thermal analysis simulations. The chapter further discusses the current work in the area of developing an appropriate weather data files required to enhance building simulations outputs.

Chapter 3: Methodology

This chapter considers the design of the research. The research is based on quantitative methodology which is underpinned by thermal simulation analysis coupled with deterministic and Monte Carlo uncertainty and sensitivity consideration to analysis and model the impact of variable current and future climatic patterns on detached dwellings energy usage, thermal performance and carbon dioxide emissions. The analysis seeks to identify input parameters and various passive design scenarios which have a significant impact on building energy and thermal performance. The methodology indicated the modelling and simulation process and further stipulates the simulation assumptions.

Chapter 4: Method comparison analysis of detached dwelling temperatures in the United Kingdom

This chapter which is the first case study investigate the use of Bland-Altman's method of comparison analysis as a building simulation validation technique. The results points to the use of this approach as a credible statistical validation method for evaluating the agreement between monitored and simulated internal operative temperatures using the EDSL TAS program.

Chapter 5: Impact of climate change variability on building thermal performance - consideration of only varying weather data sets scenarios

This chapter which is the second case study explores the variability between the CIBSE TM48 and CIBSE TM49 Design Summer Year weather files for London Heathrow, Gatwick and London Weather Centre for the current, 2020s, 2050s and 2080s weather data sets. Based on Monte Carlo simulation for uncertainty and sensitivity quantification, the chapter further seeks to investigate the key weather parameters which influence the thermal comfort on dwellings. The drive towards the use of CIBSE TM49 is also to ascertain the urban heat island effect incorporated in the London Weather Centre weather data sets as compared to the Heathrow and Gatwick weather files. The overheating analysis is underpinned by CIBSE TM52 adaptive thermal comfort criteria.

Chapter 6: Impact of climate change on building energy performance - consideration of only varying weather data sets scenarios

This chapter which is the third case study investigates the impact of changing climatic patterns on ten (10) newly built detached dwellings in the United Kingdom using the CIBSE TM48 Test Reference Year weather data sets for the current, 2002s, 2050s and 2080s timelines. The study evaluates and quantifies the predicted impact of climate change based on five key building energy performance indicators. The chapter further considers the future cooling needs of residential buildings.

Chapter 7: Impact of four standard construction specifications on thermal comfort in three major cities in the United Kingdom.

This chapter which is the fourth case study is based on deterministic analytical approach to conduct interactive investigation on four different standardized construction specifications which show a progressive increase in thermal mass and airtightness coupled with various ventilation and shading scenarios to determine their impact on thermal comfort in London, Birmingham and Glasgow. The CIBSE TM48 Design Summer Years weather data sets for the current, 2020s, 2050s and 2080s timelines and the CIBSE TM52 adaptive thermal comfort criteria for overheating analysis are used in the study.

Chapter 8: Impact of four standard construction specifications on thermal comfort in three major weather locations in London.

This chapter which is the fifth case study is based on Monte Carlo uncertainty and sensitivity analysis to conduct interactive investigation on four different standardized construction specifications which show a progressive increase in thermal mass and airtightness coupled with various ventilation and shading scenarios to determine their impact on thermal comfort of dwellings in London Weather Centre, Heathrow and Gatwick. The CIBSE TM49 weather data set for 2003_2050 medium design summer year with 50% probabilistic scenario timeline and the CIBSE TM52 adaptive thermal comfort criteria for overheating analysis are used in the study. The study further seeks to identify the most influential building envelope and systems parameters and explore their related uncertainty and sensitivity contribution of building adaptation strategies of the four standardized construction specifications which affect thermal comfort.

Chapter 9: Conservatory as a passive design solution

This chapter which is the sixth case study explores the use of dwelling conservatory as a passive design solution. The work seeks to apply integrated passive design strategies to optimize the energy performance and thermal comfort of dwellings using CIBSE TM52 adaptive thermal comfort criteria as an assessment tool.

Chapter 10: Conclusion

The final chapter highlights the main conclusions drawn from the preceding chapters and offers a summary of conclusions for the thesis. The practical application of the findings and the modest contributions of this work to knowledge are also highlighted. This is followed by suggestions for logical continuation and development of the thesis.

CHAPTER 2: Literature Review of impact of climate change on building performance and passive design strategies

2.1 Impact of Varying Climatic Patterns on Building Performance

The impact of global warming resulting to changes in the world's climatic conditions is widely acknowledged (Palme et al., 2013), (Du et al., 2011), (De Wilde and Coley 2012) (UKCP, 2010) and the evidence requires little justification to point to the impact of climate change on building. The Inter-government Panel on Climate Change (IPCC) fourth assessment report indicated that the rise of world temperature as a result of possible anthropogenic emissions of greenhouse gases in our century would vary between the ranges of 1.1 to 6.4^{o}C from a 1990s baseline towards the end of the 21th century (IPCC, 2007).

Studies related to the analysis of the future climatic patterns show increases in the number of days with high temperatures in the United Kingdom (UKCP, 2010). The mean daily maximum temperatures were observed to have an increase range between 2.2 and 9.5 ^{o}C (UKCP, 2010). Whilst the mean daily minimum observable trends in winter temperatures show a range of increase between 0.6 and 5.95 ^{o}C with reference to specific locations (UKCP, 2010).

Moreover, the projected increase in summer mean temperatures based on the UKCP09 climatic projection medium emission scenario for the 50th probability level for the Southern England, is estimated to be an increase in temperature of 4.2 degrees Celsius by the 2080s, with 2.2 to 6.8 degrees Celsius representing the 10th and 90th probability range respectively and the mean daily maximum temperatures for the 2080s were estimated to be increased by 5.4 degrees Celsius, with 2.2 to 9.5 representing the 10^{th} and 90^{th} probability range respectively (Murphy et al. 2009),(Mylona 2012). In addition, London has historic experience of heat waves in 1976 and 2003, with the August 2003 temperatures exceeding 37 degrees Celsius with over 2000 people related death from heat wave coupled with the urban heat island effect realised in Central London.

These findings present vivid evidence that the climatic projections point to a long term warming climate which will result in the reduction of winter heating demand and an increase in summer cooling demand (Palme et al., 2013). Thus, changes in weather condition may impact building performance (William et al., 2011).

As there is a direct bearing of changes in climatic conditions on buildings in relations to buildings energy performance and thermal comfort, it is necessary for the building industry to research on the impact of climate change on building performance. Furthermore, in building performance practice, it is imperative to secure reliable formatted multi-year weather files which have been prepared from reliable meteorological predictions to assess the energy performance and overheating risk in buildings.

2.2 Description of weather datasets and sources

2.2.1 The United Kingdom Climate Projections 2002 (UKCIP02)

In 2002, the Department for Environment, Food and Rural Affairs as part of the UK climate impacts programme commissioned and funded the work on the UK climate projections, UKCIP02 (Hulme et al., 2002). This fourth generation of climate change projection in the United Kingdom was based on experimental outputs from the Hadley Centre Global Climate Model (HadCM3); developed by the Hadley Centre of the Metrological Office in the UK (Hulme et al., 2002) (Tham et al. 2011). It is a deterministic climate projection which gives a single outcome for a specific variable at a given location (Jenkins et al., 2009).

Each of the four alternative climate change scenarios is based on a different IPCC Special Report on Emission Scenarios (SRES) of A1F1, A2, B2, B1 namely high, medium-high, medium-low and low respectively. These emissions scenario point to how differing future trends of 21st century society's choices of population growth, socio- economic development and technological progress might affect future global greenhouse gases emissions (Hulme et al., 2002). The four projected emission scenarios range from future low-energy carbon dioxide emission to a highly fossil fuel usage. The medium-high emission scenario pointing to an increase temperature of 3.3 degrees Celsius by the 2080s is based on the assumption of "preservation of local identities, continuously increasing population and economic growth on regional scales" which is "closest to the present world economy and patterns of energy use" (CIBSE Briefing 10, 2004). The UKCIP02 climate change scenarios are presented at a 50 km grid squares resolution (Hulme et al., 2002).

The various four climatic change scenarios of the UKCIP02 are based on conventional reference baseline period of 1961-1990 (Hulme et al., 2002) and are available for three future 30-year time-slices of 2011 – 2040 (the 2020s), 2041-2070 (the 2050s) and 2071-2100 (the 2080s) (Hulme et al., 2002).

The Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report acknowledged that the UKCIP02 scenarios do not incorporate the entire range of possible future scenarios as no probabilities were appended to the four climatic scenarios (Hulme et al., 2002).

2.2.2 The United Kingdom Climate Projections 2009 (UKCP09)

The UK Climate Projections (UKCP09) was published by the UK's Department of the Environment, Food and Rural Affairs (Defra) in 2009. The UK Climate Projections 2009 (UKCP09) is the latest climate change projection for the United Kingdom. This fifth and most comprehensive prediction of climate change projection-based statistical-probabilistic climate projections, marine and coastal projections and recent observed climate trends in the United Kingdom, were published by the United Kingdom Impacts Programme in 2009 (Jenkins et al. 2009) which has a collective contribution from the Met Office Hadley Centre, UK Climate Impacts Programme and over thirty different organisations (Jenkins et al. 2009) to provide practical support for effective adaptation to organisations whose work and functions are underpinned by climate change (Jenkins et al. 2009). This makes the UKCP09 supersedes the UKCIP02 projections which modelling uncertainty is based on only variant of one (Met Office) model. Also included in the UKCP09 projections are the effects of land and ocean carbon cycle feedbacks and uncertainties associated with land components which are not included in the UKCIP02 projections (Jenkins et al. 2009).

The UKCP09 climate change projections provide state-of-the-art information of future climatic condition predictions (UKCP, 2010) which serves as a platform for the analysis of the impact and vulnerability of climate change. The projections which are in consonance with the current scientific knowledge have been deemed appropriately for analysis of long term climate variations (UKCP09). The essence of the UKCP09 climate projections publication is due to improved understanding of the climate system, incorporating probabilistic uncertainty analysis of natural climate and future man-made emission scenarios as compared to the single projection in relation to a given emission scenario in the UKCIP02 (Jenkins et al. 2009). This probabilistic framework of the UKCP09 highlights a more transparent accounting of uncertainty associated with projected climatic patterns variations as compared to the UKCIP02 single projections for each scenario (CIBSE TM48 2009).

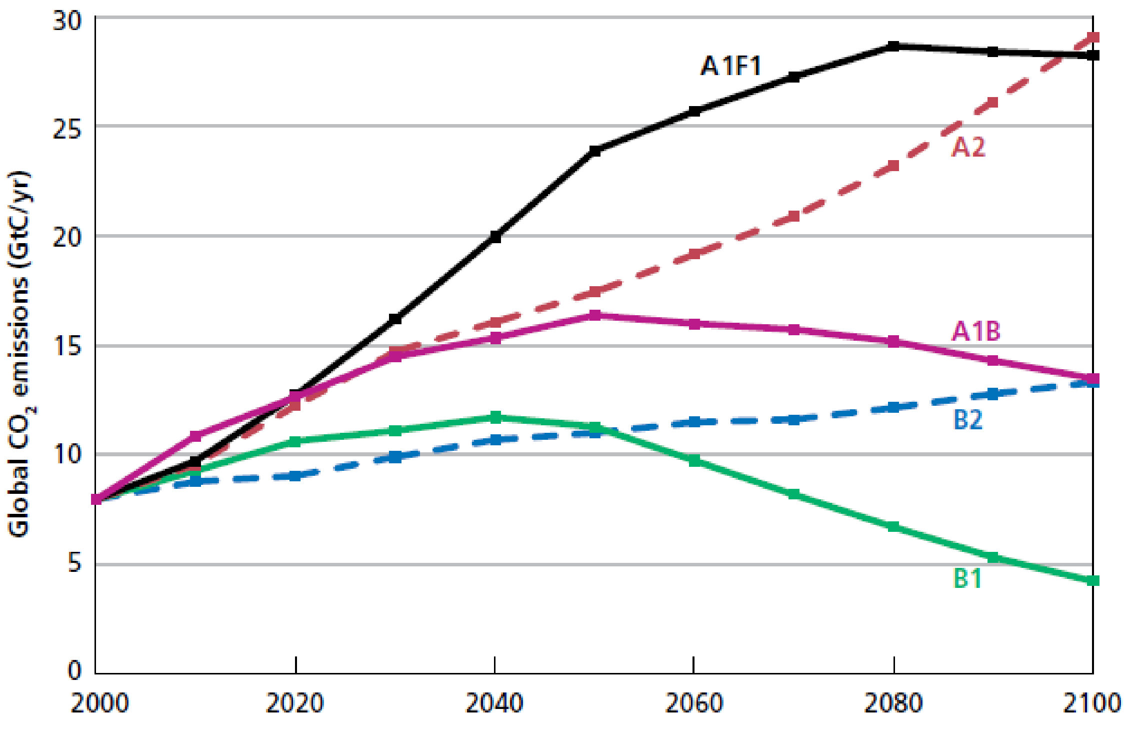
Thus, one of the key differences between the UKCIP02 and UKCP09 projections lies in the methodologies used in producing them. The UKCP09 scenarios are underpinned by probabilistic of climate change based on quantification of the known sources of uncertainty. This aspect of the UKCP09 scenarios makes it supersede the UKCIP02 scenarios (Jenkins et al., 2009).

This progression to probabilistic weather predictions is a modernistic climate projection based on cutting edge methodology which uses probabilities to different levels of future climate change to accurately model future climate patterns (Jenkins et al. 2009) (Tian and de Wilde, 2011). The UKCP09 climate projections consider uncertainties related to the “natural internal climate variability, modelling uncertainty in the climate models due to an incomplete understanding of the physical processes of the climate system, and uncertainty in future emissions" and are presented on seven overlapping 30-year time periods with projections based on 1961 – 1990 baseline time periods; similar conventional reference baseline period to that of UPCIP02 (Jenkins et al., 2009), (Mylona 2012), (Tian and de Wilde, 2011). However, the 30-year time periods covered by the UKCP09 are 2020s, 2030s, 2040s, 2050s, 2060s, 2070s and 2080s (Jenkins et al., 2009). The UKCP09 has deferring properties and characteristics when compared to UKCIP02. One key difference is the UKCIP02 data generation which based on four of the six marker projected emission scenarios of the IPCC Special Report on Emission Scenarios (SRES) of high, medium-high, medium-low and low, which underpin the United Kingdom's Meteorological Office Hadley Centre (MOHC) Climate Change Model (HadCM3) future global climate model (CIBSE 2009) whereas the UKCP09 future projected emissions scenarios are underpinned by three of the six marker emission scenarios of the IPCC Special Report on Emission Scenarios of A1F1, A1B and B1 scenarios namely high, medium and low emission scenarios respectively (William et al., 2011). Table 2.1 and figure 2.1 compare emissions scenarios used in both the UKCIP02 and UKCP09. It is observed that the only two comparable emissions scenarios of the UKCIP02 and UKCP09 are the High (A1F1) and the Low (B1) emissions scenarios.

In addition, the UKCIP02 variations are mapped to the MOHC HadRM3 regional climate models (RCM) to simulate climatic variations on a 50km grid RCM spatial resolution (Hulme et at. 2002), UKCP09 scenarios, however, include pattern-scaling and down scaling uncertainty and have a greater RCM spatial resolution of 25km grid (CIBSE 2009) coupled with a 5km resolution for a weather generator

Table 2.1 SRES marker scenarios used in UKCIP02, UKCP09 (CIBSE (2009) TM48:2009)

Scenario	UKCIP02	UKCP09
Low	B1	B1
Medium	B2 (Medium-Low) A2 (Medium-High)	A1B
High	A1F1	A1F1



A1F1 (black: High emissions); A1B (purple: Medium emissions) and B1(green: Low emissions). Also shown in dashed lines are two SRES emissions scenarios used in UKCIP02 but not in UKCIP09; A2 (red: Medium-High Emissions) and B2 (blue: Medium-Low Emissions)

Figure 2.1 Global annual CO_2 emissions under the three IPCC SREs marker scenarios used in the UKCP09: (Adapted from (Jenkins et al., 2009)

incorporated into it which facilitates an output of synthetic daily (data for 9 variables) and hourly weather data (Jones et al., 2009). The output of climate models of the UKCIP02 and UKCP09 cannot be directly used in building simulation practice. Downscaling of annual, seasonal or monthly outputs to hourly data is required. It is therefore imperative to secure reliable formatted multi-year weather files which have been prepared from reliable meteorological predictions that can be used for building energy performance and overheating risk analysis. In 2008, the Chartered Institution of Building Services Engineers (CIBSE) released two sets of future weather files, the Test Reference Years (TRYs) and the Design Summer Years (DSYs) based on the UKCIP02 climate projections. The methodology used to produce the CIBSE future weather files was the 'morphing' (time series adjustment (Gupta et al., 2013) methodology which adjusted the historic weather files to the climate projection (CIBSE TM48, 2008), (Mylona 2012). The morphing method is to stretch (by scaling current observed weather file with the predicted relative monthly mean change) and shift (of the current weather file by an amount equal to the absolute monthly mean change) of historical observed weather data which would eventually result in a future time series that will correspond to future climatic projections of average changes in a particular climate model (Gupta et al., 2013) (Eames et al., 2013). These weather datasets are based on observed measurements and they are deterministic in nature (Tian and de Wilde, 2011), (Mylona 2012). With the release of UKCP09 probabilistic climate projections it was imperative to develop new methodologies which take cognisance of probabilistic nature of the UKCP09 climate projections to advance the improvement of building simulation weather files. The Engineering and Physical Sciences Research Council (EPSRC) in 2008 founded four projects to utilize the probabilistic UKCP09 to produce weather files for building simulation analysis. CIBSE on the other hand have sought potential alternatives (with the morphing methodology in view) to offer weather files for building simulation based on the UKCP09 probabilistic climate projections (Mylona 2012).

2.2.3 Use of UKCIP02 to create future CIBSE Test Reference Years (TRYs) and Design Summer Years (DSYs) weather files.

The challenge in building simulation practise is to secure a consistent set of weather files that takes into consideration future variability of climate for building energy performance and thermal comfort analysis. In 2008, CIBSE developed two types of weather datasets for building performance analysis; the CIBSE Test Reference Years (TRYs) and Design Summer Years (DSYs) weather files. The CIBSE TRYs weather datasets are earmarked for building energy performance analysis whereas the CIBSE DSYs are for buildings overheating analysis in naturally ventilated and free running buildings (Levermore and Parkinson, 2006), (Eames et al., 2011), (Jentsch et al., 2014). The CIBSE TRYs and DSYs weather files are industrial standards for simulation practice (CIBSE TM48, 2009) and are available for 14 locations in the UK (CIBSE TM48 200).

The CIBSE TRYs weather file development is based on the morphing methodology of Belcher et al., 2005 and the previous UKCIP02 climate change data (Mylona 2012). A TRY weather file consists of twelve (12) separate months (typical months) of average month’s data from 22 years of weather data based on the past observation (Eames et al., 2011). The first TRY typical year was based on direct observation of weather source baseline period of 1983 – 2004 (CIBSE

TM48, 2009). The transitional months issues were corrected using the smoothing technique (Mylona 2012). The selection of the most average month as representative of all the years is underpinned by the use of Finkelstein-Schafer (FS) statistics to compare the cumulative distribution functions of daily mean values of dry bulb temperatures, the global solar horizontal irradiation and windspeed (Levermore and Parkinson, 2006), (Eames et al., 2011). The month with the smallest FS statistics is then chosen as the most average. The process is repeated for the other months of the year for each parameter in turn. These chosen representative months have less extreme values with a cumulative distribution function closer to that of all the years under consideration (Levermore and Parkinson, 2006), (Eames et al., 2011).

Although high level of confidence has been expressed in the weather data set based on UKCIP02 in predicting annual average temperature change and varied geographical locations (CIBSE TM48, 2009), the CIBSE TM48 outlines uncertainties surrounding the need for a better climatic projection weather data for building simulation analysis. Amongst the low level confidence issues raised are the projected changes in the cloud cover and larger projected changes in summer temperatures when compared to winter temperatures (CIBSE TM48, 2009).
The CIBSE TRYs weather files as representative weather years for building energy performance analysis is not suitable for overheating analysis and hence the DSYs weather files were developed (Eames et al., 2011). The method for developing the DSYs weather files is simple when compared to that of the TRYs weather files (Eames et al., 2011). The CIBSE DSY is a single complete weather year which gives a near extreme weather year. It is created from computing for

each year from the observation series (e.g. 1983-2004) the daily mean dry bulb temperature for six (6) months from April to September. The six months longer period was used to capture overheating problems which may be experienced in spring and autumn (CIBSE TM49, 2014). Ranking of the years of the source period in ascending order, the year in the middle third of the upper quartile of the distribution, that is the third warmest year of the 20 year baseline period is then selected as the DSY (Levermore and Parkinson, 2006), (Eames et al., 2011), (Mylona 2012), (CIBSE TM49, 2014). The DSY produced has a return period of 8 years (CIBSE TM49, 2014).

The disadvantage of this methodology stems from the fact that in practise it is being observed that at certain sites, the extent of overheating using the DSYs weather files is less than the TRYs weather files (Mylona 2012). Moreover, this methodology for determining the DSY which is based on average conditions over six-month April to September period does not take into consideration shorter periods of extreme weather which might be critical to overheating analysis (CIBSE TM49, 2014). Thus, it was realised that a new methodology for producing DSYs for use in building simulation is required, which will offer a better correlation between the likelihood of the DSY occurring and the likelihood of building overheating (CIBSE TM49, 2014).

2.2.4 The new DSYs for London

Assessing overheating of buildings in London is of prime concern to building professionals in the United Kingdom. This is due to Greater London being placed in the warmest climatic region of the United Kingdom and the strong urban heat island effect experienced in London (Mylona, 2012). The limitations identified in the use of the 2008 CIBSE DSYs weather files, make it imperative to develop a new methodology for DSYs for London which takes into consideration the geographical location, the impact of urban heat island effect and the future climate change, when performing building simulation summer overheating analysis for London (CIBSE TM49, 2014).

The new methodology considers a new metric, ‘weighted cooling degree hours’ (WCDH) which considers the frequency and severity of warm weather and its effect on thermal comfort in dwellings. The new London DSYs weather datasets also considers the urban heat island effect of London. In this wise, the new DSYs weather files for London includes two additional weather stations of London Weather Centre (LWC) and Gatwick Airport (GTW). This offers different levels of overheating risk assessment for different locations in London, namely urban, intermediate urban and suburban locations. Moreover, the new DSYs includes two additional years of 1976 (a year with two-week extreme heat wave) and 2003 (a year with more persistent warm summer) as the earlier DSY based on 1989 weather data from London Heathrow Airport (LHR) does not represent a sufficient warm year for overheating risk assessment in buildings (CIBSE TM49, 2014). Furthermore, the new London DSYs weather data sets development is underpinned by the ‘morphing’ method and make use of the latest probabilistic climate change projection (UKCP09) for the UK which considers three greenhouse emissions scenarios of high, medium and low, three future periods of 2020s, 2050s and 2080s, and differing levels of probabilities of 10th, 50th and 90th percentiles (CIBSE TM49, 2014).

2.2.5 Use of UKCP09 to create the future DSYs for London (TM49)

With the introduction of the UKCP09 probabilistic climate change projections, analysis based on these projections indicated that more extreme historical summers would be become average by the turn of the middle century and thus the use of the former DSY would be inadequate in assessing overheating of buildings in London (CIBSE TM49, 2014). The CIBSE TM49 considers the choosing of warm years and urban heat island effect of London (Virk et al., 2015).

In creating the new future DSYs for London, the UKCP09 Climate Change Projections for the United Kingdom was used to produce climate change-adjusted versions of weather years for London Weather Centre, Heathrow and Gatwick using a form of the 'morphing' methodology (CIBSE TM49, 2014). This method adjusted the observed historical data of 1977 – 2004 so that 'it has the mean monthly statistics given in the climate change projections but retains the observed hourly and day-to-day weather variability' (CIBSE TM49, 2014). The difference between the morphing methods use in the former DSY weather data sets as compared to the latter stems from the fact that the new DSY weather data which is based on the UKCP09 climate change projections uses a set of monthly change factors to generate percentile probabilities which 'relates to the change in mean monthly dry bulb temperature and the other variables are correlated to the dry bulb temperature change' (CIBSE TM49, 2014) whereas the former based on UKCIP02 projections is deterministic in nature. Percentile probabilities of 10^{th} (threshold at which climate change amount is 'very unlikely to be less than'), 50^{th} (central estimate which is the best guess) and 90^{th} (threshold at which climate change amount is 'very likely to be less than') are further provided for the various sites with their corresponding weather files coupled with the respective emission scenarios for the time periods of 2020s (2011-2040), 2050s (2041-2060) and 2080s (2071-2090) (CIBSE TM49, 2014).

The 2020s was assigned with only the high emission scenario, the 2050s medium and high emission scenarios and the 2080s all the three emissions scenarios. This was due to little observable difference between emission scenarios for the 2020s and the likelihood of the medium and high scenarios to be experienced in the 2050s. This approach thus helped in reducing the number weather datasets to reasonably working numbers (CIBSE TM49, 2014).

Furthermore, information relating to the urban heat island effect is incorporated in the creation of the new future DSYs for London. In this direction, Gatwick Airport weather datasets can be considered representative of rural areas around London, London Weather Centre to be representative of urban areas and London Heathrow weather datasets to be representative of intermediate urban areas (CIBSE TM49, 2014).

2.2.6 Justification for the choice of weather files used in the studies

Over the years, different approaches for developing weather data series for building performance analysis have been developed (Jentsch et al., 2014) (Gupta et al., 2013). In the UK, basically two differing methodologies stand out in creating hourly weather files for use in building simulation practice; the ‘morphing’ methodology which is the current industrial standard by CIBSE, which adjusted the historic weather files to climatic projections (UKCIP02 and UKCP09) (CIBSE TM48, Mylona 2012) and the development of various probabilistic projections of hourly weather datasets by the use of the UKCP09 weather generator.

The UKCP09 weather generator is a stochastic tool that uses daily precipitation to create other weather outputs of daily and hourly variables on a 5 km grid for a historical period of 1961- 1990 (Jones et al., 2009). This offers an advantage due to greater spatial resolution. In addition, the weather generator is suitable for the future TRYs and DSYs weather datasets for building performance analysis (Mylona 2012). However, the CIBSE weather datasets developed using the morphing methodology are based on observed climatic period and thus have limited uncertainties which could affect the baseline weather data (Mylona 2012). Without the implementation of change factors corrections the CIBSE weather datasets could result in overestimating of the future climate change variations due to changes in differences of climates reference points; 1961-1990 for the weather generator and 1983-2004 for the earlier CIBSE historic TRY and DSY weather files (Eames et al., 2011) (Mylona 2012).

The choice of the CIBSE morphing methodology as against the weather generation data is based on its reliability (CIBSE TM49, 2014). The weather generator does not produce extreme events (Mylona 2012). The weather generator output of weather datasets years is not as warm in terms of WCDH criterion used in the historical data development of the new CIBSE DSYs, as the 'extremes of the temperature distribution are not clustered together into particular warm years to the extent as they are in the observed data' (CIBSE TM49, 2014). Although the monthly average climate over the years changes, one advantage of the morphing methodology in the non-variant underlying characteristics of the TRY and DSY weather datasets which facilitating direct comparison between the present and future building performance analysis. On the hand, there are differences in basic weather characteristics such as timing and severity of warm spells between the timelines in using the weather generator (Mylona 2012). Furthermore, the current CIBSE DSYs weather datasets for London considers the urban heat island effects in future weather files whilst this consideration is absent in the UKCIP09 weather generator.

The use of the weather generator to statistically produce many thousands of historic and probabilistic future weather data at a high spatial resolution provides a significant advantage of a better idea of a complete dataset for overheating risk assessment when compared with the observable weather data (Smith and Hanby 2012). It has the advantage over the morphing methodology as the later when considering observed data independently produce certain weather variables in place of missing data (Mylona 2012). However, the many files generated pose a computational challenge to resources not readily available in building simulation practice (Eames et al., 2011), (Mylona 2012).

A readily acceptable methodology should produce output of weather datasets which is consistent with currently used datasets and argument the use of standardized weather datasets for use in building energy and thermal performance analysis. The weather generator's outputs of daily precipitation, partial vapour pressure, relative humidity, maximum temperature, minimum temperature, sunshine fraction, direct radiation and potential evapotranspiration are insufficient for use within thermal simulation for building energy and thermal performance analysis. Key missing parameters such as wind speed, wind direction, atmospheric pressure and cloud cover are essential in creating weather files of the same format as is used in CIBSE weather datasets for building simulation software (Eames et al., 2011), (Mylona 2012) (Smith and Hanby 2012).

Although the weather generator method is more versatile than the morphing method, in terms of observed data and location, the large amount of weather data produce is of disadvantage in simulation practice (Gupta eta al., 2013). The CIBSE weather files based on the morphing methodology are used in this work due to consistency between the present available observable historic weather files and those of the future files and a platform for direct comparison of standardized weather datasets for energy and thermal performance analysis. Majority of building performance simulators in the UK make use of CIBSE weather files as trusted consistently replicable weather datasets in their work as it offers a single data set for a particular location, climatic period, emission scenario and probability level for all designers to compare building performance (Gupta eta al., 2013), (Watkins et al., 2011). This serves as the primary reason for the use of CIBSE weather datasets for all the case studies in this thesis.

Chapter 5 analyse the variability of the selected comparable CIBSE TM48 and CIBSE TM49 weather data set on internal operative temperatures to identify the most influential weather parameters which contribute to thermal comfort. In addition the choice of these weather files is to ascertain their differences as their development is underpinned by different climatic projections. Thus, uncertainty and sensitivity analysis of the CIBSE weather datasets based on the deterministic single projection of UKCIP02 and the CIBSE weather datasets base on the probabilistic UKCP09 projections is performed to ascertain the contract between the two files. In addition, the 50^{th} percentile central estimate weather files for Heathrow 1989 was used to provide comparable outputs in relation to the CIBSE's 2008 weather files. Moreover, the UKCP09 A1B (medium emission scenario) and the UKCIP02 A2 (medium high emission scenario) are used for comparative analysis as the two emission scenarios are closer in the chosen time period.
In chapter 8, all the three weather files for London Weather Centre, Heathrow Airport and Gatwick Airport were used to investigate the sensitivity of the design to difference weather conditions in London and the urban heat island effect in central London. The choice of the 2003-2050 medium design summer year with 50% probabilistic scenario timeline is underpinned by 2003 being a year with more persistent warm summer and the 50% probabilistic scenario timeline offering the best guess of the given scenarios.

2.3 Building Performance Modelling and Simulation

Building modelling and simulation are used to predict energy performance, enhance thermal comfort, mitigated carbon dioxide emissions, and investigate the whole life cycle and maintenance of building systems (Spitz et al., 2012). It is a powerful computational tool to effect the modelling of a building envelope and its systems, taking into consideration the complex dynamic interaction between a building and the environment (Hygh et al., 2012). There is an extensive use of energy modelling to evaluate energy performance in building. Many examples of building performance modelling and simulation information are available basically to estimate energy consumption during the design stage or of existing buildings, size HVAC systems, and verify the satisfaction of building code compliance (Hygh et al., 2012). High degree of technical specification is required in building energy and thermal simulation.

Building energy modelling and simulation programs had previously been used to evaluate building performances and assessments in the areas of building design and regulatory compliance, evaluation of changing weather data for an overheating analysis, assessment of building internal conditions (infiltration, ventilation, lightning gain, occupancy sensible and latent, equipment sensible and latent, and pollution generation), evaluation and enhancement of building thermal mass, evaluation and selection of renewable energy sources, building automation systems and moisture phenomena. Moreover, modelling and simulation of buildings of selected building range could be extended to represent the entire building stock (Crawley, 2003).

Studies of the impact and vulnerability of buildings which ultimately affect building behaviour and performance due to changes in climatic conditions have been documented (De Wilde and Coley 2012). For instance in 2005 Gaterell and McEvoy presented a study on the impact of climate change uncertainties in relation to detached dwellings energy efficiency in the UK (Gaterell and McEvoy, 2005). In 2005 and 2008 Hacker et al. published their findings regarding the effect of climate change on the indoor environment and carbon dioxide emissions and thermal mass respectively (Hacker et al., 2005 & 2008), whilst in 2010, Collins et al. presented their work on the bearing of climate change on future energy consumption in the United Kingdom (UK) (Collins et al., 2010). In 2009 Lomas and Ji presented work on natural ventilated in hospital wards using alternative weather projections (Lomas and Ji 2009) and in the same year, de Wilde and Tian explored the used of probabilistic method and sensitivity analysis in assessing parameters which affect the thermal performance of a commercial building (de Wilde and Tian, 2009). In 2012, Barclays et al. also carried out work on specific building systems of natural ventilation focusing on wind prediction using information from the UKCP09 (Barclays et al., 2012). Other studies have also been conducted in countries other than the United Kingdom in relation to the impact of climate change on buildings (Frank, 2005), (Crawley, 2008) (Chan, 2011). In addition, in 2013, Gupta et al. employed the application of downscaling the UKCP09 future weather files to evaluate overheating risk in English homes in the 2050s and 2080s (Gupta et al., 2013). In 2015 Mylona et al., under the Zero Carbon Hub programme reviewed overheating evidence in UK buildings (Mylona et al., 2015) and in the same year, Virk et al. used the newly developed CIBSE DSY weather dataset to assess overheating in London taking into account the effect of the urban heat island (Virk et al., 2015).

The challenge to accurately select modelling parameters to model energy performance in buildings is attributed to over-simplified modelling assumptions or incorrect modelling of radiant surfaces (Clevenger and Haymaker 2006). Radiant systems have been earmarked as applicable technologies which can reduce energy usage and in the building envelop and improve occupants' thermal comfort (Laouadi 2004). The purpose of radiant systems "is to lower thermostat set point temperature in winter and to increase it in summer, resulting in a substantial energy savings for heating and cooling as compared with conventional systems" (Laouadi 2004). Studies have shown a 30% energy savings from the use of radiant systems (Laouadi 2004), thus, the effectiveness of building energy simulation programs will be enhanced with the integration of radiant systems.

There are other elements in design which affect building real performance. Model simplifications, poor management and maintenance practices (Demanuele et al 2010) are other factors which affect the evaluation of energy performance in buildings. Building materials and controls may be altered from the design specifications couple with poor workmanship (Demanuele et al 2010). In addition, the type of building materials and external factors such as weather variations, building schedule and occupant behaviour are contributing factors (Turner and Frankel 2008).

Disadvantages of using thermal analysis simulation software in assessing building energy and thermal performance have been documented. Azar and Menassa (2010) research combined the traditional energy simulation software with an agent-based modelling. The results showed a variance of more than 20% in consumption levels in these two approaches, an indicative of profound differences between energy estimates from building energy modelling methods and actual consumption levels. Clevenger and Haymaker (2006) also highlighted the great discrepancy in predicted energy consumption levels based on experts' acceptable values of occupant behaviour which results in inefficient evaluation of energy models to accurately predict building performance.

Azar and Menassa (2010) advance the discrepancy between predicted design energy consumption performance in buildings and the actual energy consumption levels as being due to occupant energy usage characteristics. Hoes et al. (2009) assert that an inconsistency in design predictions and actual energy performance are related to a failure to take into cognisance the occupant's energy characteristics. Pungila et al 2009 indicate that substantial energy savings in the range of 20-30 kWh/msq can be made due to change in occupant energy conservation behaviour. Thus energy simulation models do not reliably predict the post occupancy energy performance.

Some energy simulation software for example eQuest, Energy-10, TRNSys and Energy Plus take cognisance of occupant behaviours in their simulation (Azar and Menassa 2010). In 2009 Erickson et al and Li et al used agency based module to investigate HVAC energy usage. However, Hoes et al. (2009) noted that the former simulation software do not account for a change in occupants' consumption characteristics. Not much work has been done on other energy consumption sources such as lighting, computers and hot water usage although hot water usage is responsible for the greatest consumption of residential energy usage. Hence, these areas ought to be investigated (Azar and Menassa 2010) and the varying characteristics of occupants are taken care of in the energy simulation.

2.4 Energy Conservation in Buildings and Occupant Behaviour

The world domestic energy consumption accounts to about 40% of the overall energy demand and contributes to about 40% of the total carbon dioxide emissions (Yudelson 2010). The worldwide energy consumption for buildings is expected to increase by 45% from 2002 to 2025 (GeSI 2008). Studies in energy conservation are more geared toward the physical and technical determinants of energy instead of building occupants' behaviour (Brounen et al. 2011).

Various literature based on empirical evidence underpins the theoretical basis of feedback as an effective tool in energy conservation in buildings (Darby 2008). Studies have shown that substantial energy savings in the range of 20-30 kWh/msq can be made due to a change in occupant energy conservation behaviour (Pungila et al. 2009). Studies conducted in Denmark where energy consumption was made visible showed a 9% reduction of household heating and 22% reduction of electricity use within a year (Jensen 2003). Darby's (2006) work indicates that between 5 to 15% reduction could be made when direct feedback is provided. Ayers et al. (2009) confirm that knowledge of occupant current energy consumption reduces their energy usage.

Inadequate research consideration has been given to the impact of variable occupant behaviour in energy model simulation, yet empirical research shows a range of 200% to 300% variance in energy use of different occupants in identical building units (Clevenger and Haymaker 2006). Energy simulation models do not reliably predict the post occupancy energy performance. Hoes et al. (2009) note that these simulation software do not account for a change in occupants' consumption characteristics. In addition, not much work has been done on other energy consumption sources such as lighting, computers and hot water usage although hot water usage is responsible for the greatest consumption of residential energy usage (Hoes et al. 2009).

Research indicates that the energy consumption in a dwelling is influenced by the number of households, income and age, type of occupant, appliances, floor area and where the household area is located (Abrahamse et al. 2007; Anderson and White 2009; Jentsch et al 2011; Yohanis et al. 2008; Wood and Newborough 2003). The application of energy conservation "must be customized for different population groups" (Jentsch et al 2011). Great Britain's housing energy fact file 2011 indicate that, although energy consumption in a dwelling is related to the number of people in the home and the home floor area, yet the manner of energy use in a dwelling was of more significance (Palmer and Cooper 2011). Although families are aware of reducing energy consumption by turning off and buying low-energy appliances, most households do not pay attention to present energy consumption (Jensen 2003). Thus “domestic energy consumption is still largely invisible to millions of users” (Darby 2006) as most household meters show limited visual display when compared with available digital technology visual displays.

The importance of households’ constitution and type of dwelling in energy conservation studies are well noted. The energy consumption in a dwelling is influenced by the number of households, age, floor area and where the household areas are located. Research by Abrahamse et al (2007) considers the impact of gender, household size and income levels on energy conservation. Anderson and White (2009) consider focus age groups. Jentsch et al conducted studies on two female groups of 13 - 15 years and 23 - 30 years in Germany. Yohanis et al’s 2008 study in 27 households in Northern Ireland focused on type of dwelling, ownership and size, appliances, type of occupant, income and age on electricity consumption. Wood and Newborough (2003) researched into energy conservation on individual appliances focusing mostly on household cooking.

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2.5 Impact of Climate Change and Thermal Comfort

Evidence of global temperature increase as a result of climate change (IPCC, 2013), (CIBSE TM36, 2005) and the tightening of Building Regulation requirements to mitigate carbon dioxide emissions and its emphasis on energy efficiency coupled with the creation of thermally comfortable dwellings currently confront the built environment. United Kingdom Building Regulation Part L 2013 with its inclusion of fabric energy efficiency (FEE) standards will be in operation by April 2014 in England (DCLG, 2013). In addition, all newly built dwellings are designated to be zero-carbon by 2016 (CLG, 2007). Applying the axiom 'fabric first' with its increased insulation, high glazing standards, improved thermal mass and airtightness, modern building professionals have sought to improve building standards which have inadvertently led to the retention of unwanted heat gains in buildings during summer, offsetting one of the primary objectives in buildings; the provision of thermal comfort (Bessoudo et al., 2010). Thermal comfort in newly built dwellings will thus be impacted by these changes as many UK dwellings are designed to be free-running naturally ventilated buildings during the non-heating season (Hacker et al., 2008).

In general, there is a lack of research in thermal comfort analysis in dwellings (Peeter et al., 2009). Moreover, many of the thermal comfort investigations have been based on non-domestic buildings (DCLG and AECOM, 2012) during the day whereas night provides a significant motivation for domestic cooling in the urban environment where there is the existence of less air movement and urban heat island effect (CIBSE TM52, 2013).

Studies of the impact of improved building construction standards and mode of operation have been presented in many recent publications and these studies point to how the variance in climatic patterns and passive design techniques have a remarkable impact on building thermal performance. Kolokotroni (2001) evaluated night cooling strategies using natural ventilation in office building. Gan (2001) analysed the impact of varying window shapes and dimensions on thermal comfort. Kim et al. (2007) using computational fluid dynamics models and genetic algorithms considered design strategies for indoor thermal environment. Stravrakakis et al., (2008) experimentally examined the effect of cross-ventilation at non-symmetrical locations on indoor thermal environment. Lomas and Ji (2009) identified the importance of area of ventilation opening in determining internal temperatures and from their investigation into single-sided and advanced ventilation in hospital wards noted the difficulty in predicting the performance of single-side natural ventilation. Haasel et al., (2009) evaluated energy savings in different ventilated facades and in 2010, Bessoudo et al., conducted an experimental study to investigate indoor thermal environment in winter using a glass façade with different modes of shading. The effects of fenestration have also been investigated by Tzempelikos et al., (2010). Zanghirella et al., in 2011 used a developed numerical model to simulate the thermal performance of mechanically ventilated facades. In 2012 Barclays et al., carried out work on the repercussion of future natural ventilation strategies on non-domestic buildings. Stegou-Sagia et al., (2007) investigated the impact of glazing thermal properties on energy consumption and comfort. Palmer et al. (2005) provided evidence of the intended effect of the use of thermal mass to reduce overheating in buildings during summer. Hacker et al., in 2008 published their findings on the relationship between thermal mass and overheating risk in buildings using the medium-high emission climate change scenario. In 2010 Jenkins et al., and Patidar et al., in separate studies employed statistical methods to evaluate the effect of climatic change on the thermal performance of UK dwellings. Ali and Ahmed (2012) explored how different shading devices affect thermal performance of dwellings and Kamal (2012) in the same year evaluated the relationship between passive cooling techniques and thermal comfort. In 2013 Amoako-Attah and B-Jahromi using thermal analysis simulation investigated the impact of varying climatic patterns on five building performance indicators and indicated how improving building energy efficiency will challenge future innovative design and adapt the technological process. Anh-Tuan and Reiter (2014) used simulation approach to investigate the design, operation and thermal comfort of low-cost dwellings and Taleghani et al (2014) using thermal simulation investigated heat mitigation strategies using vegetation and ponds.

Studies of thermal comfort performance metrics have also been presented in many publications which have led to the development of thermal comfort models and standards. Beginning in 1970, Fanger through a steady-state experimentation in a controlled climate chamber developed a heat balance comfort model and further stipulated the predicted mean vote. In 1998 de Dear and Brager using the concept of adaptation, developed their adaptive model which later formed part of the American adaptive model ASHRAE 55. In 2002 Nicol and Humphreys developed an adaptive model which, together with Fanger comfort model, was later incorporated in the European standard EN 15251 in 2007. Another acceptable thermal comfort standard, the ISO 7730 was developed in 2005. This standard seeks to specify varying stages of thermal comfort and takes into cognisance the predictive mean vote (PMV) index and the predicted percentage of dissatisfaction (PPD). The ASHRAE 55, whilst using the PMV and PPD in the model also accounts for local thermal discomfort and dynamic effects (ANSI/ASHRAE 55, 2004) and the improved standard of 2010 accounts for mechanically conditioned buildings (ASHRAE, 2010). In 2005, CIBSE TM36 outlined thermal performance risk using the UKCIP02 medium-high emission scenarios on selected dwellings and non-dwellings in different UK locations. The criteria for assessment were the comfort threshold temperatures of 25 ^{o}C and 28 ^{o}C earmarked in the Fanger model (CIBSE 2005, Hacker et al., 2005). In 2009 Chen reviewed ventilation performance predictive tools. In 2009, Yao et al. conceptualized the adaptive predictive mean vote and in that same year, Toftum et al., in determining acceptable thermal conditions applied the adaptive thermal comfort mode. In 2010, the Zero Carbon Hub re-examined the CIBSE TM36 overheating assessment methods and metrics. In 2013 CIBSE offered the most updated assessment of thermal comfort performance based on current knowledge and this is an integration of the methodology and recommendation outline in BS EN 15251 (BSI, 2007) and additional factors to assess the overheating in naturally ventilated dwellings (CIBSE TM52, 2013). Carlucci et al., (2014) analysed various thermal comfort methods used as tools for predicting overheating but did not include the newly developed CIBSE overheating criteria in their work.

2.6 Conservatory as a Passive Design Solution

The prime goal of professionals in the built environment is to develop cost effective sustainable buildings which contribute to the attainment of climate change mitigation goals, facilitate the achievement of indoor thermal comfort and reduction of building energy demand. Improvement is the built environment has led to the design and construction of efficient buildings which require almost no energy for heating as compared to the energy consumption of 200 kWh/m^2/year a decade ago (Spitz et al., 2012). An increasing standard of living with its associated impact on energy demand is driving the advanced nations to adopt energy and carbon emission reduction strategies in buildings (Sadineni et al., 2011, Ralegaonkar and Gupta, 2010). In the United Kingdom, studies indicate that buildings account for 30% of total energy consumption and 26% of total carbon emissions (DECC, 2011) and similar trend is observed in the Economic Co-operation and Development (OECD) countries where buildings account for between 25 to 40% of total energy consumption (Morrissey et al, 2011). This trend is also observed in the European Union (Desiseri et al. 2013). Worldwide, energy consumption for buildings is expected to increase by 45% from 2002 to 2025 (GeSI, 2008). The European Union Directive2010/31 on the Energy Performance of Buildings seeks to influence the drive toward energy efficiency and thermal comfort optimization in buildings by mandating the transformation of all existing or new buildings to attain the set target of zero energy, through an established framework for energy performance calculation which include insulation, thermal capacity, passive solar heating and thermal bridges by 2020 (CEC 2010, Kim, 2014, Rodrigues et al., 2013). Moreover, the United Kingdom Climate Change Act of 2008 outlines the UK government set target of carbon dioxide emission reduction by 34% and 80% by 2020 and 2050 respectively (DECC 2011, Moran et al., 2014, Voeltzel et al,. 2001).

The current global quest for the reduction of carbon dioxide emission and energy consumption in buildings is driving professionals in the built environment toward passive design technologies for it is amongst the most economic efficient strategies to reduce energy consumption in dwellings (Kruzner et al., 2013), (Pulselli et al., 2009). This would further provide cost-effective means on daylight utilization in buildings (Zain-Ahmed et al, 2002). Passive solar energy utilization in buildings has been a relevant design feature dating thousands of years. The archaeological findings of Anastasi Indians, Egyptians, Greeks and Romans architectural buildings point to the use of passive solar ideas in buildings during these periods of civilization (Burns and Kabak, 2014). The harnessing of the abundance and relevance of passive solar energy in building cannot be over-emphasized. About 0.01% of the total amount of solar energy reaching the planet is estimated to be sufficient to meet all mankind's energy needs (BRE, 1988). The Department of Energy of the United Kingdom indicates that the amount of solar energy received by a typical dwelling in the United Kingdom in a year is more than enough compared to the total household energy consumption (BRE, 1988). Research further indicates that incorporating of passive solar energy design principles has the potential to contribute to about a third of the total heating needs in the UK buildings (BRE, 1988). Thus although the UK is not endowed with solar energy all year round, appropriate application of efficient passive solar designs principles could contribute significantly to the reduction of carbon emissions for current and future climate change mitigation and offer the economic benefits of reducing building thermal energy demand (Oliveira Panao et al., 2012) However, studies also indicate that lack of comprehensive and effective passive solar design strategies in buildings would rather lead to increase in household energy demand (Taleb, 2014)

2.6.1 Concept of Passive Solar Design

Passive solar building design entails the harnessing of solar energy to facilitate winter heating and its pragmatic exclusion during summer to offset indoor overheating temperatures in order to provide comfort, reduce energy demand and carbon dioxide emission. A comprehensive passive solar design seeks not only to optimize the use of solar energy for heating but also the provision of adequate daylighting and natural ventilation without the reliance on power driven mechanical systems. During non-heating period of the year adequate levels of shading and ventilation are provided to reduce the amount of solar energy admitted into the building. The basis of passive solar heating is the harnessing of the solar energy through a glazing element through which radiant energy is received into a building and partly used to heat it and the remaining stored in a thermal mass as thermal energy for subsequent release to the building in the absence of the sun (Mihalakakou and Ferrante, 2000), (Anderson and Michal, 1978). Kochaniuk 2012 outlined the three primary solar configurations of energy transfer mechanisms as the direct gain, indirect gain and isolated gain (Kochaniuk, 2012). This work focuses on conservatory as a form of isolated gain passive solar system (Kochaniuk, 2012).

2.6.2 Principles of Conservatory as a Passive Solar Design

A conservatory is an isolated gain passive solar system and mostly grazed enclosed space attached to one or more façade of a dwelling and serves as a thermal buffer to effect thermal and ventilation losses and also facilitates pre-heated ventilation to the main dwelling. Currently, legislation has been the main driver for buildings efficient conservatory design (Clarke et al., 2008). The UK building regulation 2010 Part LIB mandates that a conservatory will generally be exempted from the regulation if it is built at the ground level and has a floor area less than 30 square meters and the conservatory depends on the dwelling's heating system (Planning Portal 2014). With conservatories of an area more than 30 square meters, there must be effective thermal separation between the conservatory and the main dwelling and the conservatory should be glazed according to the standards set out in the building regulation (Planning Portal 2014) The window industry regulator of England and Wales, Fenestration Self-Assessment Scheme (FENSA) also stipulates that a conservatory must be physically separated from the main dwelling by an external door and or windows and should not have less than 75% of its roof area and 50% of its wall area made from translucent material (FENSA 2014,). The Standard Assessment Procedure (SAP 2012) also directs that the u-values for conservatory building fabric, windows and doors must be similar or not more than that of the "corresponding exposed elements elsewhere in the dwelling" (BRE, 2014).

Synergetic conservatory design strategies that take into account the inter-relationship of the design variables can optimize the energy balance of the dwelling, resulting in energy consumption and carbon emission reductions and thermal comfort (Bakos and Tsagas, 2010) , (BRE, 1988). The three fold energy balance optimization can be achieved through the design of the conservatory as efficient solar gain system, buffer or insulation effect and the control pre-heat ventilation of air passing through it to the dwelling (Mihalakakou and Ferrante, 2000). Boyle indicated in his publication that thermal buffering of south side conservatory, preheating ventilation air from the conservatory to the dwelling and solar gains contribute to 15%, 55% and 30% respectively of the energy gains (Boyle, 2012). Bataineh and Fayez 2011, using numerical model to analyse the thermal performance of building attached sunspace indicated that a 42% reduction in annual heating and cooling load could be achieved (Bataineh and Fayez 2011). Research work indicates that the success of an efficient solar gain system depends on complex dynamic function (Morrissey et al, 2011) of varying future climatic conditions and local topography (Lau et al., 2007), variable occupant behaviour, building orientation (Morrissey et al, 2011), adequate provision of thermal mass, advance facade glazing design, appropriate ventilation and a sufficient level of shading (Yohanis and Norton, 2002), (Ralegaonkar and Gupta, 2010), (Aksoy and Inalli, 2006). A failure to consider holistic design strategies may affect the efficient thermal performance of the whole dwelling.

2.6.3 Future Climatic Patterns

The effect of global warming on buildings due to varying world's climatic conditions has been well investigated (Palme et al., 2013), (Amoako-Attah and B-Jahromi, 2013), (Du et al., 2011), (De Wilde and Coley 2012), (UKCP, 2010). Evidence from future climatic pattern studies points to an increased number of days with high temperatures in the United Kingdom (UKCP, 2010), with the mean daily maximum temperatures range increase of between 2.2 and 9.5 ^{o}C (UKCP, 2010) and the mean daily minimum observable trends in winter temperature range increase of between 0.6 and 5.95 °C, depending on the locations of interest (UKCP, 2010). Palme et at., showed that these results give a conclusive indication of a long term warming climate which will result in the reduction of winter heating demand and subsequent increase in summer cooling demand (Palme et al., 2013). On the other hand, increasing winter temperature will augur well for conservatory space heating in the United Kingdom as the chances of harnessing solar radiation will increase. The current utilization of solar gains for space heating in winter is quite often limited due to conservatories' temperatures being only slightly above that of the dwelling to expedite the warm air to the dwelling and thus serve as an efficient solar collector (BRE, 1988).

2.6.4 Variable Occupant Behaviour

The energy balance of a dwellings and conservatories will be enhanced with the appropriate and timely occupant control of shading levels and manually operating doors and windows for adequate ventilation and air temperature. In addition, occupants must refrain from increasing the conservatory internal temperature using the heated air from the main dwelling and avoid heating the conservatory to minimize the total energy consumption. Thus the optimum energy performance of a conservatory can be accrued if it is operated correctly.

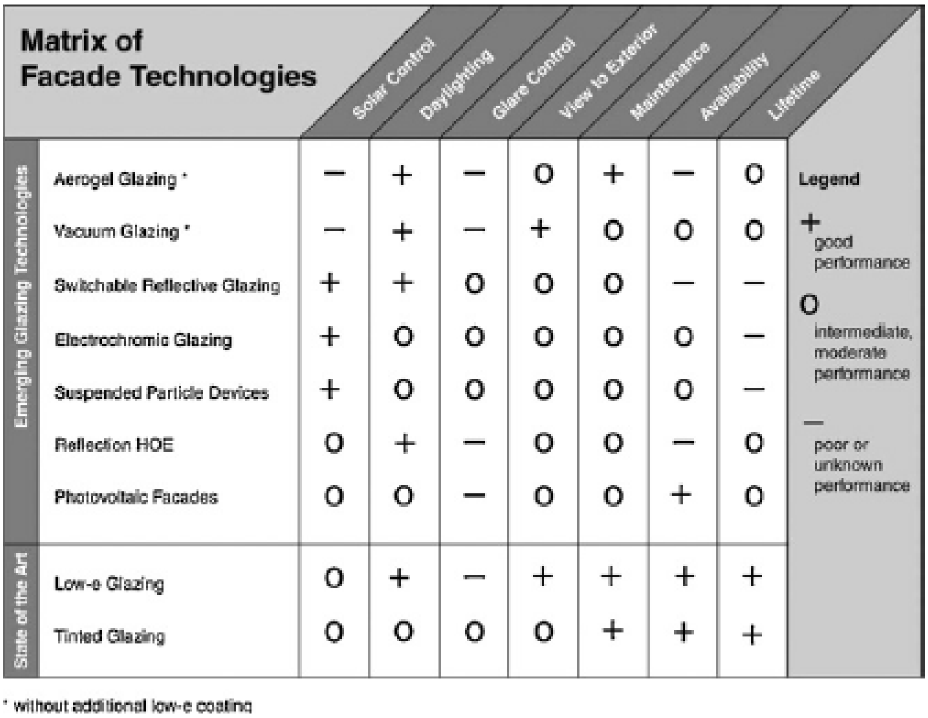
2.6.5 Building Orientation and Form

The foundation to optimized solar design strategies is mostly underpinned by a southerly orientation of the building and the effective surface area subjected to solar radiation (Morrissey et al, 2011). Orientation signifies the “axis along which a building is elongated” (Kruzner et al., 2013). The intensity of solar radiation receipt also depends on geographic location, seasonal variance of climatic conditions and the aspect ratio (surface area to volume ratio) of the building (Ralegaonkar and Gupta, 2010). The extension of the building dimension along the east-west axis maximizes the incident solar radiation on the elongated south façade in winter (Ralegaonkar and Gupta, 2010), (Kruzner et al., 2013). Spanos et al., in their cost analysis on building orientation and site location indicated that there is a potential energy performance saving of 20% in a dwelling if attention is given to orientation at the design stage (Spanos et al., 2005). Implementation of the southerly orientation low cost energy efficiency option also augments the later addition of other solar design strategies (Morrissey et al, 2011). Moreover, a south facing orientation facilitates not only optimized passive solar radiation gains but also offers efficient daylighting and enhanced natural ventilation (Morrissey et al, 2011), (GHH, 2014). Studies on conservatory design show that south facing orientation optimises passive solar performance. In winter, the southerly orientation façade takes advantage of the low-angle of sun rays to maximize solar radiation received in the conservatory for passive solar heating (English and Walker, 2000). In summer, when the sun altitude is high, the southerly orientation offers less overheating risk when compared to that experienced in the east-west orientations and also offers the easiest possible position for roof shading. Moreover, research shows that largely glazed south facing façades are more sensitive to changes in orientation (BRE, 1988). For instance, simulation research conducted on a south facing glazed house in Linford, Milton Keynes, UK, showed an increase in heating demand of about 17% when the building orientation was changed to the west (BRE, 1988).

2.6.6 Glazing

Generally glass is a poor insulator but has a high surface resistance (BRE, 1988). During the heating season glass conducts indoor heat outward of the building façade and conversely inward during the non-heating period of the year (BRE, 1988). Conservatories which by design are a highly glazed enclosure significantly contribute to the thermal efficiency and provision of daylighting to the main dwelling. Optimum conservatory design should offer balanced energy transmission and prevent heat losses outweighing the solar radiation gains during the heating season. Two important factors for determining the energy balance of glazing are the thermal transmittance (U-value) and the shading coefficient (Bahaj et al., 2008). The thermal transmittance is a 'measure of the amount of heat transmitted' by a material to the outside of the building envelope and the shading coefficient is a 'relative measure of solar energy transmitted to the interior' when compared to a single glazing (BRE, 1988). Solar heat gain coefficient (SHGC) or the G-value is used as a measure of total glass transmittance. It is the quotient of the amount of solar gain through a glazed material and the total amount of solar energy incident to its outside surface. Research shows that a fully double glazed low emissivity (low-e) argon filled south facing façade has the potential to provide an energy balance and comfortable indoor temperature during both the heating and non-heating seasons of the year (Bahaj et al., 2008). Low emissivity glazing is an advanced multiple glazing with a fused transparent coating to facilitate the radiation of indoor thermal energy back into the dwelling. It therefore has high resistance to heat loss which offsets the reduction of amount of solar gains due to an extra layer of glazing and the low emissivity coating. Its function is optimized when coupled with inert gases such as argon and krypton. This contributes to the minimization of indoor heat loss and also reflects excessive solar radiation during the non-heating seasons thereby contributing to the reduction of solar gains. This ability of the low emissivity argon or krypton gas filled double glazing is underpinned by its comparatively low thermal transmittance value and slightly low shading coefficient. A double glazed window has the potential of reducing winter heat loss by about 50% and the reduction of 10% solar radiation gain in summer (BRE, 1988). In addition, the double glazed low emissivity argon filled glazing has comparable energy efficiency to the triple-glazed regular glass and also has the other advantages of cost effectiveness and light weight (BRE, 1988).

Bahaj et al., in 2008 conducted studies and provided a thorough review of seven advanced emerging glazing technologies to determine their economic, thermal comfort and technical implications when compared with low emissivity argon filled double glazing. Figure 1 below shows the results of their investigation. Whilst Bahaj et al., admitted that no one glazing technology can currently be considered as the ultimate, their work identified the low emissivity argon filled double glazing with appropriate shading as a superior glazing that can offer optimal solar gains (Bahaj et al., 2008). Studies also shows that the reduction of solar radiation by a low emissivity argon filled double glazing unit lends to the south facing orientation offering a better optimum energy balance than the other orientations (Button, 1982), (Owens, 1984).



Matrix of Facade Technologies

		Solar Control	Daylighting	Glare Control	View to Exterior	Maintenance	Availability	Lifetime
Emerging Glazing Technologies	Aerogel Glazing *	−	+	−	O	+	−	O
	Vacuum Glazing *	−	+	−	+	O	O	O
	Switchable Reflective Glazing	+	+	O	O	O	−	−
	Electrochromic Glazing	+	O	O	O	O	O	−
	Suspended Particle Devices	+	O	O	O	O	O	−
	Reflection HOE	O	+	−	O	O	−	O
	Photovoltaic Facades	O	O	−	O	O	+	O
State of the Art	Low-e Glazing	O	+	−	+	+	+	+
	Tinted Glazing	O	O	O	O	+	+	+

Figure 2.2 Performance and risk criteria evaluation of advanced glazing technology (Adapted from Bahaj et al., 2008)

2.6.7 Thermal Mass

Thermal mass refers to materials of high heat capacity with the ability to absorb, store and progressively release thermal energy. The conservatory serves as a dual purpose system of radiant solar gain and thermal energy storage. The thermal mass absorbs and stores the radiant energy gained in the conservatory as thermal energy and through the process of thermal convection progressively releases and transfers it through the operable doors and windows to the main dwelling as the indoor temperatures fall. The thermal storage is provided by the heavy thermal mass of the conservatory floor and walls and also the inherent wall of the main building which could also transmit thermal energy by conduction to the main dwelling. The selected thermal mass for instance, concrete, stone, bricks and stone, should be capable of maximizing the thermal storage. Light construction materials are ineffective in thermal storage and could easily cause overheating. During the non-heating season, the heavy thermal mass of the conservatory buffers against high internal temperatures and reduces indoor heat fluctuations to enhance thermal comfort (Bakos and Tsagas, 2000). Thermal mass is more effective when it receives direct solar radiation rather than diffused radiation.

In general, a conservatory with optimum thermal mass and increased floor area with a converse minimum surface – to – volume ratio may offer the best form of reducing heating demand and enhance thermal comfort (GHH, 2014). Moreover, the amount of thermal mass for efficient storage of thermal energy and progressive release to maintain thermal comfort is dependent on the orientation of the conservatory and the glazing area (HLGGI, 2010). Solar gain in conservatories during the heating periods in spring and autumn and transfer through the thermal mass can potentially provide all the heating needs and further satisfy thermal comfort by raising the indoor temperature through radiant heat (HLGGI, 2010).

2.6.8 Ventilation

Holistic analysis of thermal balance must include adequate ventilation in the strategic mixed of parameters necessary to optimize energy consumption and thermal comfort. The mechanism of natural ventilation for fenestrations is dependent on wind speed and direction and ambient temperature (BS 5925, 1991) the climatic parameters which influence infiltration. During the non-heating season, provision of high and low level fenestrations facilitates the reduction of unwanted thermal energy and improves indoor temperature for comfort enhancement. Low-level ventilation is most appropriate as excessive ventilation during the heating season may lead to increase in energy demand. A study by Baker in 1984 informs us that drawing ventilation from conservatories has threefold thermal performance potential rather than through fenestration of the main dwelling (Baker, 1984). For the natural ventilation strategy to be effective during the heating season, the optimum ventilation load must coincide with the effective solar radiation gain and effective infiltration orientation (Baker, 1984). The principle of convection enables solar heated air to be transported to heat the main dwelling when the conservatory temperature is above the building demand temperature. This process, called pre-heating ventilation, consists of the control of the ventilation of a significant amount of heated air entering a dwelling through a conservatory before it is probably brought up to indoor comfort temperature levels by an active heating system with the resulting decrease in dwelling energy consumption (BRE 1988). The control of the natural ventilation for the utilization of the solar radiation gains can only be realized when the external air temperature is less than the air temperature in the conservatory (Baker, 1984). Bakos and Tsagas in their work on sunspace orientation in 2000 remarked that sunspace (conservatory) internal temperature could be noticeably higher than the ambient air temperature during the overcast winter period (Bakos and Tsagas, 2000). The warm air from the conservatory rises and is transported through the dwelling fenestrations to increase the indoor temperature. Moreover, the cold air from the dwelling is drawn to the conservatory, thus reducing the energy demand for heating the main building. This phenomenon is attributed to the temperature difference of the two air columns separated by a vertical surface (BS 5925, 1991). The effectiveness of solar pre-heating ventilation could be enhanced through the integration of ‘site micro-climate’, ‘wind pressure and stack effect on air movement’ and the control of the ‘permeability of the building fabric’ (BRE 1988).

Part F of the UK building regulations mandates that when a conservatory is used to ventilate a dwelling, the area of the operable fenestration between the adjacent habitable room and the conservatory should be “equal to at least 1/20th of the combined floor areas of the room and the conservatory”, and the fenestration in the conservatory should be “equal to at least 1/20th of the combined floor areas of the room and the conservatory” with “some part at least of the ventilation opening area [being] at least 1.75 meters above the floor level” (ODPM, 2010). The British Standard BS 5925 1991 clause 16.2(e) also stipulates the same criteria for ventilation of dwelling habitable rooms through an adjoining space such as a conservatory (BS 5925, 1991).

2.6.9 Shading

The strategic provision of shading devices help to mitigate high intensity solar radiation gains during non-heating season of the year and thus contribute to reduction in building energy consumption (Palmero-Marrero and Oliveira, 2010). Fully shaded glazed façades have the potential of reducing solar radiation gain by 80% (Palmero-Marrero and Oliveira, 2010), (ASHRAE, 1997). Shading is the most direct and effective passive solar method of avoiding overheating in dwellings and conservatories. Shading effectiveness is obtained by preventing transmission of unwanted solar radiation into the building envelope. This facilitates reduction or elimination of cooling energy demand. Shading effectiveness is underpinned by and not limited to the orientation of the building or conservatory with reference to the sun path, but also to the place of installation, the duration of provision, the shading coefficient and the shading factor (Florides et al. 2000), (BRE 1988). East and west orientations usually contribute to the greatest possibility of increased overheating in the early mornings and late afternoon respectively. However, these orientations also add to the overall balance of solar radiation gains in winter (ASHRAE, 1997).

There are basically three classifications of shading devices based on their placement position to the glazing unit; external, mid glass panes and internal shadings. Shading systems can also be grouped under fixed and operable shadings. The external shading devices, placed outside the glazing units, are the most efficient as they prevent excessive solar radiation from reaching the glazing unit by re-transmitting the radiant energy outside the building envelope. The effectiveness of external shading devices is seen in the use of sunscreens, overhangs, external blinds and awnings to control the high altitude sun in summer (BRE 1988). The external horizontal shading devices such as external awnings and overhangs offer a more comprehensive and pragmatic shading of the south-facing glazing units during summer when the sun altitude is high coupled with increased intensity of solar radiation (Palmero-Marrero and Oliveira, 2010). The overhang design solution should be based on the building geographical location, the latitude and building’s orientation to optimize solar energy utilization throughout the year. During the heating season, effective design of overhangs facilitates the efficient receipt of solar radiation due to the low angle sun (Radhi et al. 2009). Fixed overhangs offer an efficient approach to solar radiation control, reducing the excessive solar gains in summer but permitting the low altitude solar radiation in winter (Lee and Tavil, 2007). The challenge in fixed overhangs design is in the provision of horizontal levels. Inadequate overhang design could lead to overheating in late spring or early autumn (Lee and Tavil, 2007). Moreover, additional means of mitigating overheating is required beside the use of overhangs as ground reflected solar radiations could contribute to the excessive solar gains (Palmero-Marrero and Oliveira, 2010). Adjustable external shading devices offer the most efficient means of overheating control because of the asymmetry of the heating seasons (Palmero-Marrero and Oliveira, 2010). They offer the best strategy in controlling solar radiation gains in east and west orientations. External awnings used as an adjustable roof shading device is a good passive solar system in controlling the amount of incident solar radiation into a conservatory. The effectiveness of external awnings design is based on the colour, glazing orientation and adequate coverage (BRE 1988). Light colour southerly orientated awnings minimize solar radiation gains and have a 64% potential reduction of heat gains through single window glazing (BRE 1988). However, the effectiveness of the adjustable external awnings is heavily underpinned by variable occupant behaviour for proper operation. The mid glass panes shading consist of double or triple glazing units with integrated shading systems between its panes. They offer reliability in shading as they are independent of variable occupant behaviour (Bajah et al. 2008), (Nitz and Hartwig 2005). Bajah et al. in 2008 identified thermotropic glazing, electrochromic glazing and glazing covered with holographic foils as examples of shading systems assimilated into the glazing pane (Bajah et al. 2008). Internal shadings, for example curtains and internal blinds are less effective in preventing unwanted solar radiation in entering the building envelope as the solar radiation has already entered the interior of the building envelope before coming into contact with them. However, the effectiveness of internal shading is realized during the heating season as they prevent heat loss from the building's internal to the outside, thus reducing winter night heat loss (Florides et al. 2002).

There is a general lack of comprehensive studies of what encompasses the inter-relationship between all the design variables associated with optimal year-round energy conservation and thermal comfort of conservatory form and performance metrics in the United Kingdom. Moreover, there is a knowledge gap in the investigation of surface to volume ratio and aspect ratio of conservatories to facilitate optimum thermal performance design for current and future weather pattern variations. This thesis seeks to address these issues and therefore employs these integrated passive design strategies of varying future climatic conditions, variable occupant behaviour, building orientation, adequate provision of thermal mass, advance glazing, appropriate ventilation and sufficient level of external shading which influence the potential thermal performance of a conservatory and a methodology that combines thermal analysis modelling and simulation coupled with the application of CIBSE overheating criteria to investigate the thermal comfort and energy balance of habitable conservatories attached to detached dwellings in the UK using the CIBSE test reference year (TRY) and high design summer year (DSY) emission scenarios for the current and future (2020s, 2050s and 2080s) climatic change projections.

2.7 Method Comparison Analysis as a Validation Technique

The United Kingdom building regulation with its continuous emphases on improvement of building requirements is influencing the building industry toward the achievement of the set UK climate change act target of reducing greenhouse emissions by 80% in relation to 1990 emission levels by the year 2050 (Climate Change Act, 2008; Amoako-Attah and B-Jahromi, 2013). Professionals in the built environment are increasingly accepting building energy simulation as the status quo to drive the design of more energy efficient buildings (Witte et al., 2001) not only to meet the government set targets but to delight consumers in general with accurate prediction of energy performance in dwellings. However, accurate modelling and simulation of energy flows in buildings to reflect their actual thermal behaviour of temperatures, envelope losses, system performance and electrical loads (Judkoff et al., 2008) is still a challenge as numerous assumptions are made about the impact of uncertainties of a large number of building parameters. Moreover, recent studies have also shown an insignificant correlation between the design stage and the actual energy consumption in buildings (CIBSE TM54, 2013; Hogg and Botten, 2012). It is therefore obligatory to continually seek for validation techniques not only to inspire confidence and reliability in building simulation programs but also to facilitate a process of continuous improvement in the development of these software programs.

Building energy modelling and simulation programs had been used to evaluate building performances and assessments in the areas of building design and regulatory compliance, evaluation of changing weather data for an overheating analysis, assessment of building internal conditions (infiltration, ventilation, lightning gain, occupancy sensible and latent, equipment sensible and latent, and pollution generation), evaluation and enhancement of building thermal mass, evaluation and selection of renewable energy sources, building automation systems and moisture phenomena (Amoako-Attah and B-Jahromi, 2013) and there are scores of building simulation programs to undertake these task. The accuracy of building energy simulation has a direct bearing on the meticulous selection of the simulation input data ((Judkoff et al., 2008). Whilst there are no perfect modelling and simulation input data, these uncertainty parameters have to be analysed to determine their adequate values to reduce sources of discrepancy with the aim of reaching optimum design solutions of improving building performance indicators and contribute to the overall effort of greenhouse emission reduction. Thus, there is a need to examine the difference between measured and simulation predicted data to check the variance between the two.

Current validation techniques broadly include comparative studies, analytical verification and empirical validation (Judkoff et al., 2008). These methodologies have been presented by various authors in the built environment to advance the validation of building energy simulation programs. In 1999, Guyon and Palomo using analytical verification method validated two French software programs (Guyon and Palomo, 1999). Aude et al., using the adjoint-code method performed sensitivity analysis and validation of building thermal models in 2000 (Aude et al, 2000). In 2002, Palomo et al used parameter space analysis techniques for diagnostic purposes in the framework of empirical model validation (Palomo et al, 2002). In 2003, Ben-Nakhi and Aasem presented a paper outlining the use of exact analytical solution to validate ESP-r, a building simulation code (Ben-Nakhi and Aasem, 2003). Loutzenhiser et al, in 2009, conducted an empirical validation of three building energy simulation softwares (EnergyPlus, DOE-2.1E and IDA-ICE) in a test cell to validate their performance when simulating energy flows through glazing units and window frames and remarked upon the variation between the predictions from the simulation software and the experimental results (Loutzenhiser et al., 2009). In 2011, Sargent presented a paper that detailed four simulation verification and validation methodologies and recommended an approach for model validation and accreditation (Sargent 2011). In the same year, Vangimalla et al, using field measurements of building thermal loads and illuminance levels, validated the simulation accuracy of Autodesk EcotectTM for thermal and daylighting simulations of buildings (Vangimalla et al., 2011). Moreover, in 2012, Ryan and Sanquist reviewed different building energy validated methods as compared to metering data and emphasized the essence of accurate modelling of the effect of a building occupants to enhance the credibility of building simulations (Ryan and Sanquist, 2012). Korjenic and Bednar also in 2012 used dynamic simulation of total energy use in office buildings and validated the results against measured data of energy consumption of HVAC systems and electrical appliances (Korjenic and Bednar, 2012). In the same year, McNeil and Lee presented a study on the validation of radiance three-phase simulation method for modelling annual daylight performance of optically-complex fenestration systems and their work provided an insight into the simulation of emerging daylight products (McNeil and Lee, 2012). Furthermore, in 2013, Gerlich et al investigated the validity of COMSOL Multiphysics, a simulation software for the computation of heat transfer in buildings against measured temperature data (Gerlich et al, 2013). Kubilay et al, in 2013, satisfactorily validated a Computational Fluid Dynamics (CFD) simulation coupled with the Lagrangian particle tracking method against Eulerian Multiphase modelling for wind-driven rain (Kubilay et al, 2013). Montazeri and Blocken using wind-tunnel measurements also validated a 3D steady Reynolds-Averaged Navier-Stokes Computational Fluid Dynamics (CDF) use for the prediction of wind pressure distribution of medium rise buildings in 2013 (Montazeri and Blocken, 2013). Also in the same year, Bigot et al validated the combination of building thermal simulation code ISOLAB and the generic optimization program GenOpt using experimental data derived from a building roof with photovoltaic panel (Bigot et al, 2013). Again in 2013, Frances et al modelled the thermal response of a ventilated façade for a building simulation software and experimentally validated against a range of weather conditions (Frances et al, 2013).

A more recent work of validation of building simulation programs have been done by Ray et al, in February 2014. They conducted a full scale experiment within a naturally ventilated atrium and used the results to validate three Computational Fluid Dynamics (CDF) turbulence models and drew attention to the relevance of accurate modelling techniques and boundary conditions in atria design (Ray et al, 2014). Again in February 2014, Allegrini et al validated 2D steady Reynolds-Averaged Navier-Stokes Computational Fluid Dynamics (CDF) simulation for buoyant flows in urban street canyons by comparing the results with measurements from wind tunnel experiments and highlighted that Computational Fluid Dynamics can serve as a credible tool to predict the general flow fields and vortex structures (Allegrini et al., 2014). Moreover, in May 2014, Aparicio-Fernandez et al used experimental data based on the thermal behaviour of a floating external sheet to validate the energy performance of a modelled building with ventilated façade using TRNSYS simulation software (Aparicio-Fernandez et al, 2014) and in June 2014 Mateus et al, presented a paper of a thermal simulation study of a naturally ventilated double skin façade room using the EnergyPlus as the building simulation tool and obtained a good correlation when validated against air and surface temperatures in a free running weather test cell (Mateus et al, 2014).

In general, although there have been various validation studies undertaken in the use of some of these building simulation programs, there exists no explicit systematic development of validation methodology for building simulation programs (Judkoff et al, 2008). Current validation techniques broadly include comparative studies, analytical verification and empirical validation (Judkoff et al, 2008). There exists valuable technical information to help in the assessment and analysis of simulation programs. For example, the thermal analysis simulation software, TAS, used in this work has been validated through analytic verifications, intermodal comparison and experimental validation (TAS, 2014).

Studies related to the use of Bland-Altman procedure as method-comparison pervade clinical studies. For instance in 2003, Bland and Altman used the limits of agreement approach to analyse two different methods of measurement for single x-ray absorptiometry (SXA) and single photon absorptiometry (SPA) (Bland and

Altman, 2003). In the same year, Lu et al presented a study that validated a bio-impedance analysis (BIA) system by comparing it with dual-energy x-ray absorptiometry (DXA) in assessing body composition in obese children (Lu et al, 2003). Brazdzionyte and Macas in 2007 used the Bland-Altman graphical technique to evaluate the hemodynamics in patients with acute myocardial infarction using the two methods of intermittent thermodilution and impedance cardiography (Brazdzionyte and Macas, 2007) and in 2012 van Stralen et al, using the same approach, carried out work on two different blood pressure devices (van Stralen et al, 2012). To the best of the author's knowledge, Bland-Altman's method of statistical agreement evaluation has not yet been applied to the validation of building energy simulation.

Often, the goodness-of-fit measures (Mean bias error (MBE), root mean square error (RMSE), and coefficient variation of the root mean square error (CVRMSE)) are used to evaluate the validity of calibrated models, as stipulated in existing standards ASHRAE (ASHRAE 2001) and IPMVP (USDOE, 2002). This work shows what additional value this new statistical method can bring for model validation in comparison to existing methods. Bland-Altman plots are methods of agreement. This is different from the assessment of predictive performance using percentage error (PE) and root mean square error (RMSE). This work mainly introduces the method of agreement in validation of building simulations and further uses percentage error as a predictive performance method as recommended by Hanneman (2008).

In their work on error measurements in forecasting methods, Armstrong and Collopy (1992) noted the following, "The Root Mean Square Error (RMSE) is not reliable … Practitioners selected the Root Mean Square Error (RMSE) more frequently than any other measure, although it is not unit-free. Academicians had an even stronger preference for the RMSE. … in the early 1980s …. Carbone and Armstrong (1982)… asked 145 forecasting experts what error measures they preferred when generalizing about the accuracy of different forecasting methods. Practitioners selected the Root Mean Square Error (RMSE) more frequently than any other measure, although it is not unit-free." Armstrong and Collopy (1992) continued, "The RMSE has been used frequently to draw conclusions about forecasting methods. For example, Zellner (1986) claimed that the Bayesian method was the most accurate method in the M-competition because its RMSE was lowest. However, Chatfield (1988), in a re-examination of the M-Competition data, showed that five of the 1001 series dominated the RMSE rankings. The remaining 996 series had little impact on the RMSE rankings of the forecasting methods." They then concluded, "The RMSE is unreliable. Related to this is its poor protection against outliers. We do not recommend the RMSE for assessing the level of accuracy. As noted, it was not useful for the 1001 series in the M-competition (Chatfield (1988))." They then stated that, "Researchers now seem to prefer unit-free measures for comparing methods."

The root mean square error (RMSE) measures how far a typical spread of points would be from the regression line. Mantha et al (2000) indicated that correlation and least square regression analysis which often underpins calibration statistical methods are "fundamentally misleading" (Mantha et al, 2000). Pointing to the fact that, "some applications of regression are also inappropriate" (Bland and Altman, 2003), Bland and Altman wrote, "It is often thought that, as the data should cluster around the line of equality for good agreement, the regression line should be similar to the line of equality. This is not so" (Bland and Altman, 2003). They then graphically illustrated their point. They, however, indicated the appropriate use of regression when the two methods do not have the same units of measurements. Thus the Bland-Altman limits of agreement method stipulate that neither the Pearson's correlation coefficient nor regression techniques are adequate for comparison of two methods (Bland and Altman, 2007).

Moreover, the statistical coefficients of mean bias error (MBE), root mean square error (RMSE) and the coefficient of variation of root mean squared error (CVRMSE) presented in the ASHRAE Guideline-14 (ASHRAE, 2002) are done in the context of estimating building simulation model accuracy to that of actual energy consumption. Georgiou et al (2014) noted that, "currently, there is not any metric, which evaluates the space temperature," and therefore used a graphical approach in their work on modelling indoor temperature. In the same vein, this work focuses on method-comparison analysis of dwellings' temperatures to enhance validation of the building simulation process.

2.8 Monte Carlo Uncertainty and Sensitivity Analysis

The UK built environment contributes to about 40% of the total greenhouse gas emissions (Tian and de Wilde, 2011). The challenge is to build adaptable and resilience buildings which effectively balance the three important building performance criteria of efficient energy consumption, thermal comfort and the employing of low carbon technologies.

2.8.1 Uncertainty Analysis

The key to determine the target output of thermal comfort is a comprehensive building model and credible input variable information (Dominguez-Munoz et al. 2010). Though uncertainties of input variables may have significant implications on building simulations, they are quite often not identified, quantified and included in building simulations (Dominguez-Munoz et al. 2010). Most simulation programs do not incorporate uncertainties in input and thus result in outputs of single estimates (Dominguez-Munoz et al. 2010). Uncertainties in building energy simulations are associated with the variability of the weather data, the thermo-physical properties of the buildings in relations to the building fabric and systems, the associated internal heat gains coupled with variable occupant behaviour. The occurrence of uncertainties is attributed to incomplete specifications, inadequate knowledge of building characteristics, and lack of specifications in operating conditions in relation to weather, internal heat gains, and systems set points (Dominguez-Munoz et al, 2010). It may also relate to inherent simplifications of a model and lack of sufficient input data information (Rodriguez et al, 2013). The impact of these input uncertainties influence the accuracy of building energy simulations in spite of the efficacy of the applied model (Dominguez-Munoz et al, 2010). Uncertainty analysis is thus used to determine a confidence limit for a model output (Spitz et al, 2012).

Studies of uncertainty analysis of building simulation input can be seen in literature. In 2002, de Wit et al used uncertainty analysis in building design evaluations to assess the impact of summer overheating risk in naturally ventilated buildings (de Wit et al, 2002). In 2005, Breesch and Janssens presented a conference paper on uncertainty and sensitivity analysis in evaluating the performance of natural night ventilation using building simulation (Breesch and Janssens, 2005). Moreover, Hyun et al, in 2008, used uncertainty analysis to predict natural ventilation in commercial buildings (Hyun et al, 2008). Brohus et al, in 2009, also used uncertainty analysis to explore the key parameters which influence the energy consumption of domestic buildings in Denmark (Brohus et al, 2009).

This work employs the box and whiskers plot as one of the effective methods used in uncertainty analysis. The box and whiskers plot presents a summary of the important data set characteristics of the maximum and minimum values, the median, the dispersion, asymmetry, the extreme values and the percentile rank analysis (Baracos, 2011). The advantage of using box and whiskers plot in uncertainty analysis stems from its graphical clarity in representing large variability of multiple data sets which could be difficult to analyse using statistical means such as histogram and standard deviation whose interpretations may be difficult for non-technical analysts (Baracos 2011). The box and whiskers plot offers asymmetrical interpretation and data extremes. Its further advantage is the use of median as the central tendency instead of mean. The mean value used in analysis can be skewed by extreme values. However, the median which is equivalent to the 50th percentile in a percentile rank analysis is not affected by the extreme values.

2.8.2 Sensitivity Analysis

Sensitivity analysis used to investigate building thermal performance entails the modification of the model input parameters to check their resulting impact on the model output parameters (Rodriguez eta al, 2013). These input factors mainly drive the uncertainties in the target variables (Domingues-Munoz et al, 2010). Saltelli et al, in 2004, defined sensitivity analysis as: “the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input,” (Saltelli et al, 2004). Tian, in 2013, outlined the factors underpinning the choice of sensitivity analysis method as the research purpose, computational cost, amount of input variables, project allocated time and the ease of use for a particular sensitivity method and also indicated that many building performance analysis studies do not include sensitivity index as an analysis criterion (Tian, 2013).

Studies of sensitivity analysis have been conducted in the areas of building design, calibration of energy models, building retrofit, building stock and impact of climate change on buildings (Tian, 2013). In 2011, Tian and de Wilde using probabilistic climate projections applied uncertainty and global sensitivity analysis in identifying the key variables affecting climate change predictions and those of building fabric and systems, which essentially contribute to the interventions in building performance (Tian and de Wilde, 2011). Also in 2011, Hopfe and Hensen explored the importance of various building performance parameters of an office building and, using uncertainty analysis, investigated their impact on energy consumption and thermal comfort (Hopfe and Hensen, 2011). In the same year, Eisenhower et al conducted an uncertainty and sensitivity analysis based on about

1000 variables using a quasi-random sampling method and a meta-model (Eisenhower et al, 2011). In 2012, Hygh et al, using Monte Carlo analysis, developed a multivariate linear regression model for early design stage sensitivity analysis based on twenty seven building design variables and remarked upon the standardized regression coefficients which could be used to quantify the sensitivity of heating, cooling and total energy loads for four different climate zones (Hygh et al, 2012). In the same year, Tian and Choudhary, using uncertainty analysis as a criterion investigated London's non-domestic buildings as a case study and developed a probabilistic energy model for large scale analysis of diversified non-domestic building stock in urban areas (Tian and Choudhary, 2012). Moran et al, also in 2012, explored sensitivity analysis to develop a data base of energy use for historical dwellings (Moran et al, 2012). Moreover, Spitz et al, also in 2012, proposed a three step methodology to identify the influence of uncertainty parameters on building performance in the building design simulation process (Spitz et al, 2012). Burhenne et al, in 2013, proposed a Monte Carlo based methodology for uncertainty analysis for combining building performance and cost-benefit analysis which would strengthen the building design process and facilitate effective decision making (Burhenne et al, 2013).

The purpose of sensitivity analysis in building performance modelling and simulation and observational study is to explore the uncertainty of the key input parameters which influence prediction of the building performance parameters and to investigate the important varying contribution of different design parameters to building performance (Tian and de Wilde, 2011), (Tian, 2013). The regression sensitivity analysis is mostly used in building performance analysis due to its computational and results interpretation simplicity (Tian, 2013).

Basically, there are two board categories of sensitivity analysis use in building simulations: the global and local sensitivity analysis or differential sensitivity analysis (Tian, 2013). The global sensitivity analysis which is mostly used in simulation analysis entails the input of variables over a whole range and explores the interaction effect (Spitz et al, 2012) as compared to the local sensitivity that considers inputs around a point or a base case when one variance parameter is changed at a time with all others kept constant (Tian, 2013).

The simplicity of the local sensitivity analysis is underpinned by non-inclusion of sampling methods to generate combinations of inputs and with easily interpretated and applied results and has the disadvantage of a small portion of the possible space of input values (Tian, 2013). The global sensitivity analysis, however, offers a better option in sensitivity analysis in identifying the important variables which influence the target variables with some input variables for self verification (accounting for the total variances of output in the analysis) and offers variance parameter interaction analysis (Tian and de Wilde, 2011), (Tian, 2013).

There are four different methods that can be classified under the global sensitivity analysis: regression, screening based, variance-based, and meta-model sensitivity analysis (Tian, 2013).

The screening based sensitivity analysis is primarily utilized to vary certain input parameters from a large set without compromising the output variance results and it has an advantage of low computational cost as it is underpinned by the use of fewer influential parameters (Tian, 2013). The disadvantage of using the screening based sensitivity analysis stems from the qualitative presentation of the output results which presents the challenge of quantifying the impact of different factors on the outputs (Tian, 2013). Another disadvantage also results from the use of mean and standard deviation as a sensitivity index measure. In instances where convergence to the population mean of the model output cannot be achieved, the uncertainty analysis application would not suffice (Tian, 2013).

The variance-based sensitivity analysis method takes cognisance of the effects of all the inputs to quantify the output variance and it is applicable to complex nonlinear and non-additive models. The method has the disadvantage of high computational cost (Tian, 2013).

The meta-model sensitivity analysis which offers a more efficient sensitivity index measure than the variance-based method approximate objective functions by means of statistical models. It offers less running time than normal simulation models as its advantage (Tian, 2013).

Spitz et al, in 2012, indicated in their work that the most popular methods for global sensitivity analysis method include Sobal, FAST, Random Balance Design, and the Monte Carlo method (Spitz et al, 2012). There are many studies conducted on uncertainty and sensitivity analysis using Monte Carlo method and some of these authors also use the standardized regression coefficient (SRC) and Partial Correlation Coefficient (PCC) as sensitivity analysis indices.

2.8.3 Assessing the impact of different simulation input parameters

The SRC method sensitivity analysis is widely used in literature (Tian and de Wilde, 2011), (Tian, 2013), (Storlie et al, 2009) and as it offers variability measure of independent input parameters in a linear regression model. Analysis of the SRC higher absolute values indicate more important contribution of the variables whilst negative SRC values point to converse interpretations (Tian and de Wilde, 2011). Breesch and Janssens, in 2010, conducted a study thermal comfort analysis of occupants in a passive cooling office building in Belgium, and using SRC as a sensitivity analysis index pointed out internal heat gains and air tightness as the key influential parameters in determining thermal comfort (Breesch and Janssens, 2010). In the same year Dominguez-Munoz et al (2010) conducted uncertainty analysis using SRC sensitivity index criterion to determine the influential input parameters which affect the peak cooling load at the early stages of a building project. Their results pointed to an internal thermal mass and convective heat transfer coefficient between the internal mass and air as the most influential parameters (Dominguez-Munoz et al, 2010). Hygh et al (2012), in using multivariate regression as a performance assessment tool in building design, employed SRC as a sensitivity index to quantify the building energy performance across four climate zones. Their work indicated that SRC usage offers valuable information to building designers in assessing the relative importance of influential input parameters which contributed to the energy loads and stressed the need for climate-sensitive design (Hygh et al, (2012)). In 2012, Ballarini and Corrado also used SRC as an application of sensitivity analysis measure to explore the effect of thermal insulation characteristics on space cooling energy performance. Their work identified solar shading, window area and window insulation as the three most significant parameters associated with cooling energy for residential buildings in Italy (Ballarini and Corrado, 2012). In 2013, Rodriguez et al also applied the SRC as they developed a methodology to investigate sensitivity analysis of building simulation programs using law-driven simulation models that require a large set of input uncertainties (Rodriguez et al, 2013).

The Standardised Regression Coefficient (SRC) or the beta value offers a quantitative global sensitivity analysis index which is robust and easy to use (Rodriguez et al, 2013). It gives a quantitative measure of parameter sensitivity and influences the different input parameters on the output with the sign indicating the direction of the parameter sensitivity to the target parameter (Hygh et al, 2012). The SRC gives a measure of the significance of moving each input variable away from its expected value by a fixed fraction of its standard deviation while maintaining the other input parameters at their expected values (Rodriguez et al, 2013). For instance, a beta value of say ‘x’ shows that a change of one standard deviation in the output variable will result in a change of ‘x’ standard deviation in the input variable. Its equivalent is the computation of regression analysis with normalised input parameters with the mean of zero and standard deviation of one (Rodriguez et al, 2013). The sensitivity index values range between zero and one with the higher absolute indices pointing towards the more significant parameters (Spitz et al, 2012). The positive coefficient points to an increase in the output parameter with the increasing input parameter. The negative coefficient shows that an increase input parameter will result in the decrease of the output parameter (Rodriguez et al, 2013).

The Standardised Regression Coefficient (SRC) and Partial Correlation Coefficient (PCC) are chosen as regression sensitivity methods because they are appropriate for linear models (Tian, 2013). The partial correlation assists in the examination of the relationship or association between two variables whilst controlling the other variables. Whilst the two methods may give the same results in the case of uncorrelated inputs, differences in results may show if there are correlated inputs as only PCC is appropriate for both correlated and uncorrelated inputs but SRC is suitable for only uncorrelated inputs (Tian, 2013). The Standardised rank regression coefficient is not used as it is only applicable for non-linear models (Tian, 2013).

In this work, Monte Carlo approaches are used in estimating the effects of uncertainty inputs on a corresponding output uncertainty (Tian and de Wilde, 2011) in assessing the impact and adaptations to climate change. The Monte Carlo method is a computer random sampling technique that performs multiple model runs from probability distributions of inputs to provide a range of values that is used to determine the uncertainty in a model output (Dominguez-Munoz et al, 2010).

2.9 Selection of simulation and statistical analysis software

2.9.1 Why EDSL TAS is selected as the simulation software for this thesis.

Thermal Analysis Simulation software TAS, a building simulation program developed by (Engineering Development Solutions Software (EDSL, 2014), is used as a dynamic simulation modeller to model and simulate thermal and energy performance of the various prototype buildings in this work.

There exists other thermal analysis simulation software. For instance the use of Integrated Environmental Solutions (IES) and EnergyPlus (now DesignBuilder) permeate research and publications. EDSL TAS and these other dynamic simulation tools have UK building regulations Part L2 compliance. They all have the capability to use hourly weather data and import CAD plan as a template for drawing walls, creating windows and doors. In addition they have unlimited orientations, solar shading, daylight simulation to obtain daylight factors and could be utilized in summer overheating analysis.

The use of TAS and IES are preferable in some circles. Although these software are described as "black box" in computing parlance, in TAS and IES, all interaction between the user and the software is done through a graphical user interface (GIU). Thus, knowledge of computer programming or of the mathematics and equations that govern building physics are avoided. However, EnergyPlus is a stand-alone simulation program without a "user friendly" graphical interface. The program reads input and writes output as text files. EnergyPlus features have been used in developing DesignBuilder which has been around recently when compared with EDSL TAS which has been in commercial use in the United Kingdom and the rest of the world for about three decades. One advantage of TAS over IES is that in IES no dynamic modelling of plant components is involved whereas in TAS individual plant components system can be set up and hourly dynamic plant simulation is carried out.

The current version of EDSL TAS was the first dynamic simulation software to be approved and has the full accreditation for UK building regulations 2013 and it has also demonstrated compliance to various BS EN ISO standards (EDSL, 2014). Energy calculation methods of software are based on ISO 13790:2008 (Thermal Performance of Buildings – Calculation of Energy Use for Space Heating and Cooling) and other steady-state energy balance methods (Tian, 2013). TAS uses computational fluid dynamics (CFD) in its analysis and has CIBSE accreditation. The effective user interface for TAS complex computational dynamic fluid complex energy simulation engine lessens the task of constructing an energy text-based model making the process more intuitive. Moreover, TAS has both graphic user interface and text- based results viewer which facilitates the coping of text information to other programs like Excel and IBM SPSS for analysis.

CIBSE has transformed both the UKCIP02 and the UKCP09 meteorological predictions into TAS format for building simulation. These weather files are used to quantify the uncertainties in weather data sets in the prediction of future thermal performance associated with climate change.

TAS has the capability to overcome the challenge of applying the ‘vast quantity of data to assess the probabilistic performance of buildings in the future’, (William et al, 2011). It also offers a complete solution as a powerful modelling and simulation tool in the optimisation of building environment, energy performance and occupant comfort. The TAS modeller has the capability of identifying and fixing gaps in the space boundaries, incorrectly orientated surfaces and adjacency problems. Furthermore, TAS has the facility to optimise the building environment, energy performance and occupant comfort. It also offers ray tracing and radiosity results; and this TAS Daylight method can produce useful daylight illuminance (UDI), daylight autonomy (DA) and daylight distribution (EDSL, 2014).The newer versions of TAS have incorporated the CIBSE TM52 adaptive overheating criteria for building zones analysis in the TAS report generator. Moreover, TAS Result Viewer gives “Dry Bulb Temperature” and “Mean Radiant Temperature” as simulation output temperatures; key variable inputs in the application of CIBSETM52 in determining operative temperature for overheating analysis. This aspect of TAS was in effect suitable for this work. Thus, TAS offers complete solution as a powerful modelling and simulation in the optimisation of building environment, energy performance and occupant comfort.

The SAP software a “surrogate design tool” used for evaluating dwellings energy performance was not used in this work. The SAP software uses a monthly average in determining overheating risk (DCLG and AECOM, 2012) as compare to the hourly weather data sets used by TAS. As noted in the Department of Communities and Local Government (DCLG) and AECOM report in July 2012, “SAP tool is intended to be used for a compliance assessment rather than as a design tool.” Since the work on the progressive variation of the thermal mass and other construction specifications were design based, TAS was selected as the appropriate software.

However, while TAS offers an excellent means to evaluate the respective zones’ overheating based on the CIBSE TM52 adaptive overheating criteria, the analysis and graphical representation of the whole building was observed to be only weather based and does not truly reflect the indoor operative temperatures as defined in the CIBSE TM52. TAS uses variation of the external temperatures instead of the indoor operative temperatures. Thus, TAS graphical representation of the CIBSE adaptive overheating criteria is based on the external dry bulb and external running mean temperature. The authors therefore developed an Excel program for the analysis of the whole building scenario as stipulated in the CIBSE TM52 to reflect the variation of the indoor operative temperature for the clear assessment of the dwelling’s thermal comfort. Data from the TAS simulation was fed into the Excel program for this analysis.

2.9.2 Sensitivity analysis software

Many statistical programs can be used in performing sensitivity analysis. Tian (2013) in his work of review of sensitivity analysis methods in building energy analysis selected Simlab and R as suitable software for sensitivity analysis. Their recommendation stems from the free availability of this software and their capability in offering different types of uncertainty and sensitivity analysis (Tian, 2013).

IBM SPSS statistical software has a Monte Carlo simulation module design for uncertainty and sensitivity analysis. Monte Carlo simulation is the computer generation output solution to a problem through random sampling from probability distributions of input variables (IBM 2013).

CHAPTER 3: Methodology

3.1 Identification and Justification of Research Paradigm

The quest for new knowledge is underpinned by what counts as knowledge and how it is developed (Saunders et al. 2006). This theory and framework which serves as a basis of research development is the paradigm. Thomas Kuhn (1962, 1970) advanced that paradigm as "the underlying assumptions and intellectual structure upon which research and development in a field of inquiry is based.

Creswell (2003) considers three composite elements as a framework for a research design. He outlined; the philosophical assumptions about what constitute "knowledge claims", "strategies of inquiry" as the general procedures for research, and "methods" as detailed procedures of data collection, analysis and writing.

The knowledge claim of this work is based on the positivism research paradigm approach. Fundamental to the positivism epistemological approach is the objective approach to research which eventually would lead to a meaningful theory or generalized pattern which could be revised upon new findings (Connet et al, 2000). The framework focuses on the principles and assumptions of science (Connet et al, 2000). The positivism epistemological approach usually lends itself to the quantitative research approach as a structured methodology (Saunders et al, 2006). The strength of quantitative methodology lies in the fact that the research problem, objective, hypothesis, process and expectations are clearly defined at the outset (Frankfort-Nachmias and Nachmias, 1992). The arguments for the use of the quantitative research approach are related to strict adherence to methods of measurements, observation, exact analysis and general interpretations of social reality, and eliminating subjectivity (Cassell and Symon, 1994). The quantitative research approach is therefore used in gathering and analysing the data in this work. The methodology used in this work is thus underpinned by the use of thermal analysis modelling and simulation and is demonstrated by the use of various case studies which seek to assess and quantify the impact of climate change in predicting energy consumption, thermal comfort and carbon dioxide emissions in detached dwellings in the United Kingdom.

3.2 Methods

3.2.1 Research Design, Planning and Execution

Creswell (2003) notes that the choice of research method must be underpinned by the research question. This work research design is based on the investigation of impact of varying future climatic patterns on building performance and the application of passive design solutions as mitigation and adaptation techniques. It further evaluates how energy usage characteristics of building occupants, energy consumption and thermal comfort may be accurately modelled to improve the total energy consumption of detached dwellings and further lead to the decrease in carbon dioxide emission through the appropriate selection of modelling parameters. Primary data on the impact of future climate change on building energy and thermal performance is obtained through thermal analysis modelling and simulation. The researcher makes use of relevant design codes and national standards for assessing the varying building occupants’ characteristics, energy consumption, carbon dioxide emission and internal operative temperatures of residential detached buildings. Computational fluid dynamics simulation is used in the energy and thermal performance of buildings. In addition, knowledge is developed through a multi-method quantitative study design, while the data collected is analysed by statistical procedures.

3.2.2 Data Analytic Procedures

Borrego et al (2009) emphasised that, “rigorous statistical analysis is essential in quantitative reach to ensure reliability and generalizability of the results,” (Borrego et al, 2009). The current versions of SPSS and Excel statistical software packages are used in the deterministic, uncertainty and sensitivity analyses. Descriptive statistics in the form of percentages, frequency distributions, range of observed values, means and standard deviations are used to interpret various points and situations in the study (Borrego et al, 2009). Scatter plots, tornado charts and box and whiskers plots are used in the Monte Carlo uncertainty analysis. Standardized Regression Coefficient and Partial Correlation Coefficients are used as sensitivity indices for the Monte Carlo global sensitivity analysis. Subsequent interpretations of all these analyses are performed to examine the significant differences and variability in energy consumption, internal operative temperatures and carbon dioxide emission patterns.

3.2.3 Research Method 1 – For Case Study 1

The goal is to verify through an established method-comparison study of the agreement between monitored temperatures and thermal analysis operative temperatures of a detached dwelling. The detached dwelling used as the case study is 49 Carnation Drive; a 1995 three-bed room house located at Bracknell, Berkshire, about 48 kilometres from Central London, the closest weather station. Hence the current CIBSE London TRY is chosen for the analysis.

3.2.3.1 Thermal Analysis Simulation (TAS) 3D Modelling

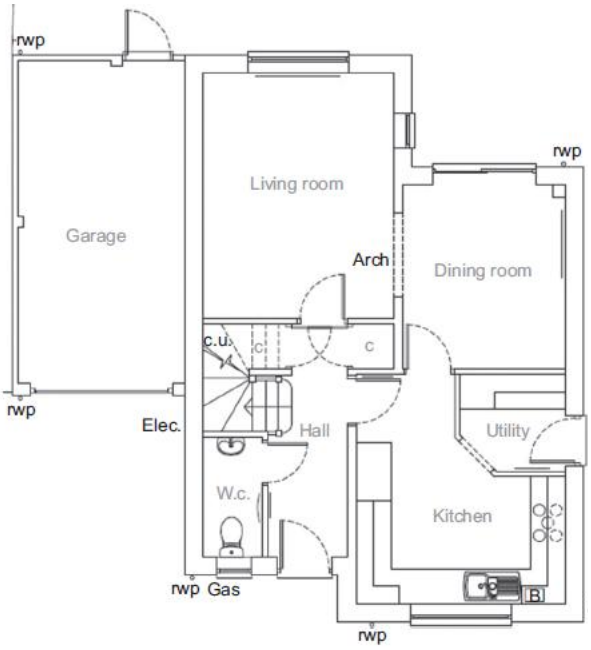
Bartak et al., identify the main current modelling and simulation techniques as; the energy and mass balance based modelling systems to predict and evaluate the energy performance of integral buildings and HVAC systems, and computational fluid dynamics (CFD) methods for prediction of air flow and temperature fields in rooms and around buildings (Bartak et al., 2001).

The CFD tools appear to be more robust as they take into consideration “more detailed radiation models for calculating the combined convective and radiative heat transfer” (Treeck et al, 2001). The thermal analysis simulation takes cognisance of building geometry, construction, equipment and systems integration and further incorporates building occupants’ energy usage characteristics, noting the important energy interactions modelled at an appropriate level of resolution and accuracy and encompassing the variance of the building 3D geometry with changes in time. In other to proceed with the dynamic simulation, various structural input data and other parameters that impact on the energy and thermal behaviour of buildings were established and categorised. These inputs were fed into the EDSL TAS computer program for modelling and simulation analysis.

EDSL TAS software, a more robust 3D modelling and simulation tool, is used as a dynamic simulation modeller to model and simulate the thermal mass of each of the case studies' prototype buildings. In each case study, the building type, AutoCAD drawings and location are indicated.

The data used are the AutoCAD two-storey residential detached buildings architectural drawings of 49 Carnation Drive, figures 3.1 and 3.2. The building drawings consisted of the ground floor and first floor plans. Measurements of floors, doors and windows dimensions were taken from the drawings of AutoCAD elevations. The floor level was measured from the ground plane at datum 0.0m. The default wall height dimensions were measured from the floor finish to directly below the floor finishing of the upper floor. The respective zones on the ground floor and first floor plans were noted and further grouped into Bedrooms, Circulation, Toilet and Miscellaneous.

To aid in the shadow calculations in the 3D Modeller, the orientation of the north angle was changed to 135 degrees clockwise to the North and the latitude, longitude and time zone changed to 51.42 degrees North, -0.75 degree East and UTC +0.0 respectively to reflect the geographical and time parameters of Bracknell, Berkshire which is about 48 kilometres from Central London, the closest weather station. The current CIBSE London TRY was chosen for the analysis. The current CIBSE Try weather data set is based on historical data for London and thus does not perfectly reflect the microclimate of Bracknell, Berkshire. The accuracy is therefore first verified through the monitoring of the outdoor temperatures and the external temperature data from the thermal analysis simulation. The flow charts in figures 3.3 to 3.5 in illustrate the drawing files' preparation for the 3D modelling process and the modelling of the ground floor, first floor and the roof arrangement respectively.



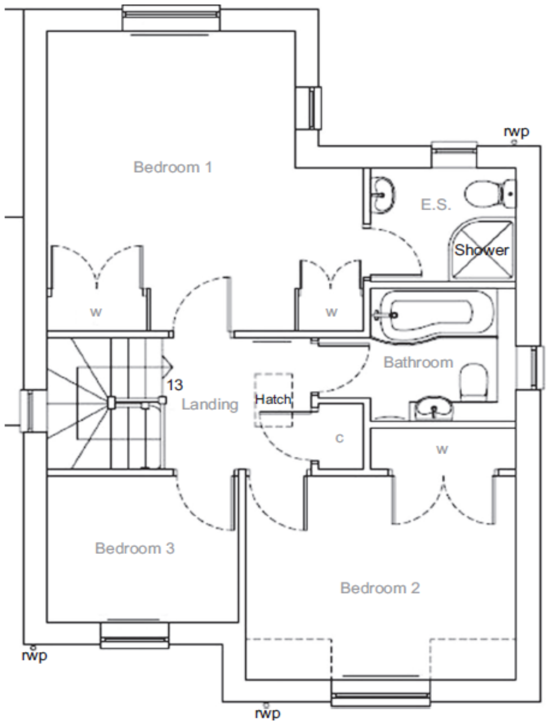


Figure 3.1 Ground Floor Plan

Figure 3.2 First Floor Plan

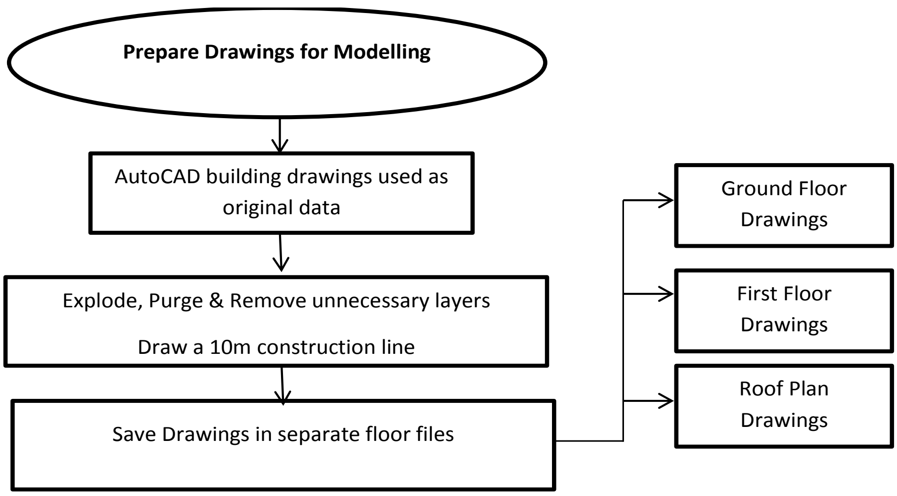


Figure 3.3 Prepare Drawings for Modelling

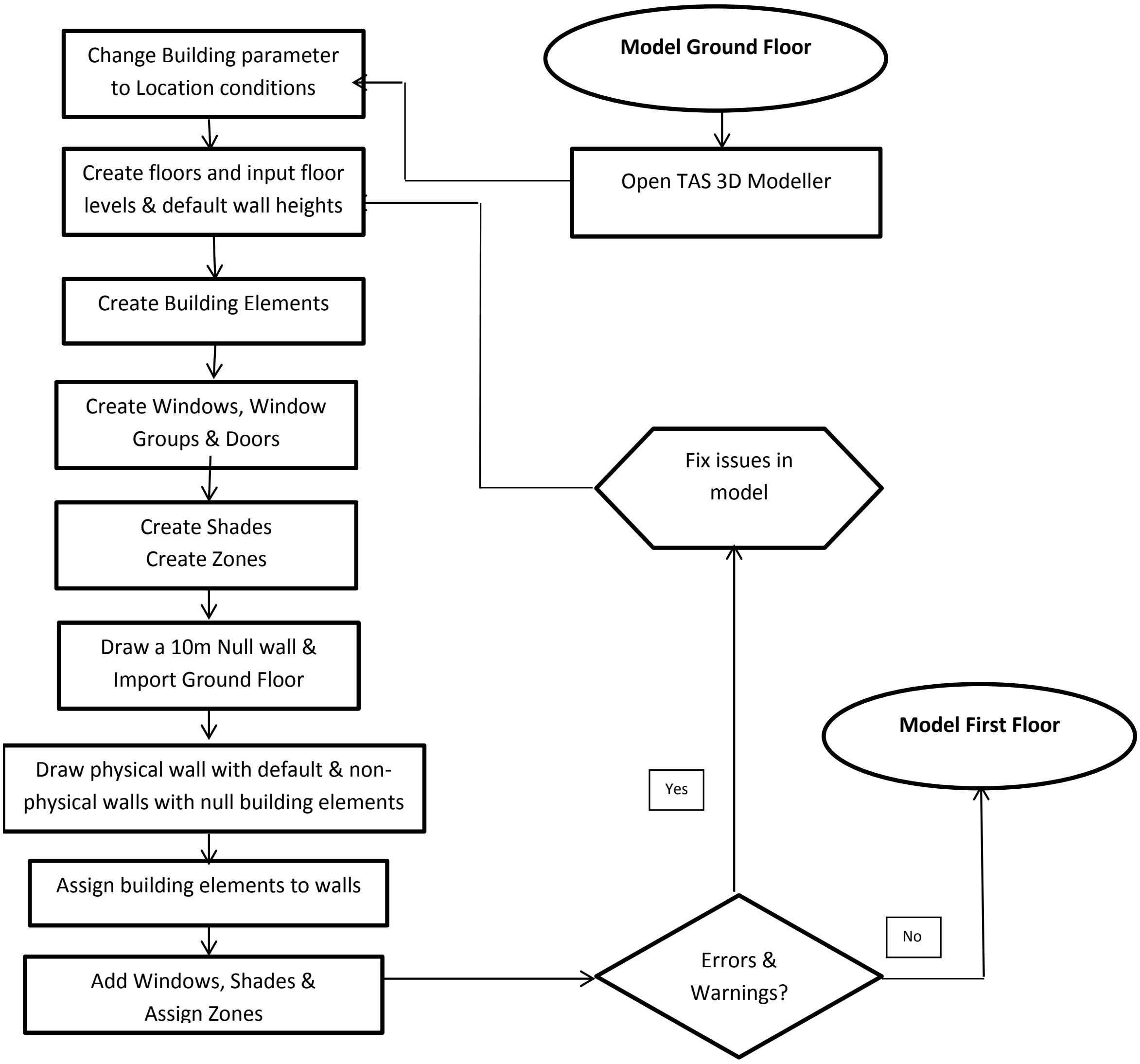


Figure 3.4 Ground floor modelling process

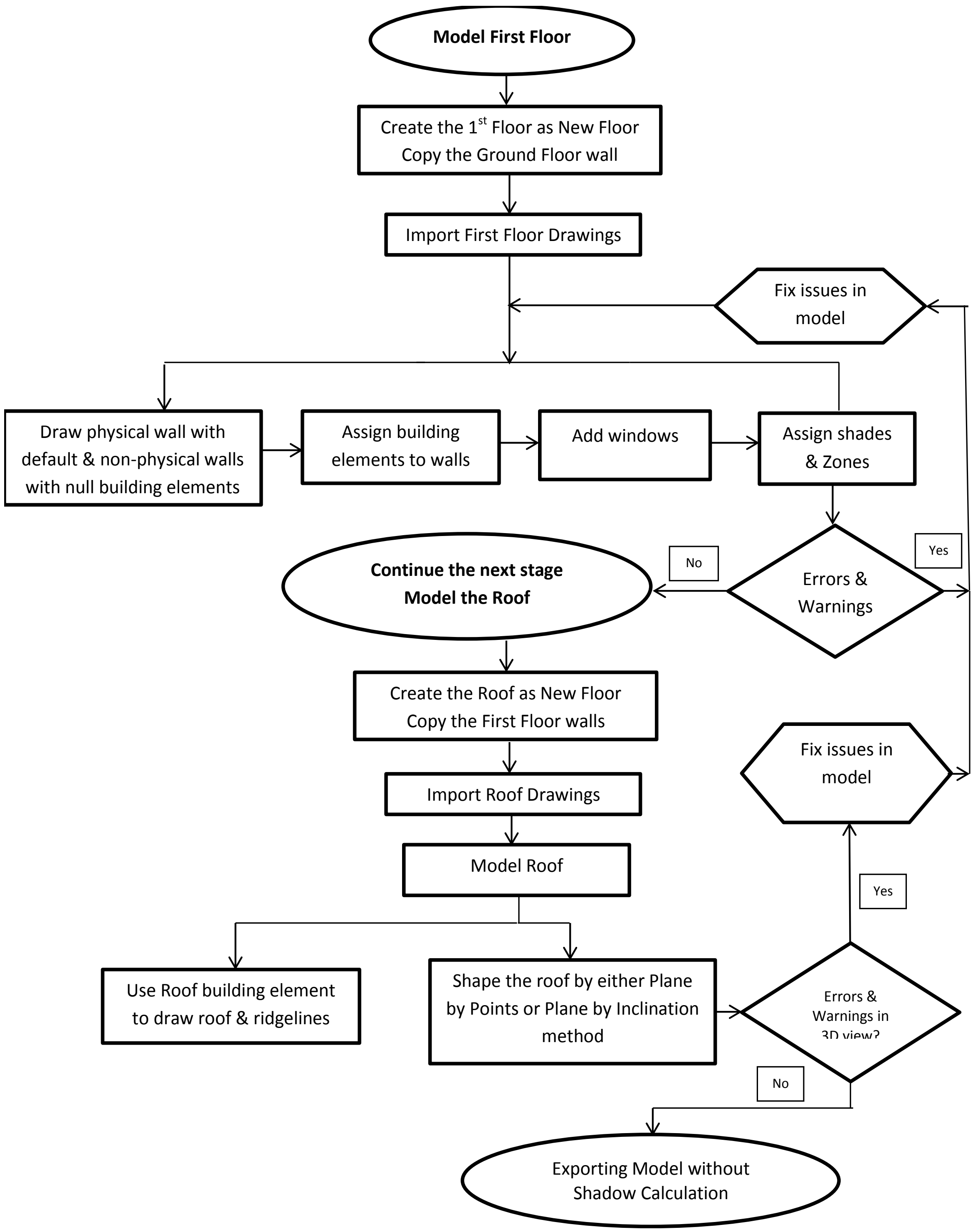


Figure 3.5 First floor/Roof modelling process

3.2.3.2 Simulation Process and Assumptions

TAS as a dynamic simulation modeller models the thermal mass of a building. Building performance simulation requires the appropriate selection of modelling parameters and assumptions. The following assumptions were made in this work;

(i) Acceptability of CIBSE TRY and CIBSE DSY weather data sets which are based on historic data patterns to be applicable to actual weather conditions of the case study building location.

(ii) Acceptability of the standardized National Calculation Methodology dwelling internal conditions activity and occupant behaviour as the prevailing conditions of the case study building.

(iii) Assuming U-values to be static instead of being dynamic as they vary with thermal and climatic conditions.

The various simulation parameters of Building Summary, Calendar, Weather, Building Elements, Zones, Internal conditions, Schedule, and Aperture Types were populated to simulate the residential building. Figure 3.6 is a flow chart which shows the thermal simulation process with its associated modelling and simulation parameters indicated in tables of each case study.

3.2.3.3 Thermal Analysis Simulation

TAS, as a dynamic simulation modeller, models the thermal mass of a building. The other simulation parameters of Building Summary, Calendar, Weather, Zones, Internal conditions, Schedule, and Aperture Types were entered to simulate the building for it to reflect the construction design criteria specified by the CIBSE

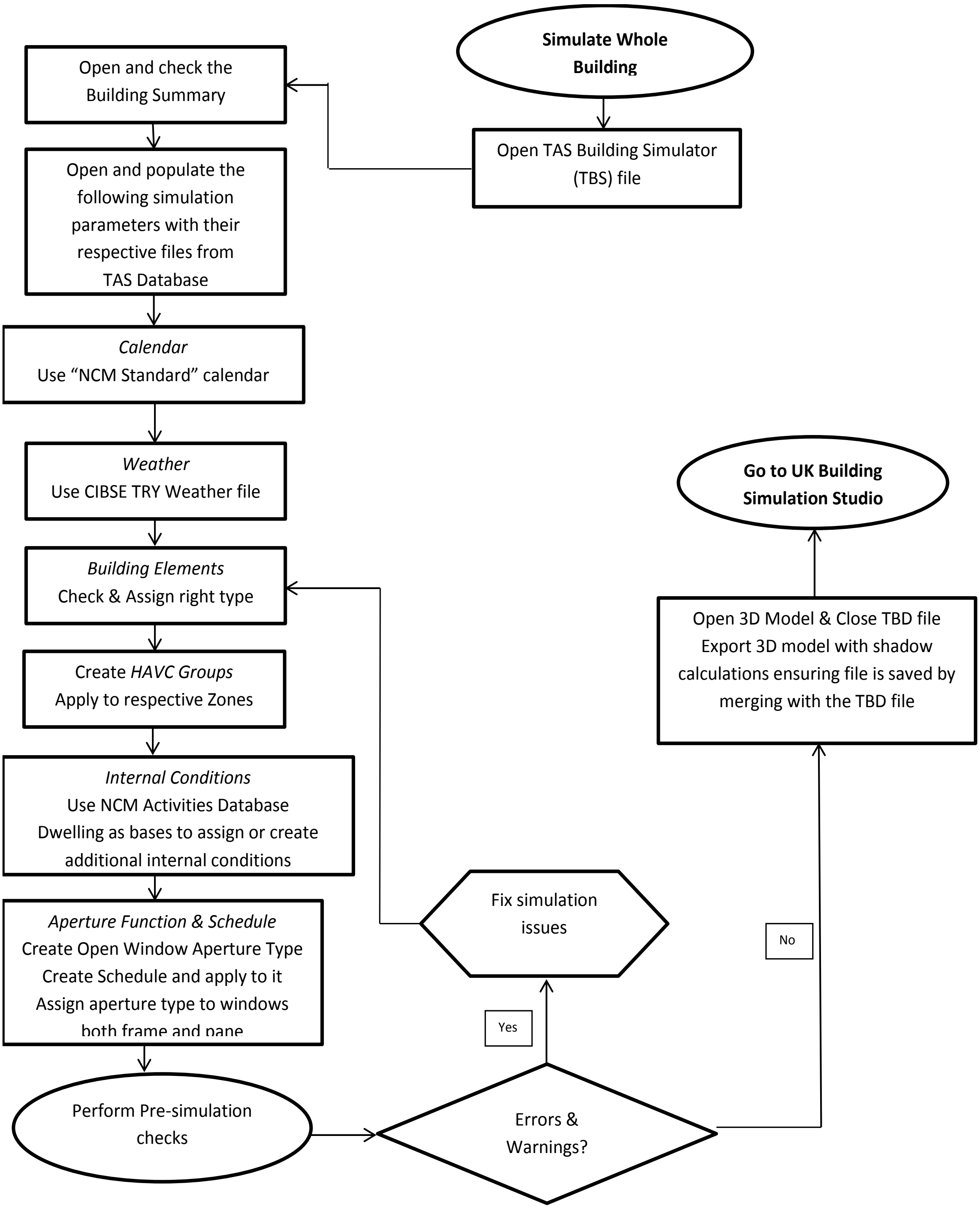


Figure 3.6 Thermal Simulation process

Guide A (2006) and TAS for dwellings. Figure 3.6 is a flow chart which shows the thermal simulation process with its associated modelling and simulation parameters in tables 3.1 and 3.2.

Table 3.1 Modelling and Simulation Parameters and Assumptions

Building fabric		
Calculated area weighted average U-values	Wall	0.24 W/m^2K
	Floor	0.21 W/m^2K
	Roof	0.13 W/m^2K
	Windows	2.30 W/m^2K
	Doors	2.05 W/m^2K
Average U-value		0.41 W/m^2K
Calendar	NCM standard	
Air permeability	5 m^3/hm^2 at 50 Pa	
Infiltration	0.250 ACH	
Lighting efficency	5.2 W/m2 per 100 lux	
Average conductance	78 W/K	
Alpha value	22.85%	

Table 3.2 Modelling and Simulation Parameters and Assumptions

Construction data base		NCM construction v4.1.tcd
Occupancy levels; People density; Lux level	Bath	0.01873684 person/m^2, 150 lux
	Bed	0.01873684 person/m^2, 150 lux
	Circulation area	0.02293877 person/m^2, 150 lux
	Dining	0.0169163 person/m^2, 150 lux
	Kitchen	0.0237037 person/m^2, 150 lux
	Lounge	0.0187563 person/m^2, 150 lux
	Toilet	0.02431718 person/m^2, 150 lux
Fuel Source	Natural gas	Carbon dioxide factor - 0.198 kg/kWh
	Grid electricity	Carbon dioxide factor - 0.517 kg/kWh

3.2.3.4 UK Building Regulation Studio

The UK Building Regulations Studio used by the TAS EDSL 9.3.1 software is based on 2013 regulations. It adheres to the National Calculation for Methodology (NCM) for the Energy Performance of Building Directive (DCLG). The UK Building Regulations Studio is systematically worked through by appropriately selecting various parameters and circuit configuration leading to the generation of series of building reports of which data based on the building energy and thermal performance indicators of total annual energy consumption, annual gas consumption, annual electricity grid consumption, building emissions rate and heating demand of for the study are extracted for analysis. The figure 3.7 illustrates the flow chart of simulation processes in the UK Building Regulation Studio.

In case study 1 simulated temperature results and thermal performance data for the study are extracted for analysis. The kitchen operative temperature was calculated as the average of the dry bulb and mean radiant temperatures. Figure 3.5 in chapter 3 illustrates the flow chart of simulation processes in the UK Building Regulation Studio.

3.2.3.5 Temperature Monitoring

The monitored outdoor and kitchen temperatures were done using temperature sensors calibrated to a highly accurate degree and with a light-emitting diode (LED) reader to facilitate accurate reading. The temperature data were recorded every fifteen minutes and the data stored online. The fifteen-minute recorded temperatures were collapsed into hourly averages to synchronise with TAS hourly dynamic simulated temperatures which are based on the CIBSE TRY weather information.

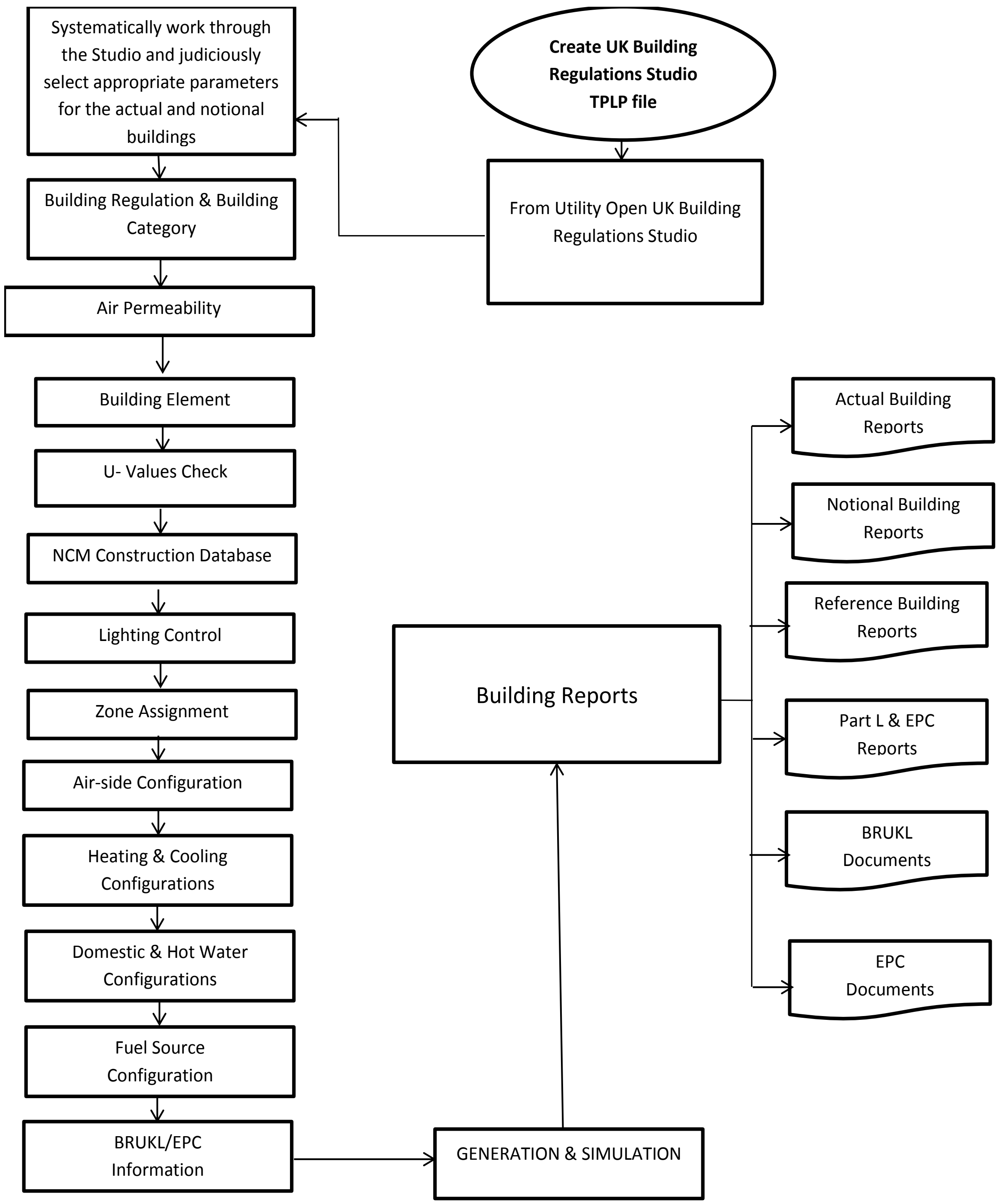


Figure 3.7 UK Building Regulation Studio Simulation process

The outdoor temperature monitoring was done between March and May 2014, to analyse the current temperature variability with the temperature data of the CIBSE weather file. The kitchen operative temperatures were monitored between February to May 2014, for the comparison with the thermal analysis simulated operative temperature results. Peeters et al (2009) indicated in their study that “thermal comfort in residential buildings shows a strong dependency on weather data”. Against the backdrop of this idea, the authors therefore first analysed the current temperature variability with the temperature data of the CIBSE weather file before applying it to the building.

3.2.3.6 Inspection of Data and Determination of Sample Size

Hanneman (2008) emphasized the importance of data inspection to remove outliers as an important step preceding the Bland and Altman plot (Hanneman 2008). This was performed as part of the steps for Bland Altman analysis. 88% and 86% of the total data collected for the kitchen and outdoor temperatures respectively were used for the current analysis. The number of measurements was checked to verified adequate sample size for the application of the bias and precision statistics to the method-comparison (Hanneman, 2008).

Cochran’s (1963) formula for determining sample size of large population was compared with Yamane’s (1967) simplified formula for proportions and the large sample size noted out of the two computations.

Cochran’s formula for determining sample size is given as

$$n_o = (Z^2pq)/e^2 \qquad \text{……….(1)}$$

where,

n_o is the sample size,

Z^2 is the abscissa of the normal curve that cuts off an area α at the tails ((1-α) equals the desired confidence level of 95%)

e is the desired precision of $\pm$5%,

p is the variability, taking p=0.5 as the maximum variability

q is (p-1).

The sample size can therefore be calculated as:

$$n_o = (1.96)^2 (0.5)(0.5)/(0.05)^2$$

$$= 385$$

Yamane's simplified formula to determine a sample size is given as:

$$n = (N)/(1+N(e)^2) \qquad \text{……….(2)}$$

where,

n is the sample size,

N is the population size,

N is given as 24(hours/day) x 365(days/year) x 2(pairs of measurements) = 17520

and e is the level of precision, taken as $\pm$5%,

The sample size can therefore be calculated as:

$$n = (17520)/(1+17520(0.05)^2)$$

$$= 391$$

Thus a sample size upward of 400 was chosen.

One source of error could be attributed to the collapse of 15 minute temperature readings into hourly averages to facilitate comparison with the hourly simulated temperatures. Moreover, Kulstad et al (2013) noted the following limitation is the use of temperature in the method of comparison analysis, “static comparisons of temperature do not take into account the lag time and dynamic changes inherent in temperature measurements,” (Kulstad et al, 2013).

3.2.3.7 Bland-Altman Method

Bland-Altman or limit of agreement plot (Bland and Altman, 2007) is a method-comparison graphical analysis which seeks to validate the inter-changeability of two techniques. This statistical evaluation indicates the agreement between the two methods. The Bland-Altman limits of agreement method stipulate that neither the Pearson’s correlation coefficient nor regression techniques are adequate for comparison of two methods (Bland and Altman, 2007). Bland-Altman’s procedure is acceptable for temperature comparison of two methods as it “assumes a linear relationship between errors and measurements,” (Hanneman, 2008). The basic steps in the Bland-Altman analysis in this work included the following;

a) Establish the priori criteria for the bias and precision.

b) Examine the data and eliminate outliers.

c) Plot scatter diagrams with line of equality of monitored and simulated temperatures.

d) Determine the normality of the temperature differences of sets of monitored and simulated temperature distribution using histogram and normal probability plot (Normal Q-Q plot).

e) Plot the differences of temperature of each pair of monitored and simulated temperatures on the vertical axis against the means on the horizontal axis.

f) Determine and plot the mean difference and the limits of agreement based on 95% confidence limits of normal distribution, that is $\pm$ 1.96 standard deviation of the mean difference.

g) Determine the limit of agreement recommended conditional agreement between the two methods when 95% of the plotted data lies between the limits of agreement.

h) Determine the percentage error.

i) Report and discussion should be based on findings against the set priori criteria, the mean value of the two techniques, the standard deviation of the difference and the limits of agreement.

3.2.3.8 Establishing the Bias and Precision Priori

In their ASHRAE RP-84 and the New Adaptive Comfort Standard for ASHRAE Standard 55 studies, de Dear et al defined the width of comfort range of temperatures for naturally ventilated buildings with 90% and 80% acceptability to be 5 and 7 degrees Celsius respectively with their corresponding mean thermal sensation of $\pm$0.5 and +0.85 respectively (Brager and de Dear, 2001), (de Dear et al, 1998). These are acceptable international standards. Figure 3.9 below indicates the comparison of adaptive thermal comfort standards and their limits of applicability.

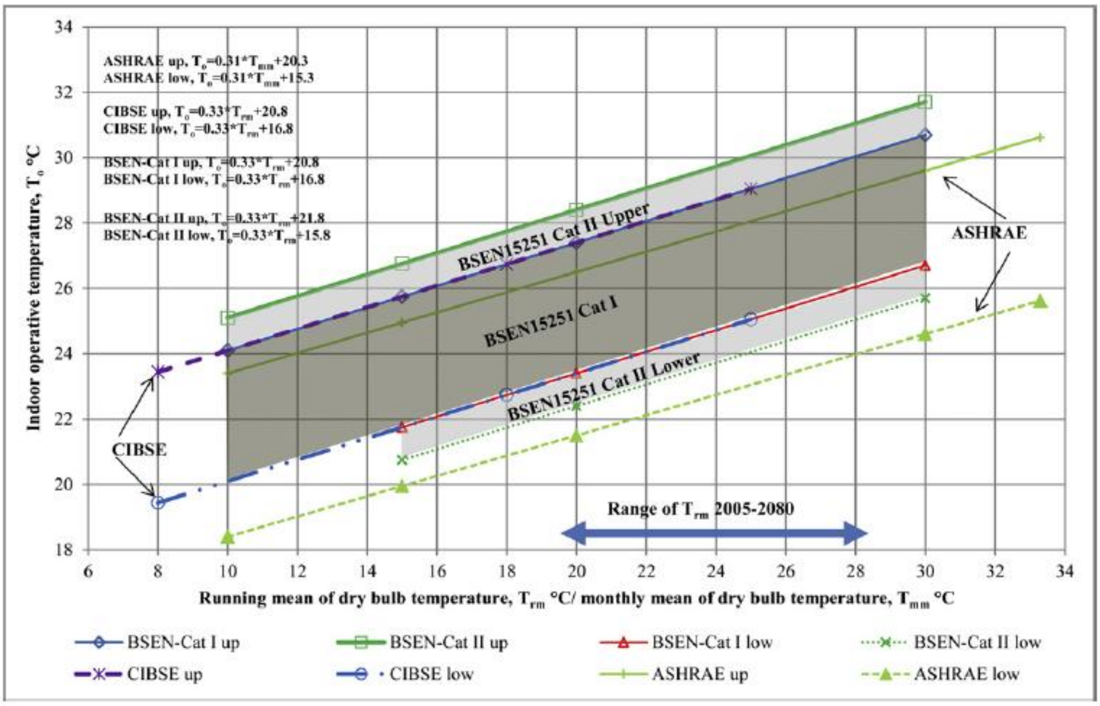


Figure 3.8 Comparison of adaptive comfort standards and limits of applicability – Adapted from Lomas and Giridharan (2012) Building and Environment 55.

Peeters et al (2009) indicated the asymmetrical split of the thermal comfort width band. Hanneman (2008) indicated that a higher priori criterion for bias could be set, “to account for the inherent measurement error,” if the bias of the findings and the agreement between the methods would be avoided. Thus a higher bias priori criterion of $\pm$0.85 with a precision priori criterion band width of 7 °C for the priori definition for the limits of agreement could be set to correspond to the 80% acceptability of thermal comfort range.

3.2.3.9 3D Modelling and Simulation Analysis and Verification

The uncertainties associated with building modelling and simulations are related to measurement errors, occurrence of stochastic events and inadequate understanding and oversimplified assumption on parameters used in simulations (Triantaphyllou, 1997). To maximize the level of confidence in the results, the modelling and simulation results are validated using a reference house to ascertain that the reference module internal operative temperatures comply with the actual monitored temperatures. Moreover, Bland-Altman's method of comparison technique is used as the validation method to affirm the accuracy of the building thermal performance and thereby assist in the successful implementation of the final solution. Monte Carlo sensitivity analysis is also used to as a quality assurance tool to test the robustness of the simulation results. It is an appropriate tool as it is able to identify the factors most responsible for generating high or low values of the output.

3.2.4 Research Method 2 – For Case Study 2

The goal is to perform climatic deterministic, uncertainty and sensitivity analysis through a series of simulations using the UK Charted Institution of Building Services Engineers CIBSE UKCIP02 future weather years, CIBSE TM48 for Design Summer Years (DSY) and the latest CIBSE TM49 DSY future weather data which incorporates the UKCP09 projections, to evaluate the variance in climatic projections and the impact of future climate change on thermal comfort of a detached dwelling in the United Kingdom using the CIBSE TM52 overheating criteria. The global sensitivity analysis used in the study incorporates Standardised

Regression Coefficient (SRC) and the Partial Correlation Coefficient as sensitivity indices and Tornado plot as a deterministic sensitivity method to identify the key parameters which contribute to thermal comfort implications in the dwellings due to climate change. In building simulation practices it is acceptable for two different sensitivity analysis methods to be used to ascertain their robustness and further inspire confidence in the results (Tian and de Wilde, 2011).

The essence for the climatic sensitivity analysis is based on the following;

1. The limitations of the CIBSE TM48 morphing methodology in producing certain variables which independently have no relationship to the probabilistic consideration of the UKCP09 CIBSE TM49 weather series, making the output different from the latest weather data series.
2. Differences in the baseline periods for the two climate projections: 1983-2004 and 1961-1990 baselines for the UKCIP02 and UKCP09 projections respectively.
3. Consideration of London urban heat island effect in the CIBSE TM49 weather files leading to the generation of three different weather data sets for London.
4. The consideration of extreme heat waves experienced in 1976 and 2003 years to examine overheating risk under different scenarios.

3.2.4.1 Thermal Analysis Simulation (TAS) 3D Modelling

It is generally recommended that for naturally ventilated buildings, the 50th percentile (best guess) projections and the medium greenhouse gas emission scenario has to be used in the building simulation analysis (Mavrogianni et al, 2012). This choice of UKCP09 future weather file based on the 50th percentile of external temperature and 2050s emission scenarios was used because of its usage by other studies. For example, Mavrogianni et al in 2012 used this criterion for their dynamic thermal simulation work for identifying factors that affect the high indoor summer temperatures in London dwellings (Mavrogianni et al, 2012). The medium-high climate change emission scenario was chosen in the UPCIP02 weather file consideration. The CIBSE TM36, using dynamic thermal modelling, offered quantitative assessment of risks of overheating in 13 case study buildings comprising of houses, offices and schools for three locations in the UK, used the UKCIP02 medium-high climate change scenario and the CIBSE Guide A (2006) as the overheating criteria (CIBSE TM36, 2005).

The various modelling and simulation parameters of Building Summary, Calendar, Building Elements, Zones, Internal conditions (which include thermostat set up, infiltration and ventilation, occupancy, lighting and equipment details), Schedule, and Aperture Types which were used to populate and simulate each building, are maintained with the only variant being the weather data.

A series of scenarios based on the current and the future climate variables on different timelines of 2020s, 2050s and 2080s with their respective medium-high carbon scenarios for the CIBSE TM48 UKCIP02 weather files and similar time slice of 2020s, 2050s and 2080s for CIBSE TM49 UKCP09 weather files are simulated for Gatwick Airport, London Weather Centre and Heathrow Airport.

The new weighted cooling degree hours (WCDH) metric of CIBSE TM49 was not used in this work for the overheating analysis because of its over-simplistic nature and significant variance from the comfort temperature of people uncomfortable in the adaptive thermal comfort after some point. However, the CIBSE TM52 overheating criterion which is underpinned by the BS EN15251 adaptive thermal comfort model which is a criterion for determining thermal comfort in naturally ventilated buildings in free-running mode was used.

3.2.4.2 Developing multivariate linear regression for uncertainty and sensitivity analysis

The case study is based on a building simulation and global sensitivity analysis which explore the analysis of uncertainties and sensitivities related to climate change variability. The IBM SPSS statistics Monte Carlo sensitivity analysis tool is used to identify the influential parameters that affect the internal operative temperature (thermal comfort) of dwellings.

The CIBSE weather data set used in the EDSL TAS simulation has seven key weather variables of global horizontal radiation, cloud cover, relative humidity, wind direction, wind speed, diffused horizontal radiation and dry bulb temperature. The CIBSE weather data used are the Design Summer Years (DSY) CIBSE TM48 UKCIP02 weather files and the CIBSE TM49 UKCP09 weather files for Gatwick Airport, London Weather Centre and Heathrow Airport.

The detached dwelling used as the case study is 49 Carnation Drive; a 1995 three-bed room house located at Bracknell, Berkshire, about 48 kilometres from Central London, the closest weather station for CIBSE TM48 UKCIP02. In using CIBSE TM49 UKCP09 weather files the case study building location is located at 48.87 kilometres, 48 kilometres, and 18.71 kilometres respectively from Gatwick Airport, London Weather Centre and Heathrow Airport.

EDSL TAS simulations are performed on two scenarios. The first scenario entailed the variation of climate change as input parameters and considers uncertainties in various CIBSE DSY weather files in predicting indoor operative temperature as a thermal comfort indicative parameter. The second scenario relates to the four standardized construction specifications which have been designated by various organisations with the aim of adapting buildings to the impact of climate change and facilitates the improvement of building performance parameters. The uncertainty and sensitivity analysis of the four standardized construction specifications based on the UKCIP02 and UKCP09 weather projections for 50% probability and the medium emission scenario results are the most important factors which impact thermal performance of detached dwellings and are fully developed in chapter eight of this work.

3.2.4.3 Multivariate linear regression analysis due to climate change alone

Simulation runs were performed using EDSL TAS program initially using the CIBSE DSYs weather files based on UKCIP02 and UKCP09 climatic projections. The EDSL TAS dynamic simulation results in an hourly historical output data. The weather variables and the indoor operative temperature and other performance indicators, regression analysis from the EDSL TAS simulation and CIBSE TM52 analysis results were based on all the input parameters with the weather files as the only variance parameter in the case of the first scenario. The selection of the input variables was based on heuristic method of past experience, educated guesses, available literature and rules of thumb. The various input parameters and the targets outputs parameters are shown in table 3.3. All the parameters were entered simultaneously to generate the multivariate linear regression model.

The EDSL TAS coupled with the developed Excel CIBSE TM52 overheating criteria historical data are then sent to IBM SPSS statistical software to create a multivariate linear regression XML model. The aim of this multivariate linear regression model is to capture the complex thermal interaction of parameters used in the EDSL TAS program. The uncertainty and sensitivity analysis on the multivariate linear regression model is then subsequently analysed using the IBM SPSS statistics software.

Table 3.3 Input parameters with their probability distributions for the uncertainty and sensitivity analysis for the climate change impact on thermal comfort

Input Parameter	Acronym	Units	Probability Distribution
Global Radiation	GR	W/m^2	Normal
Diffused Radiation	DR	W/m^2	Normal
Cloud Cover	CC	(0-1)	Normal
External Temperature	ET	(°C)	Normal
External Humidity	EH	(%)	Normal
Wind Direction	WD	(°)	Normal
Wind Speed	WS	(m/s)	Normal
Average Radiant Temperature	ART	(°C)	Normal
Average Dry Bulb Temperature	ADBT	(°C)	Normal
Daily hourly exponentially weighted running mean temperature	DHEWRMT	(°C)	Normal

3.2.4.5 Uncertainty and sensitivity analysis due to climate change alone.

Sensitivity analysis involves changes of different design parameters to ascertain their relative influence on the target variable. As indicated earlier on in this chapter, the initial process of uncertainty and sensitivity analysis is done to identify the range of inputs, usually using heuristic method. In the case of Monte Carlo sensitivity analysis, the input probability distribution is also defined, thus characterizing assigned probability distribution to the uncertain input factors and where the appropriate value of each parameter is believed to be located. The thermo-physical properties probability or convection property distributions of the building envelope and systems were considered to be of normal distribution as the work seeks to explore the possible variations of energy performance and thermal comfort of an existing building in its operational state. This assumption is based on the work done by Tian in 2013 in reviewing sensitivity analysis methods in building energy analysis. Tian indicated that sensitivity analysis of inputs of existing buildings could be considered as normally distributed and further pointed out that negative values of the distribution of certain cases are to be avoided by truncating the normal distribution. However, distribution of design input variables were to be considered as continuously uniformly distributed (Tian, 2013).

The developed multivariate linear regression XML model is used to run the uncertainty and sensitivity analysis in the IBM SPSS statistical software. The Monte Carlo simulation was set to 100,000 iteration runs for each target parameter to provide adequate coverage of the solution space. The results of the uncertainty analysis are presented as scatter plots, tornado plots and box and whiskers plots. The scatter plots are used to investigate the correlation between the input variables and the target or output variables. The tornado plot compares the relative significance of the various input parameters to the output parameter. The box and whiskers plot also shows the variations of sensitivity measures for various input parameters (Tian, 2013).

The IBM SPSS software is then used to calculate the Standardised Regression Coefficient (SRC) and Partial Correlation Coefficient (PCC) to ascertain the input parameters that are most sensitive and thus explain the high variability in the models.

3.2.5 Research Method 3 – For Case Study 3

3.2.5.1 Thermal Analysis Simulation (TAS) 3D Modelling

The goal is to verify through a series of simulations using the latest UK Charted Institution of Building Services Engineers CIBSE TRY of current and future weather data which incorporates the UKCIP02 Projections to evaluate and predict the impact and vulnerability of future climate change on a detached dwelling stock in the United Kingdom. Ten residential dwellings of Persimmon South East Ltd Sheppey General Hospital dwelling are selected as building prototypes. Sheppey, Sheerness is 59.4km from London, the closest weather station. Hence the current and future CIBSE London TRY are chosen for the analysis.

The data used, are the AutoCAD two-storey residential detached building drawings of Persimmon South East Ltd Sheppey General Hospital. The building drawings consisted of the front elevation, rear and side elevation, a section through the elevation, ground floor plan, first floor plan and the roof arrangement plan. The figures 3.9 to 3.12 below indicate the architectural plan of one of the selected houses, the drawing data for 0712 House Type G Pri used in this work.

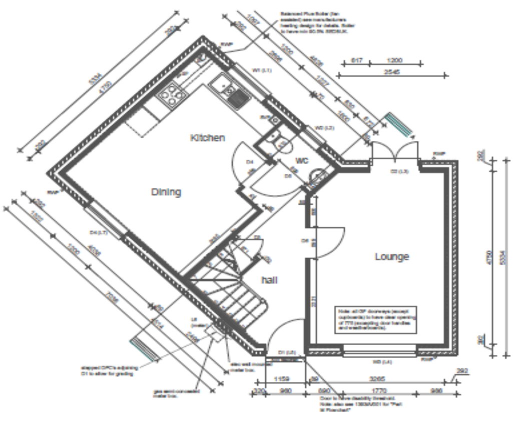


Figure 3.9 Architectural Ground Floor Plan

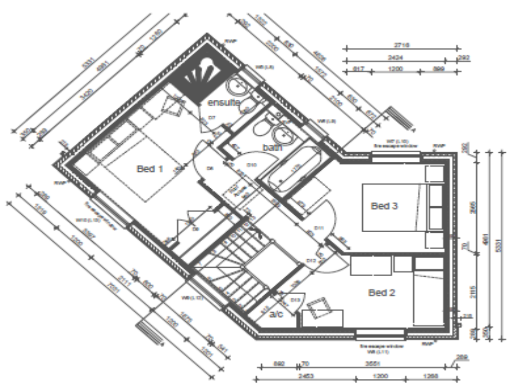


Figure 3.10 Architectural First Floor Plan

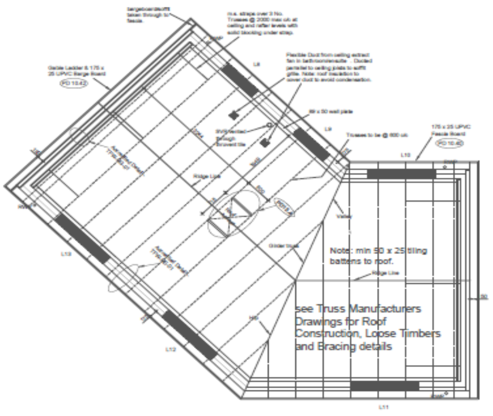


Figure 3.11 Architectural Roof Arrangement

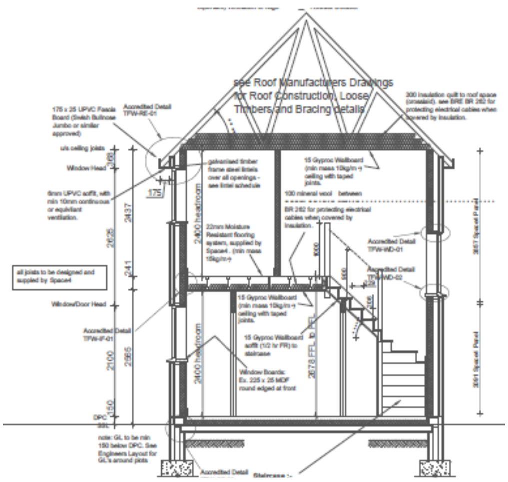


Figure 3.12 Architectural Building Section

3.2.5.2 Modelling Process

Measurements of floors, doors and windows dimensions were taken from the AutoCAD elevations drawings. The floor level was measured from the ground plane at datum 0.0m. The default wall heights dimensions were measured from the floor finish to directly below the floor finishing of the upper floor. The respective zones on the ground floor and first floor plans were noted and further grouped into Bedrooms, Circulation, Toilet and Miscellaneous.

To aid in the shadow calculations in the 3D Modeller, the orientation of the north angle was changed to 135 degrees clockwise to the North and the latitude, longitude and time zone changed to 51.5 degrees North, -0.4 degree East and UTC +0.0 respectively to reflect the geographical and time parameters of London. Sheppey, Sheerness is 59.4km from London, the closest weather station. The flow charts in figures 3.3 to 3.5 in this chapter illustrate the drawing files preparation for the 3D modelling process and the modelling of the ground floor, first floor and the roof arrangement respectively.

3.2.5.3 Simulation Process

TAS as a dynamic simulation modeller models the thermal mass of a building. Building performance simulation requires the appropriate selection of modelling parameters and assumptions. The various simulation parameters of Building Summary, Calendar, Weather, Building Elements, Zones, Internal conditions, Schedule, and Aperture Types were populated to simulate the building. Figure 3.6 in this chapter is a flow chart which shows the thermal simulation process with its associated modelling and simulation parameters in tables 3.4 and 3.5.

Table 3.4 Modelling and Simulation Parameters and Assumptions

Building fabric		
Calculated area weighted average U-values	Wall	0.24 W/m^2K
	Floor	0.21 W/m^2K
	Roof	0.13 W/m^2K
	Windows	2.30 W/m^2K
	Doors	2.05 W/m^2K
Average U-value		0.41 W/m^2K
Calendar	NCM standard	
Air permeability	5 m^3/hm^2 at 50 Pa	
Infiltration	0.250 ACH	
Lighting efficency	5.2 W/m2 per 100 lux	
Average conductance	78 W/K	
Alpha value	22.85%	

Table 3.5 Modelling and Simulation Parameters and Assumptions

Construction data base		NCM construction v4.1.tcd
Occupancy levels; People density; Lux level	Bath	0.01873684 person/m^2, 150 lux
	Bed	0.01873684 person/m^2, 150 lux
	Circulation area	0.02293877 person/m^2, 150 lux
	Dining	0.0169163 person/m^2, 150 lux
	Kitchen	0.0237037 person/m^2, 150 lux
	Lounge	0.0187563 person/m^2, 150 lux
	Toilet	0.02431718 person/m^2, 150 lux
Fuel Source	Natural gas	Carbon dioxide factor - 0.198 kg/kWh
	Grid electricity	Carbon dioxide factor - 0.517 kg/kWh

3.2.5.4 UK Building Regulation Studio

The UK Building Regulations Studio used by the TAS EDSL 9.2.1.4 software is based on 2010 regulations. It adheres to the National Calculation for Methodology (NCM) for the Energy Performance of Building Directive. The UK Building Regulations Studio is systematically worked through by appropriately selecting various parameters and circuit configuration leading to the generation of series of building reports of which data based on the five (5) key building performance indicators of total annual energy consumption, annual gas consumption, annual electricity grid consumption, building emissions rate and heating demand for the study are extracted for analysis. The figure 3.7 in this chapter illustrates the flow chart of simulation processes in the UK Building Regulation Studio.

3.2.5.5 Future Weather Data Simulation Process

The various modelling and simulation parameters of Building Summary, Calendar, Building Elements, Zones, Internal conditions (which include thermostat set up, infiltration and ventilation, occupancy, lighting and equipment details), Schedule, and Aperture Types which were used to populate and simulate each building are maintained with the only variant being the weather data.

A series of scenarios based on the current and the future climate variables at different time lines of 2020s, 2050s and 2080s with their respective four carbon scenarios of high, medium-high, medium-low and low are simulated. The modelling and simulation processes were followed through for the rest of the nine (9) detached dwellings.

3.2.6 Research Method 4 – For Case Study 4

The goal is to verify through a series of simulations using the UK Charted Institution of Building Services Engineers CIBSE Design Summer Year (DSY) of current and future weather data which incorporates the UKCIP02 projections to verify if the optimization of thermal comfort performance depends on variable climatic conditions, enhanced thermal mass, building orientation and location, ventilation strategy, external shading and varying occupant characteristics using the newly developed CIBE overheating criteria (CIBSE TM52, 2013) as an assessment tool on detached dwelling stock in the United Kingdom.

As TAS graphical representation of the CIBSE adaptive overheating criteria is based on the external dry bulb and external running mean temperature. An Excel program for the analysis of the whole building scenario as stipulated in the CIBSE TM52 was developed to reflect the variation of the indoor operative temperature for clear assessment of the dwelling thermal comfort. Data from the TAS simulation was fed into the Excel program for this analysis.

Four typical energy efficient standard construction specifications previously identified as part of the core standard construction specifications in the work of the Zero Caron Homes practise (ZCH, 2009) were used. These standard construction specifications used are underpinned by the fabric energy efficiency standards on dwellings which was developed by an Industry Task Group led by the Zero Carbon Hub in 2009 (ZCH, 2009) whose work was based on well recognized energy efficient design standards. The 'Baseline' specification was set based on current building practice (ZCH, 2009) and conforms to the 2010 Building Regulations Part L compliant for dwelling. The 'Fabric Energy Efficiency Standard' (FEES) specification is based on the Energy Saving Trust Best Practice Energy Efficiency (EST BPEE) Standard. The third specification; 'Beyond Fabric Energy Efficiency Standard' is based on the Energy Saving Trust Advanced Practice Energy Efficiency (EST APEE) Standard and the fourth specification is equivalent to the PassivHaus Standard. Table 3.6 stipulates the summary of the four construction specification as indicated in the Zero Carbon Homes report (ZCH, 2009) and their equivalent as the result of the modelling and simulation of this work.

3.2.6.1 Thermal Analysis Simulation (TAS) 3D Modelling

The data used are the AutoCAD two-storey residential detached buildings drawings of Persimmon South East Ltd Sheppey General Hospital. The building drawings consisted of the front elevation, rear and side elevation, a section through the elevation, ground floor plan, first floor plan and the roof arrangement plan. The figures 3.9 to 3.12 in this chapter indicate the architectural plan of the selected houses, the drawing data for 0712 House Type G Pri used in this study.

3.2.6.2 Modelling Process

Measurements of floors, doors and windows dimensions were taken from the AutoCAD elevations drawings. The floor level was measured from the ground plane at datum 0.0m. The default wall heights dimensions were measured from the floor finish to directly below the floor finishing of the upper floor. The respective zones on the ground floor and first floor plans were noted and further grouped into Bedrooms, Circulation, Toilet and Miscellaneous. To aid in the shadow calculations in the 3D Modeller, the orientation of the north angle was changed to 135 degrees clockwise to the North and the latitude, longitude and time zone changed to 51.5 degrees North, -0.4 degrees East and UTC +0.0 respectively to reflect the geographical and time parameters of London. Also the latitude and longitude were changed to 52.45 degrees North, -1.74 degrees East and 55.87 degrees North, -4.43 degrees East to reflect the geographical and time parameters of Birmingham and Glasgow respectively. The flow charts in figures 3.3 to 3.5 in this chapter illustrate the drawing files preparation for the 3D modelling process and the modelling of the ground floor, first floor and the roof arrangement respectively.

Table 3.6 Standard Construction Specifications and Modelling Assumptions Zero Carbon Homes and TAS results

		Standard construction specifications and modelling assumptions (ZCH 2009)				Equivalent standard construction specifications and modelling assumptions (TAS results)			
		Baseline	FEES / EST BPEE	Beyond FEES / EST APEE	PassivHaus Equivalent	Baseline	FEES / EST BPEE	Beyond FEES / EST APEE	PassivHaus Equivalent
U-value (W/m^2K)	Wall	0.28	0.18	0.15	0.1-0.15	0.25	0.16	0.15	0.1
	Party wall	0.5	0	0	0	0.5	0	0	0
	Floor	0.2	0.18	0.15	0.1-0.15	0.16	0.15	0.13	0.09
	Roof	0.16	0.13	0.11	0.1	0.14	0.12	0.1	0.09
	Windows	1.8	1.4	0.8	0.8-1.0	1.8	1.4	1	1
	Doors	1.6	1.2	1	0.8	1.7	1.24	1.24	1.24
	Air permeability ($m^3/hr/m^2$)	5	3	1	0.41-0.5	5	3	1	0.5
	Thermal bridging (W/m^2K)	0.08	0.05	0.04	0.04	0.8	0.05	0.4	0.04
	Ventilation	Natural (extract fans)	Natural (extract fans)	MVHR	MVHR	Natural (extract fans)	Natural (extract fans)	Mechanical	Mechanical
	Low energy lighting	100%	100%	100%	100%	100%	100%	100%	100%
	MVHR spec (where used)	-	-	SFP = 1 W/l/s	SFP = 1 W/l/s	-	-	SFP = 1.0 W/l/s	SFP = 1 W/l/s
	Orientation (max glazed area)	East	East	East	East	East	East	East	East
	Gas boiler efficiency	90%	90%	90%	90%	90%	90%	90%	90%
	DHW storage	200 Litres	200 Litres	200 Litres	200 Litres	200 Litres	200 Litres	200 Litres	200 Litres

3.2.6.3 Simulation Process

TAS as a dynamic simulation modeller models the thermal mass of a building. Building performance simulation requires the appropriate selection of modelling parameters and assumptions. The various construction elements' thermal mass as specified by the Zero Carbon Hub Work Group were designed in the TAS software to reflect the standard construction specifications for the 'Baseline', 'Fabric Energy Efficiency Standard' (FEES) / Energy Saving Trust Best Practice Energy Efficiency (EST BPEE) Standard, 'Beyond Fabric Energy Efficiency Standard'/ Energy Saving Trust Advanced Practice Energy Efficiency Standard and the PassivHaus Standard as outlined in Table 3.6. Figures 3.13 and 3.14 show an example in the case of the PassivHaus Equivalent Standard external wall with totalling width of 515.5 mm of 13mm plaster internal finish, 100mm 4N/mm^2 ACC block work, full-fill 300mm glass wool insulation and 102.5mm external leaf brick work.

The other simulation parameters of Building Summary, Calendar, Weather, Zones, Internal conditions, Schedule, and Aperture Types were populated to simulate the building for it to reflect the construction design criteria specified by the CIBSE Guide A (2006) and TAS for dwellings. These are shown in Table 3.6. The flow chart of figure 3.6 shows the thermal simulation process with its associated modelling and simulation parameters.

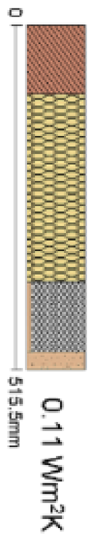


Figure 3.13 ZCH (2009) PassiHaus External Wall Specification

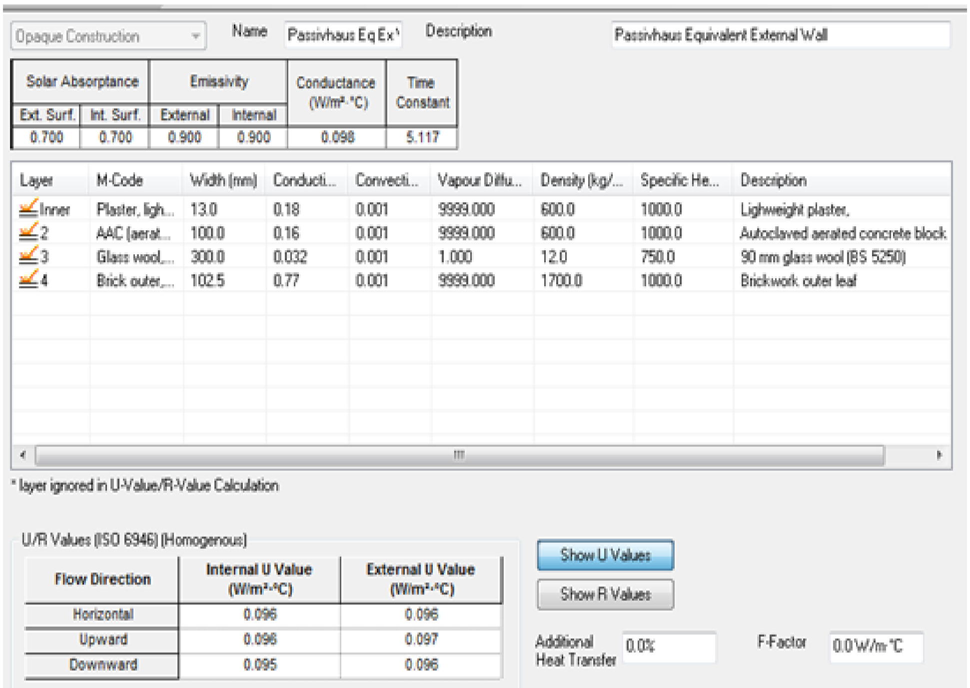


Figure 3.14 Equivalent PassiHaus External Specification as designed for TAS

3.2.6.4 UK Building Regulation Studio

The UK Building Regulations Studio used by the TAS EDSL 9.2.1.6 software is based on 2010 regulations. The UK Building Regulations Studio is systematically worked through by appropriately selecting various parameters and circuit configuration leading to the generation of a series of building reports of which data based on the external temperature, the dry bulb temperature and the mean radiant temperatures are extracted and sent to the developed Excel program for CIBSE TM52 whole building overheating analysis. The CIBSE TM52 overheating analysis is carried out in TAS report generator. Figure 3.7 illustrates the flow chart of simulation processes in the UK Building Regulation Studio.

3.2.6.5 Future Weather Data Simulation Process and Mitigation Scenarios

The various modelling and simulation parameters of Building Summary, Calendar, Building Elements, Zones, Internal conditions (which include thermostat set up, infiltration and ventilation, occupancy, lighting and equipment details), Schedule, and Aperture Types which were used to populate and simulate each building are maintained with the only variant being the weather data.

A series of scenarios based on the current and the future climate variables at different timelines of 2020s, 2050s and 2080s with their respective high design summer year (DSY) as the worst case analysis carbon scenarios are simulated. Most existing buildings in the UK are naturally ventilated during the day, thus the methodology begins with this design consideration seeing its advantages of reduced carbon dioxide emissions when compared with mechanical ventilation. The modelling and simulation processes were followed through for the mitigation scenarios of night ventilation and night ventilation with external shading. External shading was used as it is observed to be most effective shading strategy for provision of passive cooling in buildings (DCLG and AECOM, 2012). The shading was a combination of both vertical and horizontal shades. Windows were opened 50% at all times in all scenarios.

3.2.6.6 CIBSE TM52 Criteria as an Overheating Assessment Tool

Thermal comfort (indoor operative temperature) depends on four basic environmental factors of air temperature, the mean radiant temperature, the relative air velocity and relative humidity. One of the main functions of residential buildings is to provide healthy and comfortable environments to the occupants. Buildings must therefore be designed and built by taking cognisance of the physiological reactions of the occupants due to temperature and humidity tolerance of occupants.

The CIBSE TM52 (2013) limits of thermal comfort focus mainly on avoiding overheating in free running European building during non-heating season. The European standard BS EN 15251(BSI, 2007) in which the CIBSE TM52 is based provides both upper and lower limiting values for operative temperatures under various categories. Figure 3.15 below shows the acceptable comfort temperature limiting values as stipulated the BS EN 15251 (BSI, 2007).

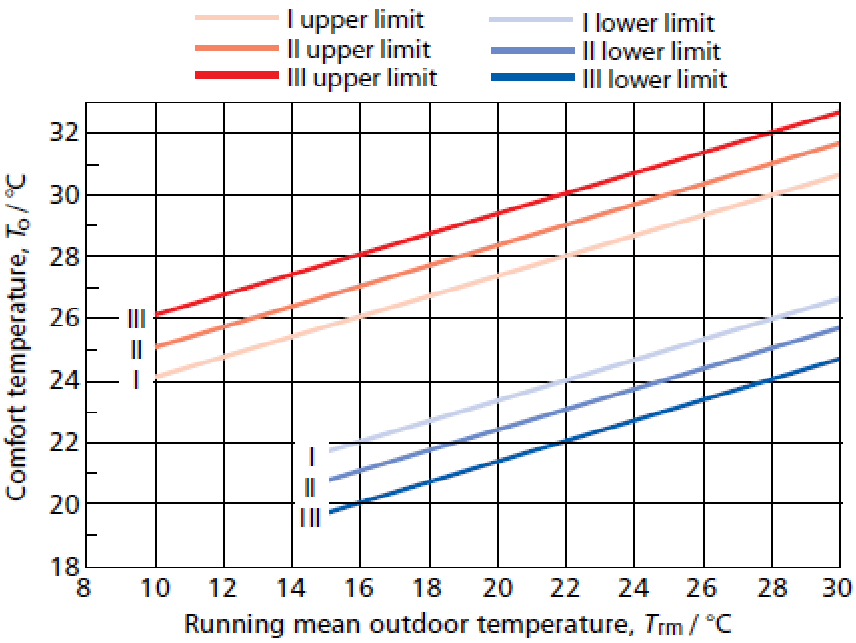


Figure 3.15 Limiting design values for the building operative temperature as against the exponentially weighted running mean of the external temperature. (Adapted from (BSI, 2007) and (CIBSE TM52))

The BS EN 15251 equation for comfort temperature is given as:

$$T_{comf} = 0.33\ T_{rm} + 18.8 \qquad \text{Eq. (3.1)}$$

Where, T_{comf} is the comfort temperature and T_{rm} is the exponentially weighted running mean of the daily mean outdoor air temperature.

The general equation of the exponentially weighted running mean temperature for any day is given as;

$$T_{rm} = (1-\alpha)\ (T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3}\ \ldots) \qquad \text{Eq. (3.2)}$$

Where α is a constant less than one and T_{od-1}, Tod_{-2}, Tod_{-3}, etc. are the daily mean outdoor temperatures for yesterday, the day before, and so on.

The simplified equation of the exponentially weighted running mean is given as:

$$T_{rm} = (1-\alpha)\ Tod_{-1} + \alpha T_{rm-1} \qquad \text{Eq. (3.3)}$$

In situations of lack of extensive run of days, the BS EN 12521 (BSI, 2007) specifies Eq. (3.4) as an approximated method for computing the exponentially weight running mean using the outdoor mean temperatures for the last seven days with the 'α' value equal to 0.8.

$$T_{rm} = (T_{od-1} + 0.8T_{od-2} + 0.6T_{od-3} + 0.5T_{od-4} + 0.4T_{od-5} + 0.3T_{od-6} + 0.2T_{od-7})/3.8 \qquad \text{Eq. (3.4)}$$

The CIBSE TM52 criteria are underpinned by the Category II in BS EN 15251 (BSI, 2007) which earmark a maximum acceptable temperature of three degrees above the comfort temperature for naturally ventilated buildings as shown in table 3.7.

Table 3.7 Recommended categories and acceptable temperature range for free-running buildings. (Adapted from (BSI, 2007) and (CIBSE TM52)).

Category	Explanation	Suggested acceptable range (K)
I	High level of expectation only used for spaces occupied by very sensitive and fragile persons	± 2
II	Normal expectation (for new buildings and renovations)	± 3
III	A moderate expectation (used for existing buildings)	± 4
IV	Values outside the criteria for the above categories (only acceptable for a limited periods)	>4

With known value for the exponentially weighted running mean, T_{rm}, the limiting maximum acceptable temperature can be calculated using Eq. (3.5).

$$T_{max} = 0.33T_{rm} + 21.8 \qquad \text{Eq. (3.5)}$$

All the CIBSE TM52 criteria are governed by the difference between the actual operative temperature in the room (T_{op}) and the limiting maximum acceptable temperature, T_{max} and it is given by Eq. (3.6) as:

$$\Delta T = T_{op} - T_{max} \qquad \text{Eq. (3.6)}$$

The exponentially weighted running mean Eq. (3.4), the limiting maximum acceptable temperature Eq. (3.5) and the difference between the actual operative temperature and the limiting maximum acceptable temperature Eq. (3.6) were used by the authors in developing the Excel program used for the whole building overheating analysis.

The CIBSE TM52 guideline specifies three criteria for defining overheating in free running buildings as the 'Hours of Exceedance', 'Weighted Exceedance' and 'Upper Temperature Limit' as first, second and third criteria respectively. A dwelling would be considered overheated if any two of the three criteria are exceeded (CIBSE TM52, 2013). The hours of exceedance criterion, stipulates the duration of temperatures above thermal comfort levels and sets the limit of the number of hours during which the operative temperature can exceed the limiting maximum acceptable temperature by one degree Kelvin or more during a non-heating season of 1 May to 30 September (CIBSE TM52, 2013). This number of hours shall not exceed 3 percent of a particular zone's occupied hours. The daily weighted exceeding criterion stipulates a daily limit of severity (a function of temperature increase and duration) above which overheating can be classified (CIBSE TM52, 2013).

CIBSE TM52 designates the limiting value of 6 for the severity of overheating for the daily weighted exceedance criterion (CIBSE TM52, 2013). The upper limit earmarks an absolute maximum temperature; a set temperature value for the difference between the indoor operative temperature and limiting maximum acceptable temperature to be not more than four degrees (CIBSE TM52, 2013).

Thus, $$T_{upp} = T_{max} + 4 \qquad \text{Eq. (3.7)}$$

3.2.7 Research Method 5 – For Case Study 5

The underlying method and assumptions underpinning the uncertainty and sensitivity analysis are presented in detail in section 3.2.4 of this chapter.

3.2.7.1 Multivariate linear regression analysis due to climate change and future building adaptation measures

To determine the relationship between climate change of three locations of Gatwick, Heathrow and London Weather Centre and building adaptation parameters in relations to the output (target) parameters of indoor operative temperature, regression analysis from the EDSL TAS simulation and CIBSE TM52 analysis results were based on all the input parameters with the four standardized construction specifications as variance parameters. All the twenty two parameters were entered simultaneously to generate the multivariate linear regression model.

The input parameters with their probability distributions for the uncertainty and sensitivity analysis for the dwelling overheating mitigation using standardized construction specifications parameters are shown in table 3.8.

Table 3.8 Input parameters with their probability distributions for the uncertainty and sensitivity analysis for the standardized construction specifications parameters impact on thermal comfort

Input Parameter	Acronym	Units	Probability Distribution
Sensible Load	SL	W	Normal
Solar Gain	SG	W	Exponential
Lighting Gain	LG	W	Exponential
Infiltration/Ventilation Gain	IVG	W	Normal
Air Movement Gain	AMG	W	Normal
Building Heat Transfer	BHT	W	Triangular
External Conduction Opaque	ECO	W	Triangular
External Conduction Glazing	ECG	W	Normal
Occupancy Sensible Gain	OSG	W	Uniform
Equipment Sensible Gain	ESG	W	Triangular
Occupancy Latent Gain	OLG	W	Exponential
Equipment Latent Gain	ELG	W	Triangular
Infiltration	I	(kg/s)	Normal
Ventilation	V	(kg/s)	Normal
Internal Solar Gain	ISG	(W)	Exponential
Aperture Opening	AO	(0-1)	Exponential
Wall U-value	WUV	(W/m^2K)	Normal
Floor U-value	FUV	(W/m^2K)	Normal
Roof U-value	RUV	(W/m^2K)	Normal
Window U-value	WinUV	(W/m^2K)	Normal
Air Permeability	AP	$(m^3/hr/m^2)$	Normal
Total Transmittance G-value	TT	( )	Gamma

3.2.8 Research Method 6 – For Case Study 6

The goal is to verify through a series of simulations using the UK Charted Institution of Building Services Engineers CIBSE Test Reference Year (TRY) and Design Summer Year (DSY) of current and future weather data which incorporate the UKCIP02 projections if the optimization of energy consumption and thermal comfort performance of habitable conservatories attached to detached dwellings stock in the United Kingdom depend on integrated passive design strategies of varying future climatic conditions, variable occupant behaviour, building orientation, adequate provision of thermal mass, advanced glazing, appropriate ventilation and sufficient level of external shading using the newly developed CIBSE criteria (CIBSE TM52, 2013) as an assessment tool.

3.2.8.1 Thermal Analysis Simulation (TAS) 3D Modelling and Simulation

Building performance simulation requires the appropriate selection of modelling parameters and assumptions. The assumptions underpinning this case study are stipulated in section 3.2.3.2 of this chapter. The detached dwelling used as the case study is 49 Carnation Drive, a 1995 three-bed room house located at Bracknell, Berkshire, with the latitude, longitude and time zone of 51.42 degrees North, -0.75 degree East and UTC +0.0 respectively. Bracknell, Berkshire is about 48 kilometres from Central London, the closest weather station. Hence the current CIBSE London test reference year (TRY) and design summer year (DSY) are chosen respectively for the heating season and non-heating season analysis. The thermo-physical properties of the conservatory design were selected using heuristic approach based on knowledge in building regulations, educated guess, rule of thumb and experience in the use of design standards. The outputs used in the analysis are the indoor operative temperatures for thermal comfort analysis, total annual energy consumption, annual natural gas consumption and building emission rate for both the main dwelling and the conservatory.

The floor area of the main building is 115.3 square metres with a total surface area of 17.16 square metres of glazing. Three typical dwarf wall conservatory designs were built at the ground floor with varying internal floor area of between four (4) and thirty (30) square metres to determine the optimum design for efficient thermal performance. The conservatory design is thus within the limits specified by the UK Building Regulations which mandates a conservatory with a floor area not exceeding 30 square meters to be exempted from planning application. The maximum height for all design consideration is four (4) metres. The height of the dwarf wall is 525mm.Thermal mass specification for the conservatory dwarf wall and floor is equivalent to the PassivHaus Standard. The chosen dwarf wall design for the conservatory with its vertical thermal mass surfaces will facilitate the absorption of excess solar radiation during non-heating period and thus reduce temperature swing. Low emissivity argon filled double glazing is selected for all design consideration based on findings outlined in previous studies, for it offers the most efficient thermal performance and economic benefits as indicated earlier on in this paper. The roof and the wall of the conservatory consisted of at least 75% and 50% of glazing material respectively. The frame selected material was PVC. The conservatory fenestration dimensions were selected to meet the design criteria specified in the British Standard BS 5952:1991 and Part F of the UK Building Regulations. The conservatory is separated from the main dwelling by an operable door and windows and in heating scenario 3 (as shown in table 3.9) the conservatory was heated, but never air-conditioned in all scenarios.

The data used are the AutoCAD two-storey residential detached buildings architectural drawings of 49 Carnation Drive as shown in figures 3.1 and 3.2 of this chapter. Detailed modelling and simulation processes using Thermal Analysis Simulation (TAS) software by Engineering Development Solutions Software (EDSL) and the modelling assumption have been clearly outlined in this chapter. Figure 3.17 outlines the methodological process used in the modelling and simulating of the detached dwelling with attached conservatory. The steps include the CIBSE Guide A (2006) internal conditions specifications used in the simulation process as indicated in tables 3.4 and 3.5 of this chapter and the UK Building Regulation studio simulation process given in figure 3.16.

The summary of the external shading and ventilation scenarios in this work are stipulated in table 3.9. For instance, scenario 2, have the same ventilation strategy as scenario 3, but a different shading strategy. In this scenario the investigations focuses on the shading strategy but not the ventilation strategy. Similar, idea is seen in other scenarios.

The choice of the 10-11^{o}C temperature for the conservatory lower windows opening in the heating season scenarios is underpinned by the use of conservatory for pre-heating ventilation air. This is done to reduce the dwelling heating load. Generally, for a conservation to function as a solar collector, the temperature of the conservatory must be higher than the main dwelling (BRE, 1988). However, conservatories used for pre-heating ventilation air can change the energy balance of a house. Pre-heating ventilation air is a phenomenon where heat gain from the main dwelling by the conservatory raises the conservatory's air temperature above the ambient temperature and on the basis of controlled ventilation the incoming external air is heated up before it is being heated by the dwelling auxiliary heating system to the desired temperature for the attainment of thermal comfort (BRE, 1988). This process facilitates the reduction of auxiliary heating demand of the dwelling. According to BRE 1988, "there will be no threshold above which the conservatory temperature has to rise before solar gain can be used. Any increase in temperature represents a useful heat gain" (BRE, 1988). However, BRE 1988 indicated that with a scenario of 4^{o}C external temperature and about 9^{o}C day time air temperature, there is a potential of reducing the dwelling auxiliary heating load by a third. The study thus sets the conservatories openable windows temperature for pre-heating to be 10 – 11^{O}C. The basis of this is optimising solar radiation gain and adequate ventilation in the dwelling throughout the seasons. Thus this work uses awnings incorporated with overhang design as external shading to control the admission of solar radiation gains. In addition, low emissivity argon filled double glazing is used for all glazed areas with an overall width of 4+16+4 and solar heat gain coefficient (SHGC or g-value) of 0.578. The low emissivity argon filled double glazing contributes to the maximization of solar gains in heating season and its mid glass panes also offers shading effect to mitigate overheating. Moreover, vertical conservatory glazing design consideration was selected instead of sloped glazing to minimize overheating.

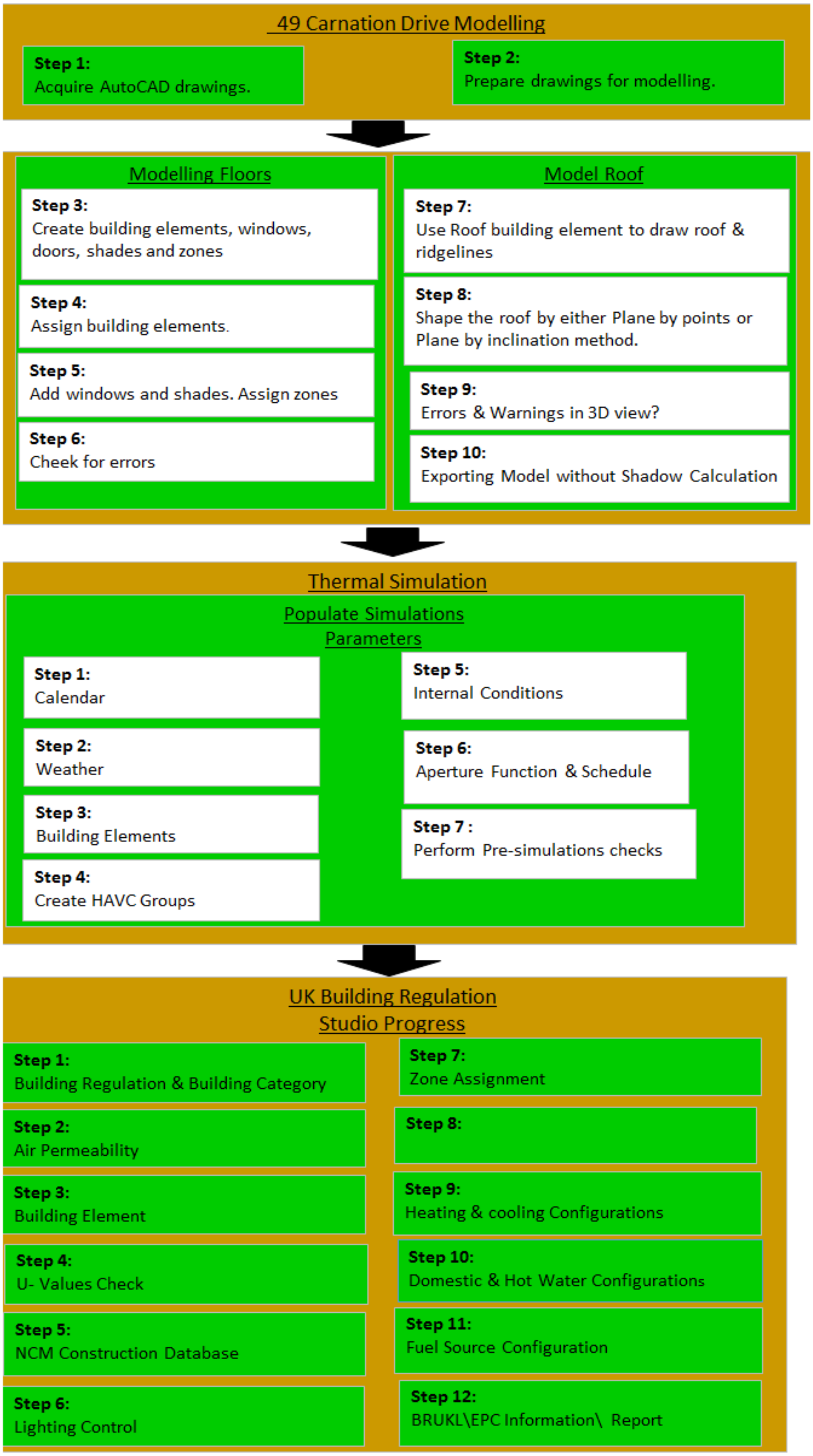


Figure 3.16 Methodological processes for modelling and simulating detached dwelling with attached conservatory thermal performance.

Table 3.9 Modelling and Simulation Parameters and Assumptions

Modelling assumptions and parameters

		Non Heating Season – *Day*	Non Heating Season – *Night*	Heating Season – *Day*	Heating Season – *Night*
Day lighting		Clear Sky Accuracy - Reflectance convergence for detailed analysis	N/A	Overcast Sky Accuracy - Reflectance convergence for detailed analysis	N/A
Weather Data		DSY	DSY	TRY	TRY
Ventilation	*Scenario 1*	Adequate Cross ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area. Set openable window temperature 20°C-21°C. Openable window Schedule 4am - 8pm	N/A	Optimum Cross ventilation between conservatory south facing fenestration and main building north fenestration, Openable conservatory lower/bottom window proportion 25%. Openable main building north facing window proportion 5% Set conservatory openable window temperature 10°C-11°C, main building 20°C-21°C Openable window Schedule 10am - 3pm	Doors/windows between conservatory and main building CLOSED. Conservatory serve as buffer
	Scenario 2	Adequate Cross ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area. Set openable window temperature 20°C-21°C. Openable window Schedule 24 hrs	Adequate Cross ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area. Set openable window temperature 20°C-21°C. Openable window Schedule 24 hrs	Optimum Cross ventilation between conservatory south facing fenestration and main building north fenestration, Openable conservatory lower/bottom window proportion 25%. Openable main building north facing window proportion 5% Set conservatory openable window temperature 10°C-11°C, main building 20°C-21°C Openable window Schedule 10am - 3pm	Doors/windows between conservatory and main building CLOSED. Conservatory serve as buffer
	Scenario 3	Adequate Cross ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area. Set openable window temperature 20°C-21°C. Openable window Schedule 24 hrs	Adequate Cross ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area. Set openable window temperature 20°C-21°C. Openable window Schedule 24 hrs	Optimum Cross ventilation between conservatory south facing fenestration and main building north fenestration, Openable conservatory lower/bottom window proportion 25%. Openable main building north facing window proportion 5% Set conservatory openable window temperature 20°C-21°C, main building 20°C-21°C Openable window Schedule 10am - 3pm	Doors/windows between conservatory and main building CLOSED. Conservatory serve as buffer
Shading	*Scenario 1*	No shading	N/A	N/A	Internal shading device coupled with coated low-e double glazed
	Scenario 2	Roof (overhang/awnings) and south facing conservatory side shading South shading schedule 10am - 3pm	N/A	N/A	Internal shading device coupled with coated low-e double glazed
	Scenario 3	Roof (overhang/awnings), south, east and west facing conservatory sides shading East shading schedule 4am - 11am West shading schedule 12 noon - 8pm	N/A	N/A	Internal shading device coupled with coated low-e double glazed
Heating & Cooling	*Scenario 1*	*Main Building* No Cooling applied *Conservatory* No Cooling applied	*Main Building* No Cooling applied *Conservatory* No Cooling applied	*Main Building* Fuel Source - Natural Gas HVAC Type - Central heating using water radiators Design flow rate - 200 l/s , SFP - 0.4 w/l/s Distribution Efficiency - 90% Boiler Efficiency - 91% *Conservatory* No heating applied	*Main Building* Fuel Source - Natural Gas HVAC Type - Central heating using water radiators Design flow rate - 200 l/s , SFP - 0.4 w/l/s Distribution Efficiency - 90% Boiler Efficiency - 91% *Conservatory* No heating applied
	Scenario 2	*Main Building* No Cooling applied *Conservatory* No Cooling applied	*Main Building* No Cooling applied *Conservatory* No Cooling applied	*Main Building* Fuel Source - Natural Gas HVAC Type - Central heating using water radiators Design flow rate - 200 l/s , SFP - 0.4 w/l/s Distribution Efficiency - 90% Boiler Efficiency - 91% *Conservatory* No heating applied	*Main Building* Fuel Source - Natural Gas HVAC Type - Central heating using water radiators Design flow rate - 200 l/s , SFP - 0.4 w/l/s Distribution Efficiency - 90% Boiler Efficiency - 91% *Conservatory* No heating applied
	Scenario 3	*Main Building* No Cooling applied *Conservatory* No Cooling applied	*Main Building* No Cooling applied *Conservatory* No Cooling applied	*Main Building* Fuel Source - Natural Gas HVAC Type - Central heating using water radiators Design flow rate - 200 l/s , SFP - 0.4 w/l/s Distribution Efficiency - 90% Boiler Efficiency - 91% *Conservatory* Heating applied as main building	*Main Building* Fuel Source - Natural Gas HVAC Type - Central heating using water radiators Design flow rate - 200 l/s , SFP - 0.4 w/l/s Distribution Efficiency - 90% Boiler Efficiency - 91% *Conservatory* Heating applied as main building
	Scenario 4	*Main Building* No Cooling applied *Conservatory* Cooling applied Fuel Source - Grid Supplied Electricity Aircondition set cooling temp - 25°C Distribution Efficiency - 80% COP - 2.4	*Main Building* No Cooling applied *Conservatory* Cooling applied Fuel Source - Grid Supplied Electricity Aircondition set cooling temp - 25°C Distribution Efficiency - 80% COP - 2.4	*Main Building* Fuel Source - Natural Gas HVAC Type - Central heating using water radiators Design flow rate - 200 l/s , SFP - 0.4 w/l/s Distribution Efficiency - 90% Boiler Efficiency - 91% *Conservatory* Heating applied as main building	*Main Building* Fuel Source - Natural Gas HVAC Type - Central heating using water radiators Design flow rate - 200 l/s , SFP - 0.4 w/l/s Distribution Efficiency - 90% Boiler Efficiency - 91% *Conservatory* Heating applied as main building

3.2.8.2 UK Building Regulation Studio

The UK Building Regulations Studio used by the TAS EDSL 9.3.1 software is based on 2010 regulations. It adheres to the National Calculation for Methodology (NCM) for the Energy Performance of Building Directive (DCLG). The UK Building Regulations Studio is systematically worked through by appropriately selecting various parameters and circuit configuration leading to the generation of series of building reports of which data based on the external temperature, the dry bulb temperature and the mean radiant temperatures are extracted and sent to the developed Excel program for CIBSE TM52 whole building overheating analysis. The CIBSE TM52 overheating analysis is carried out in TAS report generator. Figure 3.16 illustrates simulation processes in the UK Building Regulation Studio

3.2.8.3 Sizing of Awnings/Overhangs

Awnings are one of the effective ways to optimize solar radiation gains in the heating season by allowing low angled sun to penetrate the conservatory and to provide adequate shading in the non-heating season by excluding the high angled sun. As indicated earlier on, southerly orientation optimum performance of awnings is not only based on the period of usage in the day but it is also underpinned by its sizing design. The procedure below (adapted from EREC 2000 and BRE 1988) outline the sizing of the awnings/overhang used in the conservatory design of this work and it is based on the figure 3.17 below;

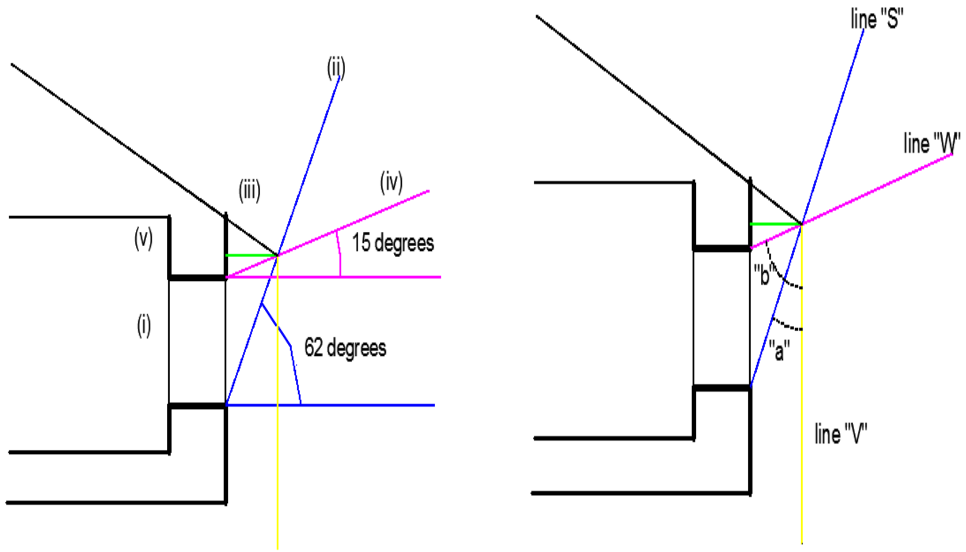


Figure 3.17 Sizing of overhang/awnings adapted from EREC 2000 and BRE 1988

(i) Draw the wall to be shaded to scale.

(ii) Draw the summer sun angle upward from the bottom of the glazing.

The angle of solar elevation at the summer solstice (June 22), α, is given as

$$\alpha = 90^o - (\text{latitude} - 23.5^o) \qquad \text{Eq. (3.8)}$$

The latitude of Bracknell, Berkshire is 51.42 degrees North, thus the angle of solar elevation at the summer solstice where the sun is at its highest altitude given as α is 62.08^o.

(iii) Draw the overhang (awning) until it intersects the summer sun angle line.

(iv) Draw the line at the winter sun angle from the bottom edge of the overhang (awning) to the wall.

$$\alpha = 90^o - (\text{latitude} + 23.5^o) \qquad \text{Eq. (3.9)}$$

The latitude of Bracknell, Berkshire is 51.42 degrees North, thus the angle of solar elevation at the winter solstice where the sun is at its highest altitude given as α is 15.08^o.

(v) Use a solid wall above the line where the winter sun hits. The portion of the wall below that line should be glazed.

Figure 3.17 shows the scale drawing of the awning sizing, with the distance from the conservatory to the bottom edge of the awnings estimated to be 0.888 metres to provide shading during non-heating season and distance of the vertical solid wall portion below which the conservatory should be glazed for effective solar radiation gain during the heating season estimated to be 0.413 metres.

To verify the accuracy of the above procedure, the results are compared to the BRE method of sizing southerly overhangs;

(i) To prevent summer gains, the angle “a” between a line “S” from the edge of the overhang (awning) to the bottom of the window and a vertical line “V” should be approximately equal to the latitude minus 18.5 degrees.

The latitude of Bracknell, Berkshire is 51.42 degrees North, thus “a” should be approximately 32.92^o.

When compared to the EREC procedure, the value of “a” obtained was 33.50° indicating a good agreement between the two methods for sizing southerly overhangs.

(ii) To prevent winter shading, the angle “b” between a line “W” from the edge of the overhang (awning) to the top of the window (conservatory opening) and a vertical line should be approximately equal to the latitude plus 18.5 degrees.

The latitude of Bracknell, Berkshire is 51.42 degrees North, thus “b” should be approximately 69.92°.

Again, when compared to the EREC procedure, the value of “b” obtained was 68.50° indicating a good agreement between the two methods for sizing southerly overhangs.

3.2.8.4 CIBSE TM52 Criteria as an Overheating Assessment Tool

The use of CIBSE TM52 criteria as an overheating assessment tool for this thesis is presented in detail in section 3.2.6.6 of this chapter.

3.3 Exclusions from case studies

The results of the case studies are situations specific based on the various scenarios detailed in the methods. The case studies do apply to the following conditions;

- CIBSE Internal Conditions: The data used for the internal conditions in the building prototypes are the CIBSE internal conditions as stipulated in the CIBSE Guide A. Therefore, the outcomes of the case study should be considered as evaluating alternative passive solar design strategies to improve energy consumption, carbon dioxide emissions and thermal comfort in newly built detached domestic buildings. The results may differ with varying occupant behaviours different from the conditions earmarked in the CIBSE Guide A.

- The case study outcomes should be considered as location specific and will not apply to the UK in general as the CIBSE weather datasets used are locations specific.
- The ventilation and shading strategies explored in the case studies if not adhere to in practice by varying occupants use of heating, ventilation and air-conditioning (HVAC) system may affect the results of the passive design strategies.
- The case studies are not about cost implications to newly detached residential buildings due to climate change adaptations in terms of initial capital cost and running cost neither do they consider the cost of passive building elements and building systems. Moreover, they do not include cost benefit analysis of household types.
- The case studies do not include reduce energy use in lightning and domestic hot water (DHW). Moreover, the sensitivity analyses exclude variance in lightning energy.
- The case studies exclude maintenance of building fabric and services to maximise performance.
- The case studies do not include varying building controls and systems. Control settings for example in heating and cooling for respective scenarios are done using heating and cooling efficiencies.

- In the use of CIBSE weather datasets underpinned by the UKCP09 climatic change projections, the 50% probabilistic scenarios (the best guess) are used. The probabilistic scenarios of 10% and 90% are excluded.
- The sensitivity analysis case studies (case studies 2 and 5) input and output variables are selected to be in consonance with EDSL TAS input/output variables.
- The case studies do not seek to bridge performance gap between the expected simulation energy performance of new buildings and the realised energy performance during occupancy.

CHAPTER 4: Bland-Altman method as a simulation validation technique

4.0 Case study 1: Method comparison analysis of detached dwelling temperatures in the United Kingdom

4.1 Introduction

The credibility and usage confidence of a simulation program must be underpinned by an acceptable robust validation process. Over the years, various techniques have been employed to validate thermal simulation programs of buildings to facilitate continuous improvement of software development and acceptability. However, emergent understanding of the topic shows that some applications of the goodness-of-fit measures use in validating simulation software in order to achieve Part L2 & EPC compliance are inadequate. Moreover, the present validation techniques are geared towards validating energy consumption results and currently there is not any metric, which evaluates the space temperature of dwellings. In addition, all TAS validations have been done for non-dwellings but not for residential buildings.

This study introduces Bland-Altman method-comparison analysis as a simulation validation tool to statistically evaluate the agreement between monitored temperatures and predicted thermal analysis simulated operative temperatures of detached dwellings in the UK using an approved thermal analysis building simulator.

In employing Bland-Altman's limit of agreement method to validate the simulated internal operative temperature and monitored temperature, the analysis showed a substantial plotted data (greater than 95%) lay between the limits of agreement indicating a very strong relationship between the building monitored temperatures and the EDSL TAS simulated temperatures. The findings show that Bland-Altman method validates the TAS program as credible and acceptable software for building thermal analysis simulation and that Bland-Altman comparison-method can be used as a thermal analysis simulation program validation technique.

4.2 Research Method 1 – For Case Study 1

Detailed method for case study 1 is discussed in chapter 3 section 3.2.3.

4.3. Results and Discussion

4.3.1 Bland-Altman Method

The analysis of 49 Carnation Drive two-storey residential detached building is presented below. Figures 4.1 and 4.2 represent the outcome of the modelling process.

Figure 4.1 Front Elevation Modelling Results

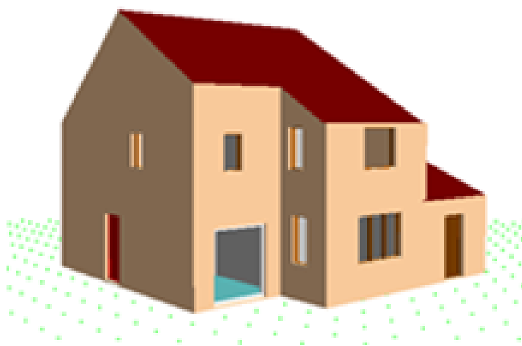


Figure 4.2 Rear and Side Elevation Modelling Results

Figures 4.3 to 4.10 show the results of the Bland-Altman method for the analysis of the outdoor and kitchen operative temperatures. Hanneman (2008) emphasized the importance of data inspection to remove outliers as an important step preceding the Bland and Altman plot, (Hanneman, 2008). Analyses of both scatter plots with their line of equality figures 4.3 and 4.4 show the visual impression of the agreement between the two methods. The line of equality is a line on which all the points should lie if the two methods gave the exact temperature values and thus formed a perfect agreement (Bland and Altman, 1986). The Pearson correlation coefficients (r) of the 0.86 and 0.75 for the outdoor and kitchen temperature analyses points to a strong positive linear relationship (Pallant, 2013). Moreover, the p values of the two analyses are less than 0.0001 which points to a significant statistical relationship between the simulated and monitored temperatures with a very low probability of the association between the simulated and monitored temperatures due to chance. It is obvious from the scatter plots that not all of the set paired data points lie on the line of equality. Thus, further analysis is required in the form of the Bland-Altman method.

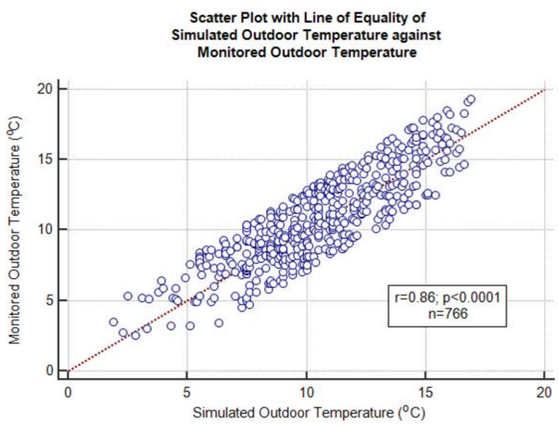


Figure 4.3 Outdoor Temperatures Scatter plot with Line of Equality

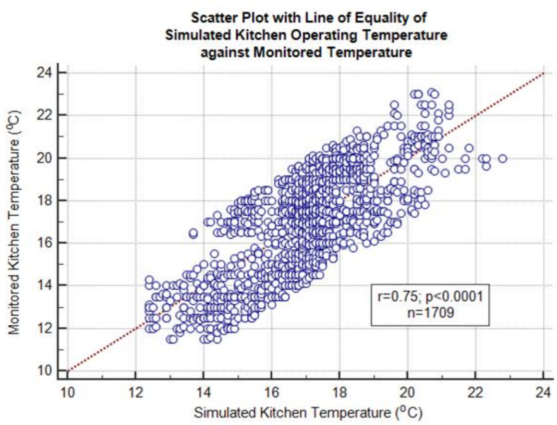
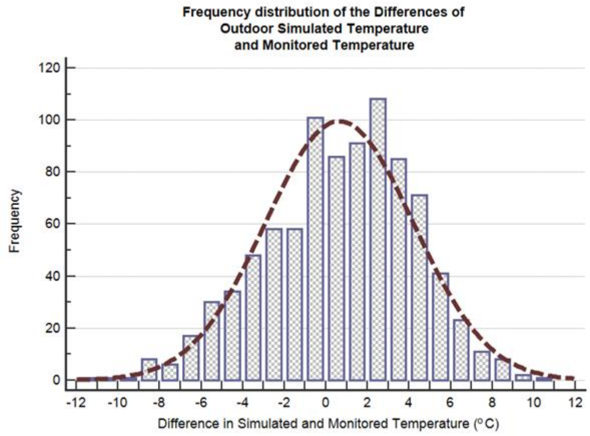


Figure 4.4 Kitchen Operative temperatures Scatter plot with Line of Equality



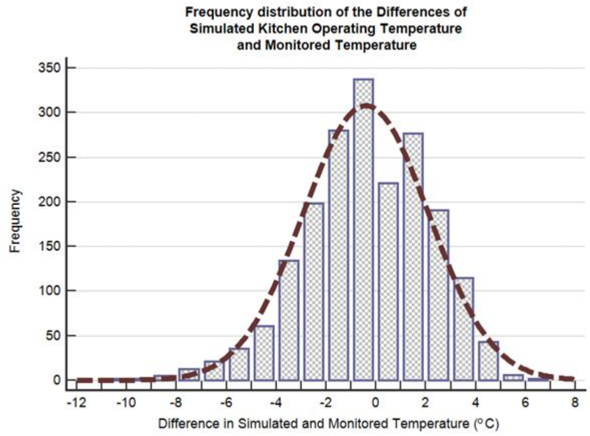
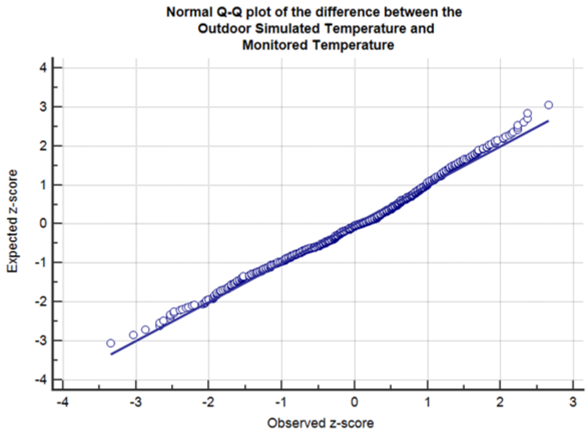


Figure 4.5 Frequency distribution of Outdoor Simulated and Monitored Temperatures

Figure 4.6 Frequency distribution of Kitchen Simulated and Monitored Temperatures

The Bland-Altman plot is underpinned by the parametric statistical test of normal distribution of the differences of the sets of paired simulated and monitored temperatures. This is due to the fact that the 95% limits of agreement depend on the statistical assumption that the differences of the paired set of temperatures will give constant mean and standard deviation (Bland and Altman, 2003). Thus, figures.4.5 and 4.6 show histograms of the differences of the temperatures which give evidence of being reasonably normally distributed. The normal distribution assertion is re-inforced by the inspection of the normal Q-Q plots figure 4.7 and 4.8 which show the observed values plotted against the expected values to be a reasonably straight line further pointing to normal distribution (Pallant, 2013). The Kolmogorov-Smirnov statistic was not used in the analyses as its significant value tends to be quite small when dealing with large sample size, making it inappropriate to be used in this instance to assess the distribution normality (Pallant, 2013).



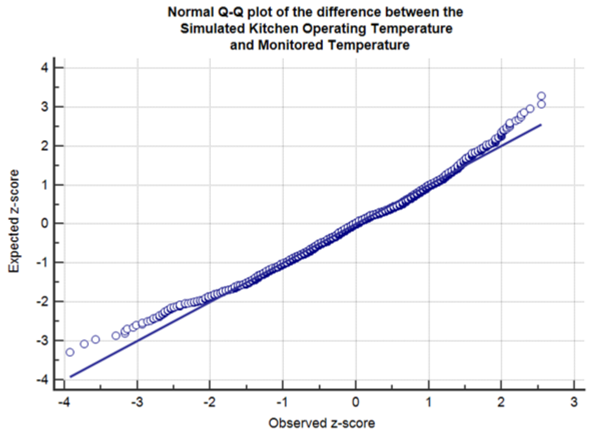
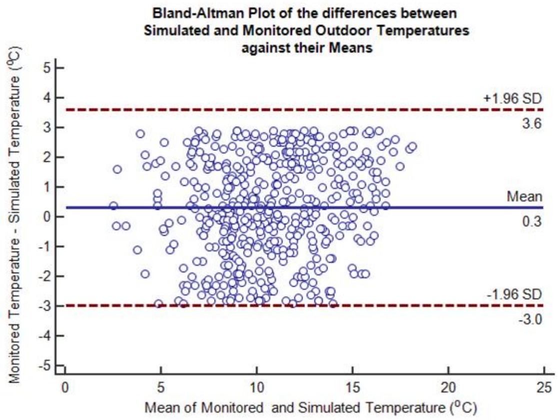


Figure 4.7 Normal Q-Q plot of the difference between Outdoor Simulated and Monitored Temperatures

Figure 4.8 Normal Q-Q plot of the difference between Kitchen Simulated and Monitored Temperatures



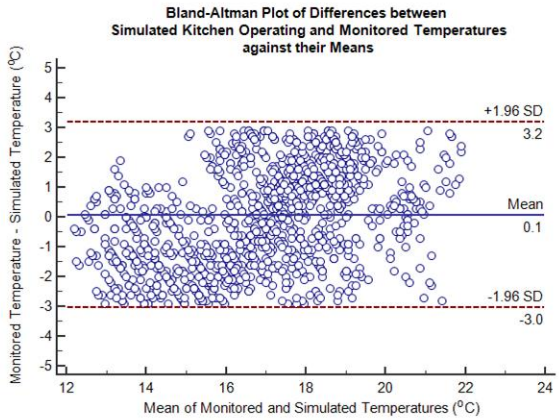


Figure 4.9 Bland-Altman plot Outdoor temperatures

Figure 4.10 Bland-Altman plot Kitchen temperatures

Figure 4.9 gives the Bland-Altman plot for the differences between the outdoor simulated and monitored temperatures against their means. 86% of the total 890 sets of paired temperature data collected in the period ranging from March to May 2014 were used for the analysis after the removal of outliers. The mean difference of the temperatures was 0.3 °C with the standard deviation 1.7 °C, giving the 95% limit of agreements of -3.0 °C to 3.6 °C. The bias and the precision are within the priori criteria set at the beginning. The standard errors of the limits is expressed as $((3 \times \text{standard deviation}^2)/n)^{1/2}$, where n is the number of sets of paired temperatures. The standard error is thus given as 0.11.The analysis showed a substantial plotted data (greater than 95%) lay between the limits of agreement indicating a very strong relationship between the outdoor monitoring temperatures and the TAS simulated external temperature based on the CIBSE weather data file. Thus, with the external temperature as the only uncertainty in the simulation analysis, a very strong agreement is realized between the monitored outdoor temperatures and the thermal analysis simulated temperatures, which therefore validates the TAS program based on the weather data alone.

Further Bland-Altman analysis which takes cognisance of the simulation of kitchen operative temperatures coupled with the monitoring temperatures is shown in Figure 4.10. 88% of the total of 1942 sets of paired temperature data collected in the period ranging from February to May 2014 were used for the analysis. The mean difference in the kitchen operative temperatures was 0.1 $^{\circ}$C and the standard deviation was 1.6 ^{o}C. The 95% limits of agreements were -3.0 $^{\circ}$C to 3.2 $^{\circ}$C. The bias and the precision are again within the priori criteria set at the beginning. The standard error is calculated to be 0.07. The analysis of the kitchen operative temperatures indicated that substantial plotted data (greater than 95%) lay between the limits of agreement, showing a very strong agreement between the kitchen monitoring temperatures and the TAS simulated kitchen operative temperatures, and thus the analysis using Bland-Altman method validates the TAS program as credible and acceptable software for building thermal analysis simulation.

4.4 Summary and Conclusion

The work presented the use of Bland-Altman comparison-method as a thermal analysis simulation program validation technique and affirmed that the accuracy of building thermal performance can be predicted using TAS program. The analysis entailed statistical evaluation of the agreement between monitored temperatures and predicted thermal analysis simulated operative temperatures of detached dwellings in the UK. The analysis showed a very strong agreement between the outdoor monitoring temperatures and the TAS simulated external temperature based on CIBSE weather data file. Thus with the external temperature as the only uncertainty in the simulation analysis a very strong agreement is realized between the monitored outdoor temperatures and the thermal analysis simulated temperatures which thus validates the TAS program based on the weather data alone. The analysis of the kitchen operative temperatures also indicated a substantial plotted data lay between the limits of agreement, which showed a very strong agreement between the kitchen monitoring temperatures and the TAS simulated kitchen operative temperatures, and thus the analysis using the Bland-Altman method validates the TAS program as credible and acceptable software for building thermal analysis simulation.

The conclusions are drawn from the British Standards Institute definition of a repeatability coefficient which stipulates that 95% of the differences ought to be less than two standard deviations (BSI, 1975). Professionals in the built environment may be required to make a judicious decision as to what level of agreement would be acceptable in simulation practice. The procedure outlined is acceptable for temperature comparison of two methods as it assumes a linear relationship between errors and measurements. For non-linear and perhaps more complicated uncertain parameters, additional numerical issues may have to be addressed.

CHAPTER 5: Impact of climate change variability on building thermal performance - consideration of only varying weather data set scenarios

5.0 Case study 2: Deterministic, uncertainty and sensitivity analysis on CIBSE TM48 and CIBSE TM49 future weather files using CIBSE TM52 as overheating criteria.

5.1 Introduction

In 2008, CIBSE released two sets of future weather files, the Test Reference Years (TRYs) and the Design Summer Years (DSYs) based on the UKCIP02 climate projections. The methodology used to produce the CIBSE future weather files was the ‘morphing’ methodology which adjusted the historic weather files to the climate projection (CIBSE TM48, 2008), (Mylona, 2012). Analytical studies performed on the UKCP09 projections indicate that extreme historical summers will become average summers by the middle of the 21st century and therefore overheating risk analysis will require the use of adjusted projected weather years (CIBSE TM49, 2014). CIBSE has therefore released the TM49 future data sets.

The Monte Carlo sensitivity analysis consideration of the case study examines the implication of thermal comfort in dwellings by these two differing future weather files. The overall pattern of variability of the UKCIP02 and UKCP09 Heathrow weather data sets under Monte Carlo sensitivity consideration seems to be not very different from each other as analysis of results show that the median operative temperatures changes from 23.5 °C to 25.4°C and 23.5°C to 25.5°C respectively for the various times lines of 2020s, 2050s and 2080s.

However, the deterministic results show that the operative temperatures of the UKCIP02 are slightly higher than those of UKCP09 with the UKCP09 having narrow range of operative temperatures.

The difference in the maximum operative temperatures between the various timeline scenarios of Gatwick when compared with Heathrow and London Weather Centre show a difference of about 0.6 °C and 1.0 °C for Heathrow and London Weather Centre respectively locations using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios . The highest maximum operative temperatures for the London Weather Centre timelines could be attributed to the urban heat island effect. Similar trends are observed when comparing the minimum internal operative temperatures for the three locations. Moreover, the Monte Carlo sensitivity analysis quantified and identified the dry bulb and radiant temperatures as the most influential weather parameters which affect thermal comfort on dwellings. This finding agrees with published literature (CIBSE TM52, 2013; CIBSE Guide A, 2006).

5.2 Research Method 2 – For Case Study 2

Detailed method for case study 2 is discussed in chapter 3 section 3.2.4.

5.3 Results and Discussion

5.3.1 Results of the Deterministic Analysis

Figures 5.1 to 5.4 illustrates the deterministic analysis results in the form of histogram analysis comparison of the maximum, minimum, average and range of operative temperatures and appendix 5.1 shows the time series analysis of internal operative temperatures using CIBSE TM52 as overheating criteria and of UKCIP02 Heathrow DSY Medium High and the UKCP09 Heathrow 1989 medium 50% probabilistic scenarios weather data sets.

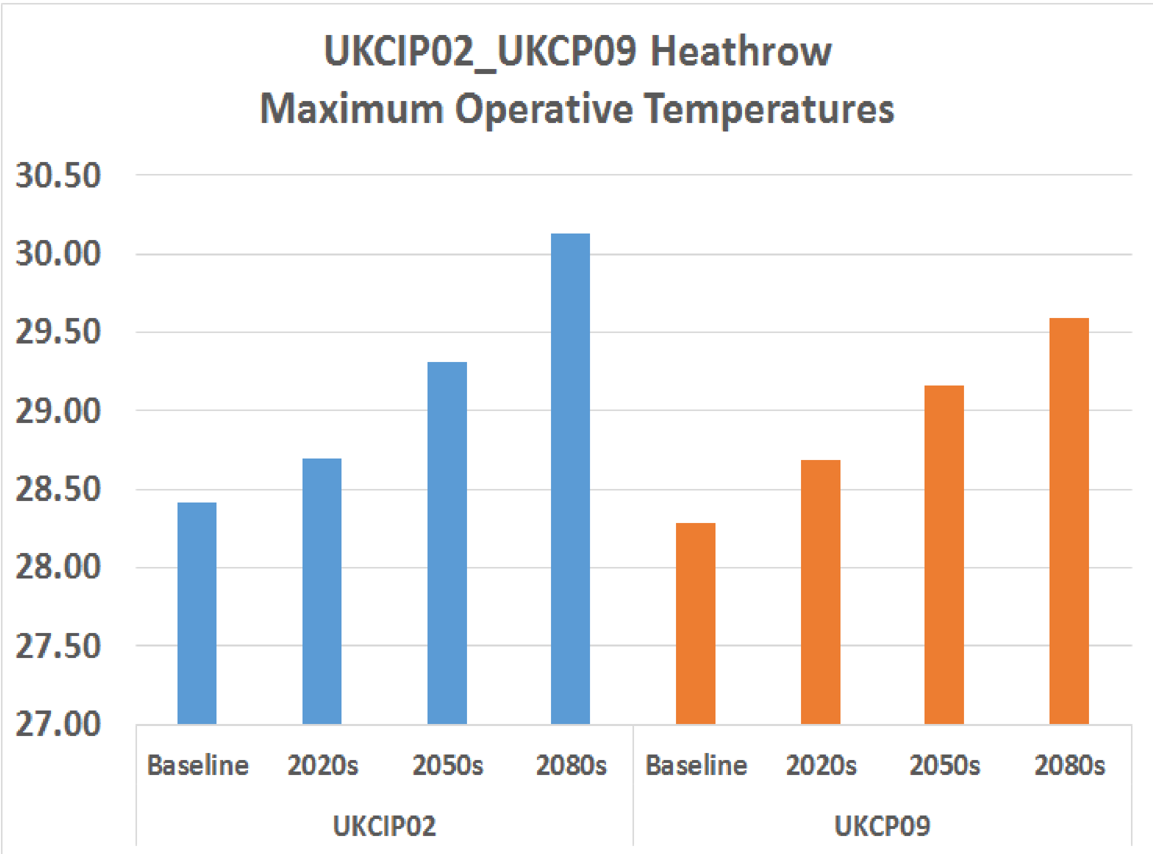


Figure 5.1 Maximum operative temperatures for UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios

Figure 5.1 indicates a marginal difference in maximum operative temperatures for the Heathrow DSY Medium High and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios for the baseline, 2020s and 2050s weather data sets with the former being slightly higher. For the 2080s scenarios, the difference in operative temperature for the two weather data sets is about 0.5 °C. Figure 5.2, the minimum operative temperature variability, indicates a similar trend of marginal difference to that of figure 5.1. While the minimum operative temperatures for the UKCP09 Heathrow DSY 1989 medium 50% probabilistic scenarios' weather data sets for the baseline, the 2020s and 2050s timelines show slightly higher temperatures in the range of about 0.1 °C for all respective comparative scenarios. The 2080s scenario variation is the opposite to that observed in other timelines with the UKCIP02 showing slightly higher minimum temperatures. Figure 5.3 shows the average internal operative temperatures for the two weather data sets. The two weather data sets' respective timelines show a strong similarity in the trend of average operative temperatures. In figure 5.4, the range operative temperatures for the UKCIP02 Heathrow DSY medium high are slightly higher than their respective comparative timelines for the UKCP09 Heathrow 1989 medium 50% probabilistic scenarios, ranging from about 0.25 °C to 0.42 °C for the baseline and 2080s scenarios respectively.

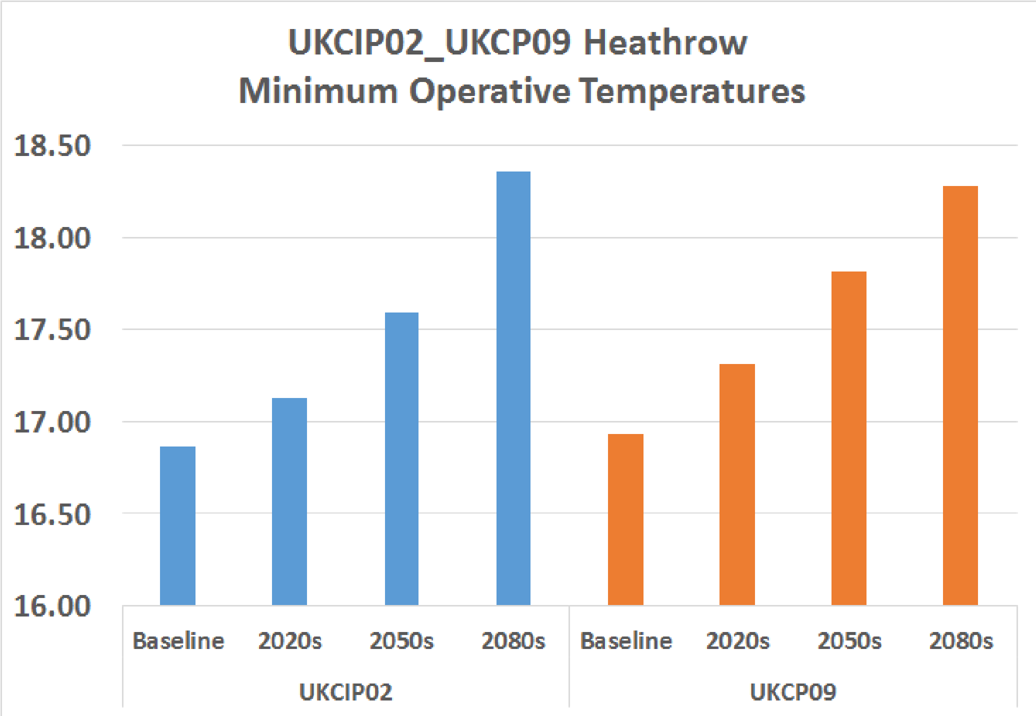


Fig 5.2 Minimum operative temperatures for UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios

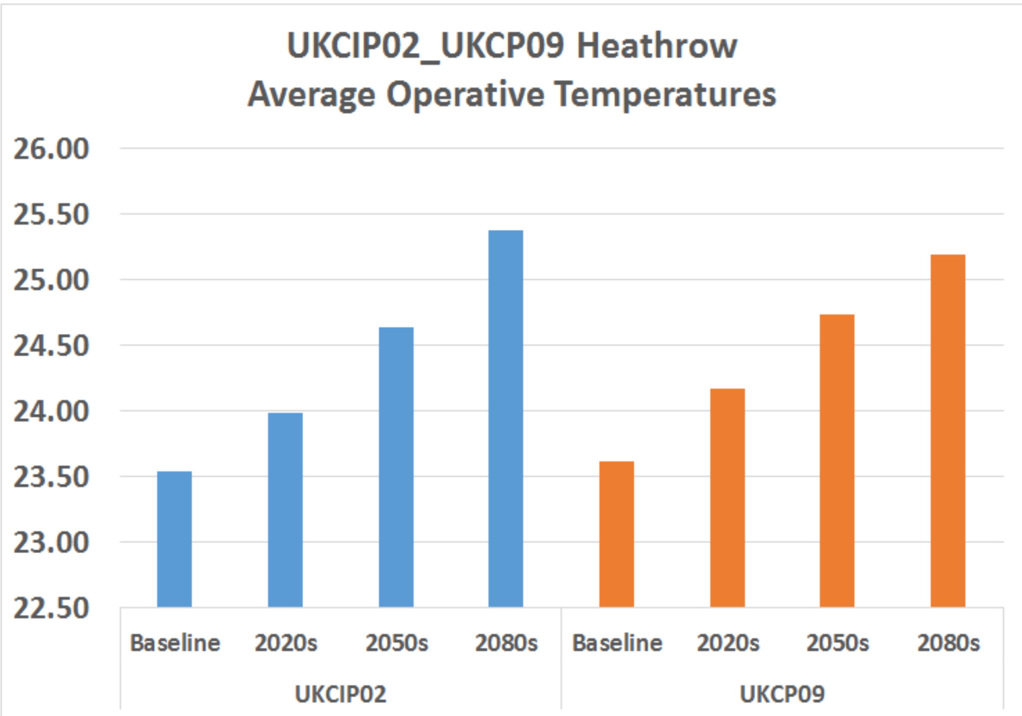


Figure 5.3 Average operative temperatures for UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios

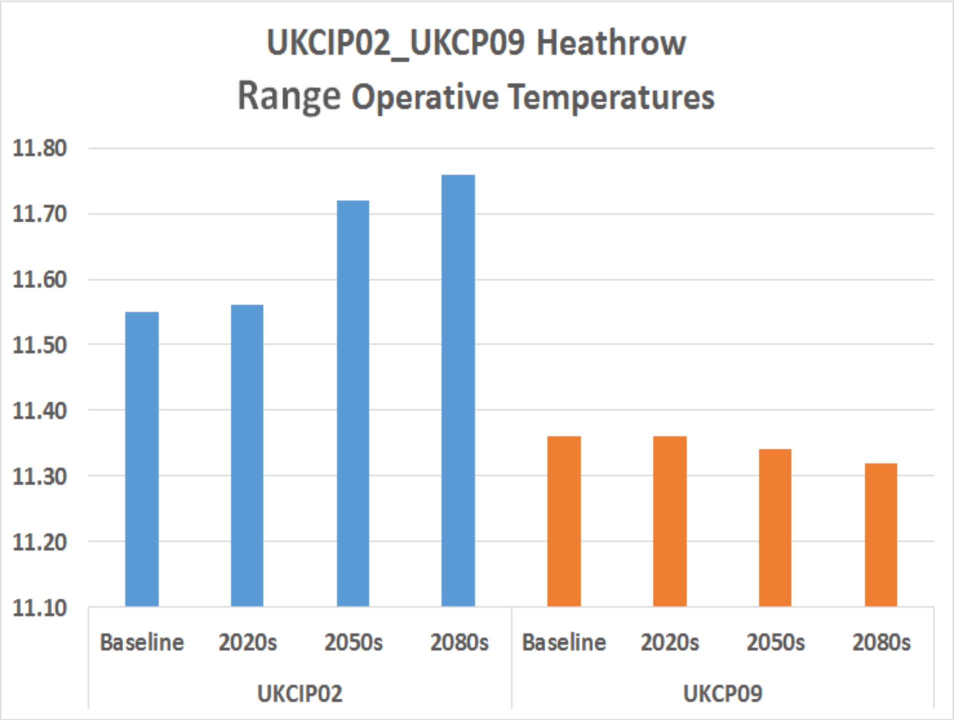


Figure 5.4 Range operative temperatures for UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios

Appendix 5.1 indicates the time series analysis of internal operative temperatures using CIBSE TM52 as overheating criteria for the UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow DSY 1989 Medium 50% probabilistic scenarios' weather data sets. The trend analysis shows a very strong similarity in the respective timelines for the two weather data sets.

Figure 5.5 to 5.8 illustrate the deterministic analysis results in the form of histogram analysis comparison of the maximum, minimum, average and range of operative temperatures of UKCP09 Heathrow DSY Medium 50% probabilistic scenarios for 1976, 1989 and 2003 and the time series analysis of internal operative temperatures using CIBSE TM52 as overheating criteria.

UKCP09 London Maximum Operating Temperatures for Med 50%

	Gatwick				Heathrow				London Weather Centre			
	Baseline	2020s	2050s	2080s	Baseline	2020s	2050s	2080s	Baseline	2020s	2050s	2080s
1976	28.36	28.77	29.23	29.64	28.99	29.35	29.77	30.18	29.11	29.50	29.92	30.66
1989	27.85	28.28	28.81	29.28	28.28	28.68	29.16	29.59	28.40	28.79	29.24	29.24
2003	28.33	28.83	29.32	29.82	29.06	29.55	30.00	30.47	29.41	29.87	30.30	30.75

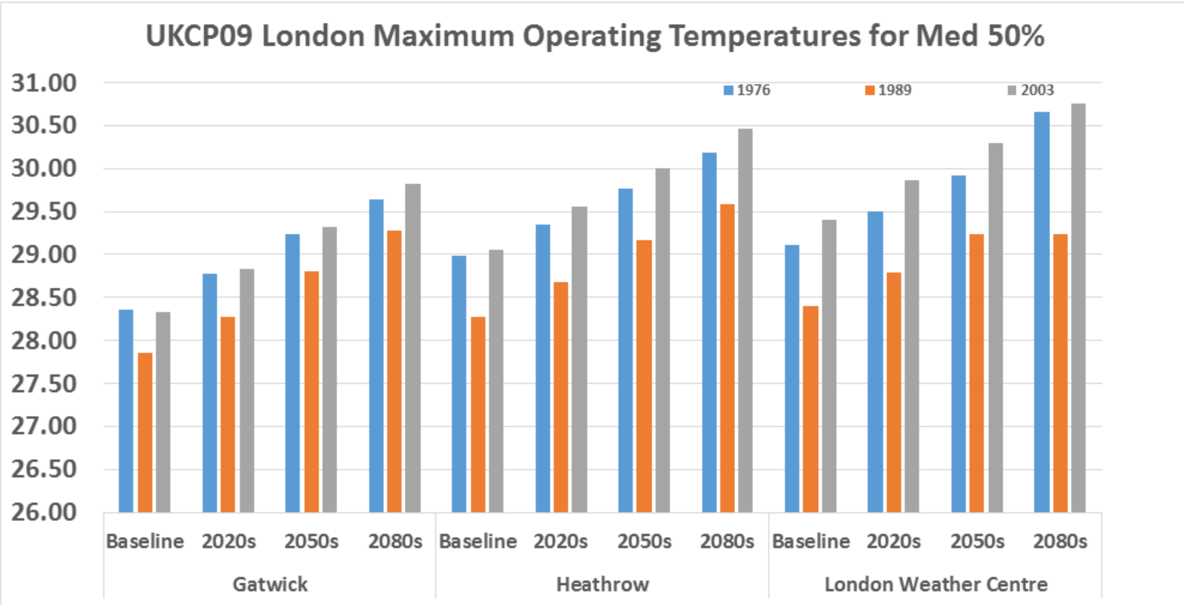


Figure 5.5 A comparison of maximum internal operative temperatures for Gatwick, Heathrow and London Weather Centre using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

As expected, there is a progressive increase in maximum internal operative temperatures for 1976 and 2003 for all timeline scenarios. Gatwick has the lowest maximum operative temperatures whilst London Weather Centre is observed to have the highest operative temperatures. The difference in the maximum operative temperatures between the various timeline scenarios of Gatwick when compared with Heathrow and London Weather Centre show a difference of about 0.6 $^{\circ}$C and 1.0 $^{\circ}$C for Heathrow and London Weather Centre respectively. The highest maximum operative temperatures for the London Weather Centre timelines could be attributed to the urban heat island effect. Similar trends are observed in figure 5.9 which compares the minimum internal operative temperatures for the three locations using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

The average operative temperatures for the three locations indicated as expected, with London Weather Centre having the highest average temperatures followed by Heathrow. With Gatwick having the least average operative temperatures when compare to the other two locations. The 1989 medium 50% probabilistic weather data set appears to have slightly higher average operative temperatures of about 0.5^{o}C when compared to for all scenarios when compared to the 1976 and 2003 weather data sets. Comparison of the range operative temperatures shows the 2003 medium 50% probabilistic weather data set to have the lowest when compared to the other years.

UKCP09 London Minimum Operating Temperatures for Med 50%

	Gatwick				Heathrow				London Weather Centre			
	Baseline	2020s	2050s	2080s	Baseline	2020s	2050s	2080s	Baseline	2020s	2050s	2080s
1976	16.70	17.13	17.67	18.16	17.15	17.60	18.18	18.78	17.37	17.81	18.44	19.80
1989	16.46	16.82	17.27	17.67	16.93	17.31	17.82	18.28	16.90	17.30	17.80	17.80
2003	16.95	17.60	18.42	19.16	17.85	18.56	19.49	20.30	18.47	19.25	20.22	21.01

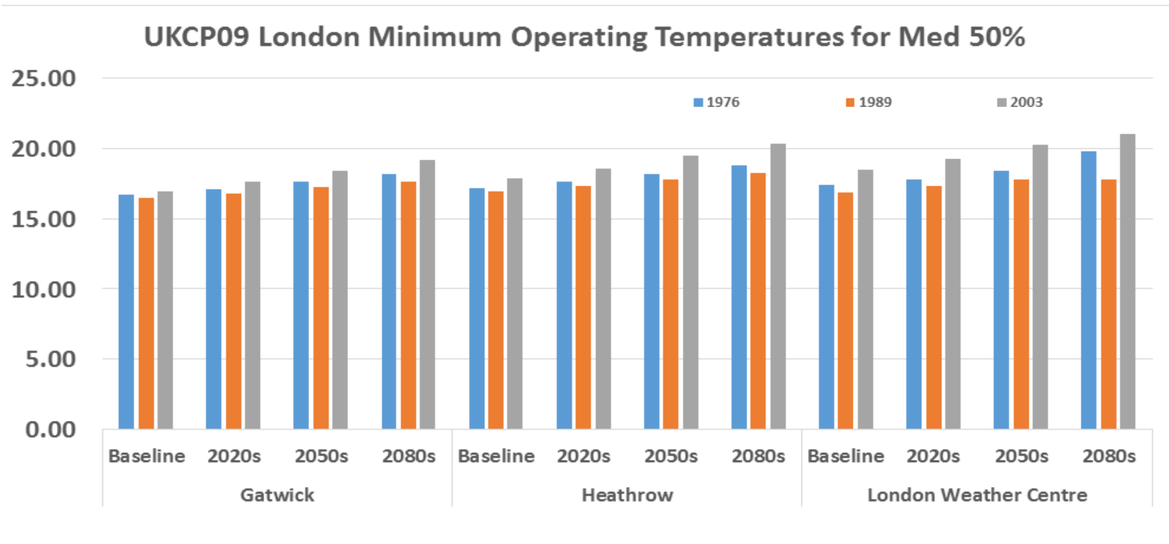


Figure 5.6 A comparison of minimum internal operative temperatures for Gatwick, Heathrow and London Weather Centre using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

UKCP09 London Average Operating Temperatures for Med 50%

	Gatwick				Heathrow				London Weather Centre			
	Baseline	2020s	2050s	2080s	Baseline	2020s	2050s	2080s	Baseline	2020s	2050s	2080s
1976	22.62	23.25	23.93	24.49	23.28	23.87	24.48	24.97	23.40	23.99	24.59	25.47
1989	23.01	23.63	24.27	24.77	23.61	24.17	24.74	25.19	23.71	24.26	24.81	24.81
2003	22.61	23.24	23.93	24.48	23.32	23.91	24.53	25.02	23.72	24.27	24.84	25.29

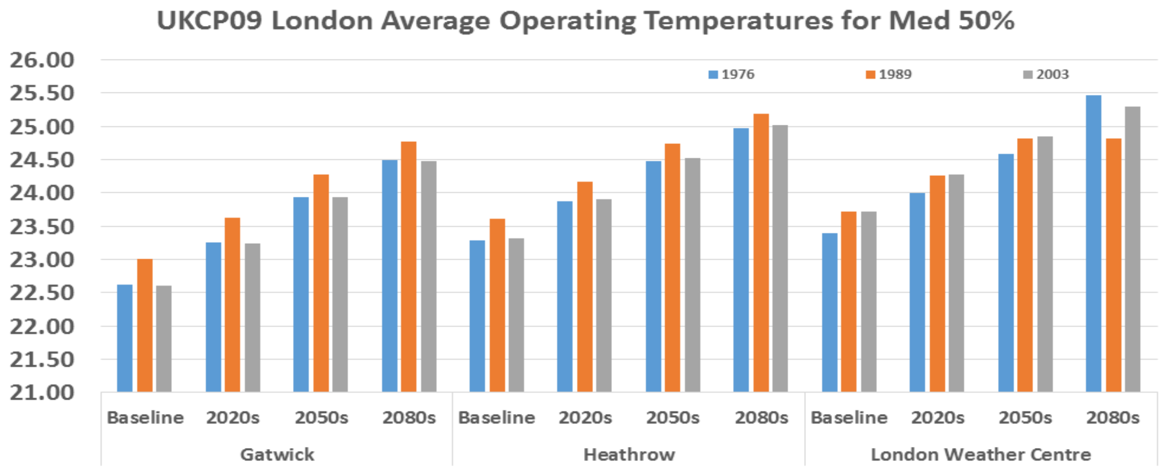


Figure 5.7 A comparison of average internal operative temperatures for Gatwick, Heathrow and London Weather Centre using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

UKCP09 London Operating Temperatures Range for Med 50%

	Gatwick				Heathrow				London Weather Centre			
	Baseline	2020s	2050s	2080s	Baseline	2020s	2050s	2080s	Baseline	2020s	2050s	2080s
1976	11.67	11.64	11.56	11.48	11.83	11.75	11.60	11.40	11.73	11.69	11.48	10.86
1989	11.39	11.64	11.54	11.61	11.36	11.36	11.34	11.32	11.50	11.49	11.45	11.45
2003	11.37	11.23	10.89	10.67	11.21	10.99	10.50	10.17	10.95	10.62	10.08	9.74

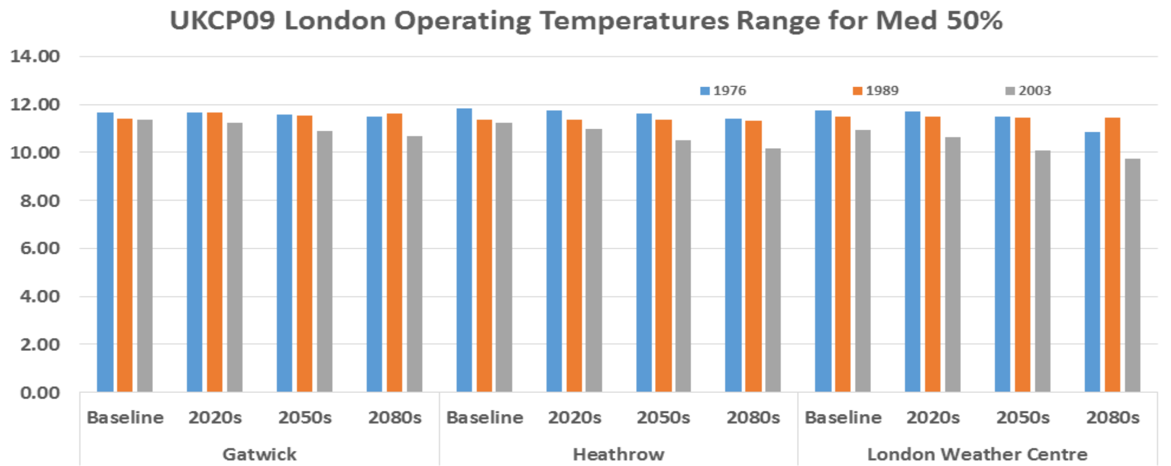


Figure 5.8 A comparison of the range internal operative temperatures for Gatwick, Heathrow and London Weather Centre using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 5.2 to 5.4 show the time series CIBSE TM52 thermal comfort analysis results for Heathrow, Gatwick and London Weather Centre base on the UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios .

5.3.2 Results of the multivariate linear regression analysis due to climate change alone

The linear regression analysis indicated that average dry bulb temperature and average radiant temperature input parameters were the most significant factors and thus they can be used as good indicators for the sensitivity analysis of the weather data. To check for the variability of the multivariate linear regression analysis for the uncertainty and sensitivity analysis, the following results from the model output were examined. The adjusted R square value for the scenarios was 1.0 which gives 100% of variability of the target variable of the internal operative temperature accounted for by the selected input variables, giving an indication of a very good model. The adjusted R square gives the total variability of the input variables on the target variable percentage variability explained by the multivariate linear regression module. The adjusted R square exceeding 96% shows an excellent fit (Hyph et al, 2012) to the TAS simulation results, which show that the multivariate linear regression model is an acceptable model for the analysis. Dominguez-Munoz et al even set the acceptable R square to be greater than 70% (Dominguez-Munoz et al, 2010). The UKCIP02 Heathrow DSY 2020 Medium High results summary is shown in table 5.1 below as an example.

Table 5.1 Table of Model Summary Box for UKCIP02 Heathrow DSY 2020 Medium High results

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	1.000[a]	1.000	1.000	.00352	1.946

a. Predictors: (Constant), DHEWRMT, Diffused Radiation, Wind Direction, Cloud Cover, Wind Speed, External Humidity, External Temperature, Average Dry Bulb Temperature, Global Radiation, Average Radiant Temperature

b. Dependent Variable: Internal Operative Temperature

The ANOVA table, table 5.2 below, gives the assessment of the overall significance of the models. The p value for the output parameters of internal operative temperatures was less than 0.05 indicating the statistical significance of the model. Moreover, the F-test values show that the models are a good fit for the data with p values also less than 0.05.

Table 5.2 ANOVA table of outputs

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	10765.385	10	1076.538	86916033.249	.000[b]
	Residual	.045	3661	.000		
	Total	10765.430	3671			

a. Dependent Variable: Internal Operative Temperature

b. Predictors: (Constant), DHEWRMT, Diffused Radiation, Wind Direction, Cloud Cover, Wind Speed, External Humidity, External Temperature, Average Dry Bulb Temperature, Global Radiation, Average Radiant Temperature

The examinations of the standardized beta coefficients table 5.3, which give the measure of contribution of each variable to the models, were performed. Large values show that a unit change in a particular predictor input variable has a large effect on the output variable. Analysis of the internal operative temperature model indicated that the average dry bulb temperature and the average radiant temperature values were the largest of the standardized beta coefficients. Moreover, the t-test also showed higher values for these parameters with p values less than 0.05 all pointing to the identified parameters having significant influence on the output variables.

Table 5.3 Statistical coefficients of the model

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.001	.002		-.365	.715
	Global Radiation	-1.924E-7	.000	.000	-.277	.782
	Diffused Radiation	4.438E-7	.000	.000	.330	.741
	Cloud Cover	.000	.000	.000	.533	.594
	External Temperature	3.579E-6	.000	.000	.163	.870
	External Humidity	-9.874E-7	.000	.000	-.174	.862
	Wind Speed	-7.552E-5	.000	.000	-2.045	.041
	Wind Direction	-2.343E-7	.000	.000	-.445	.657
	Average Dry Bulb Temperature	.500	.000	.486	2878.716	.000
	Average Radiant Temperature	.500	.000	.520	2813.320	.000
	DHEWRMT	-1.828E-5	.000	.000	-.406	.685

a. Dependent Variable: Internal Operative Temperature

5.3.3 Uncertainty analysis due to climate change alone

5.3.3.1 Scatter Plots

Appendix 5.5 illustrates the scatter plots of the input weather variables for the sensitivity analysis module. Analysis of the parameters shows that the dry bulb temperature and the radiant temperature are strongly positive correlated to the internal operative temperatures. The external temperature and the daily hourly exponential running mean temperature show fairly positive correlation with the internal operative temperature with external humidity being negatively correlated with the internal operative temperature. The internal operative temperature appears not to show a strong dependency on the cloud cover and wind direction parameters.

5.3.3.2 Box and whiskers plots

Figure 5.9 illustrates the comparison of the UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow DSY 1989 Medium 50% probabilistic weather data set effect on internal operative temperature to ascertain the impact of climate change on thermal comfort of residential buildings. The box and whiskers plot is a graphical method of representing data through their quartiles. The plots show the uncertainty associated with Monte Carlo simulation of overheating analysis with internal operative temperatures as the output parameter using the various weather scenarios indicated above as the only variants. The ten (10) input variables as displayed in table 5.3 are used in the analysis and the same sample size of 3672 hourly data between May1 and September 30 as specified in the CIBSE TM52 overheating criteria which were used in each analysis.

The key features of the box and whiskers plot are the interquartile range, the median, the outer range, the outliers and the extreme values. The median value is the solid horizontal line within the box. It represents the 50th percentile of the total ranked data set. The box section represents the interquartile range of the data set. This range extends from the 25th to 75th percentile taking cognisance of the middle 50% of the ranked data. The height of the box thus indicates the proportionality of the statistical spread of the central half; the inner 50% of rank data. This is the region where there is a 50% probability of occurrence of chance of a future variable. The outer range or whiskers (shown as vertical lines extending from the top and bottom ends of the box) extends to the 10th and 90th percentiles of the dataset. This conversion is acceptable in Meteorological analysis (Baracos 2011; Thompson et al, 2007). The outliers and extreme values are represented by the dots and crosses respectively outside the whiskers. The outliers offer 10% probability of occurrence of the data set.

Analysis of the heights of the two weather data sets' boxes of the interquartile range, representing the proportionality of the statistical spread of the inner 50% of the ranked data and further pointing to the portion of the plot where there is 50% chance of future variables probability of occurrence, show a progressive decrease providing greater confidence in the future weather data sets and further showing the strong influence of the effect of changing of climatic weather conditions over the years on internal operative temperatures used in this work as a measure of thermal comfort based on the CIBSE TM52 criteria.

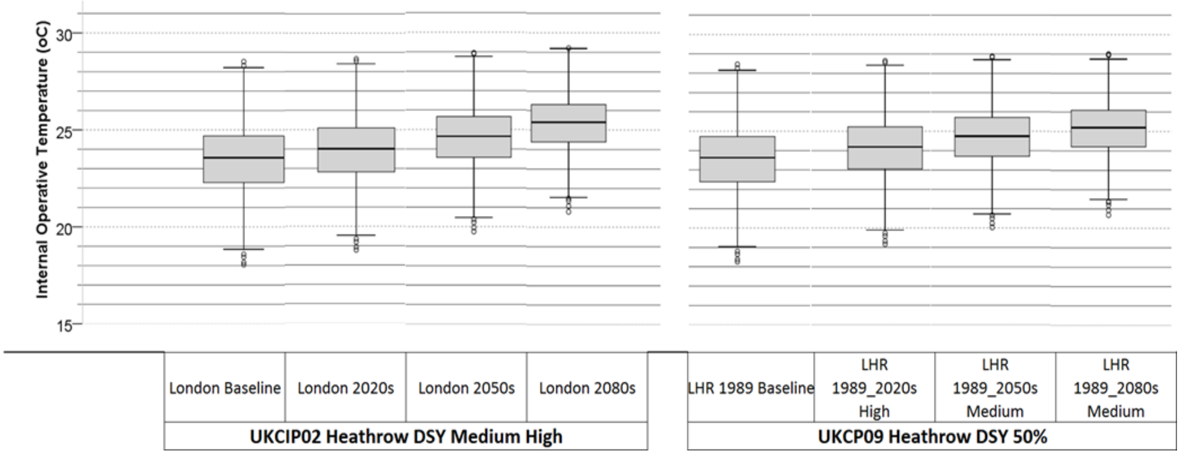


Figure 5.9 Box and whiskers plots of the UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow DSY 1989 Medium 50% probabilistic weather data set

The median lines (50th percentile) of all the plots are equidistant from the ends of the interquartile range (end of the box) indicating that not all the data sets are skewed. There is a progressive increase of the median lines of the uncertainty distribution along the timelines in both the UKCIP02 and the UKCP09 weather data sets. This marked progressive increase shows that the influence of the weather on internal operative temperatures of dwellings is strong.

A comparison of the median lines shows that the 50th percentiles of the UKCP09 for the 2020s and 2050s are slightly higher than that of the UKCIP02 weather projections, whilst the opposite is realised with regards to the 2080s weather data set. However, the overall pattern of variability of the two weather data sets seems to be not very different from each other as analysis of the UKCIP02 and UKCP09 results show that the median changes from 23.5 $^{\circ}$C to 25.4 $^{\circ}$C and 23.5 $^{\circ}$C to 25.3°C respectively. Thus, there is no marked observable effect of change in internal operative temperatures in the two sets of the uncertainty analysis results.

The whiskers of the plots, indicated by the extended vertical lines above and below the plots and which show the variability of the internal operative temperatures outside the upper (75th percentiles) and lower quartiles (25th percentiles) to the 90th percentile and 10th percentile of the data sets respectively, also show symmetry pointing to the non-skewedness of the data. The whisker plots progressively decrease along the time lines of the two different weather data sets with the decrease in the UKCP09 Heathrow 1989 DSY Medium 50% probabilistic weather data sets slightly more pronounced than the UKCIP02 Heathrow DSY Medium High data sets.

The outliers showing the individual points outside the whiskers with 10% probability of occurrence are virtually similar when comparing the respective timeline scenarios of the two different weather data sets. The outliers for both the maximum and minimum values generally lie close to the whiskers' end.

Figures 5.10 to 5.12 illustrate the box plots comparison of the internal operative temperatures reported in relation to the effect of the design summer year (DSY) medium 50% probabilistic scenarios of the 1976, 1989 and 2003 weather data sets of Gatwick, Heathrow and London Weather Centre. In general, there is zero skewedness of the interquartile ranges and the whiskers. A progressive decrease of variability of the length of the interquartile ranges (IQR) is observed along the years also coupled with a progressive decrease in the whiskers. Thus, the baselines have larger dispersion for both the box and the whiskers and they progressively decrease along the timelines.

Moreover, the variability of the interquartile range and the relative dispersion of the data set outer range are larger in the 1976 and 2003 scenarios than that of 1989 indicating a clustering of parameters near the 25th and 75th percentiles and further large dispersion of the outliers.

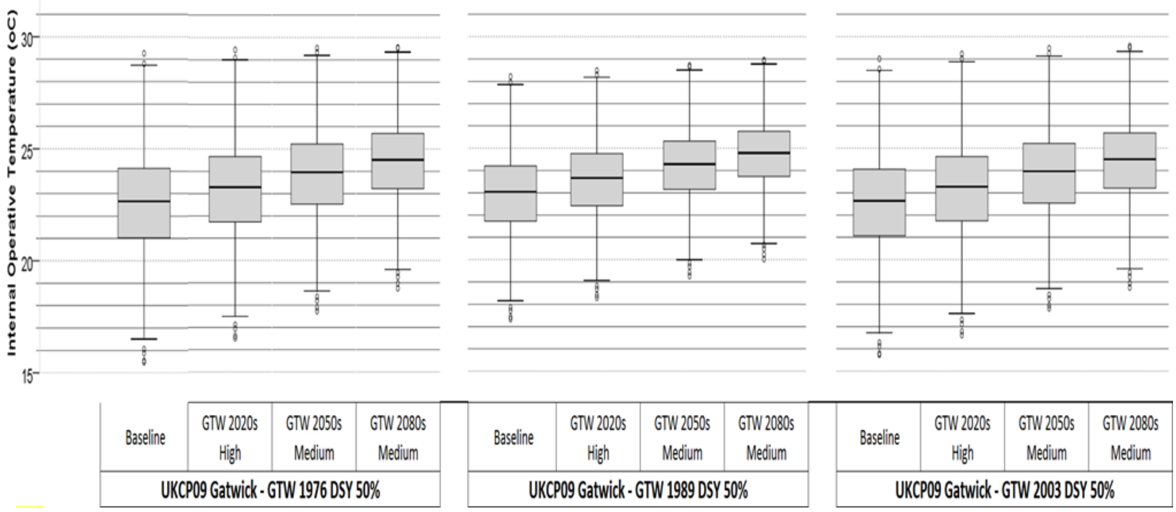


Figure 5.10 Box and whiskers plot comparison of the internal operative temperatures reported in relation to the effect of the design summer year (DSY) medium 50% probabilistic scenarios of the 1976, 1989 and 2003 weather data sets of Gatwick

As expected, the medians of the 1989 scenarios of Gatwick, Heathrow and London Weather Centre are comparatively lower than those of the 1976 and 2003 scenarios. In addition the interquartile ranges and the whiskers are relatively smaller. This observation points to a relatively middle clustering of data about the medians, 25th percentiles and the 75th percentiles of the 1989 timeline scenarios indicating less uncertainty in the target variable of internal operative temperatures.

In general, the medians for the 2003 scenarios are higher than those of the 1976 scenarios. Furthermore, analysis of figures 5.10 to 5.12 shows that the medians of London Weather Centre timeline scenarios are higher than those of their comparative Heathrow timelines scenarios and further higher than those of the

Gatwick timeline scenarios. This could be attributed to the urban heat effect in the city of London. As anticipated, the outliers of the 1976 and 2003 weather scenarios lie further away from the whiskers when compared to that of the 1989 data set point towards more extreme internal operative temperatures in those years' weather data sets.

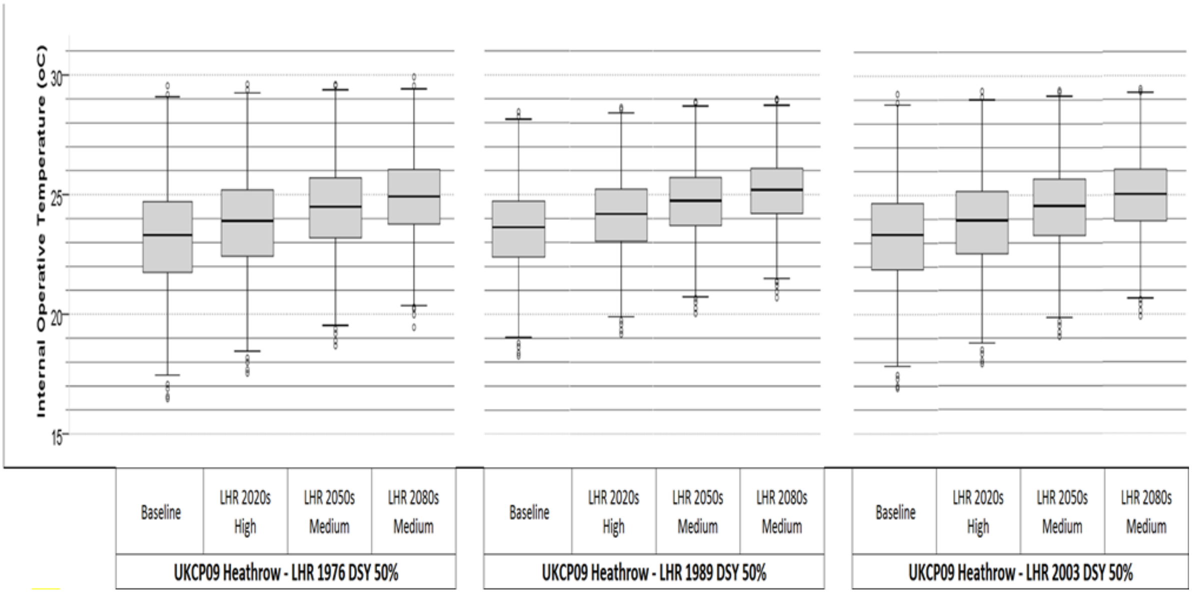


Figure 5.11 Box and whiskers plot comparison of the internal operative temperatures reported in relation to the effect of the design summer year (DSY) medium 50% probabilistic scenarios of the 1976, 1989 and 2003 weather data sets of Heathrow

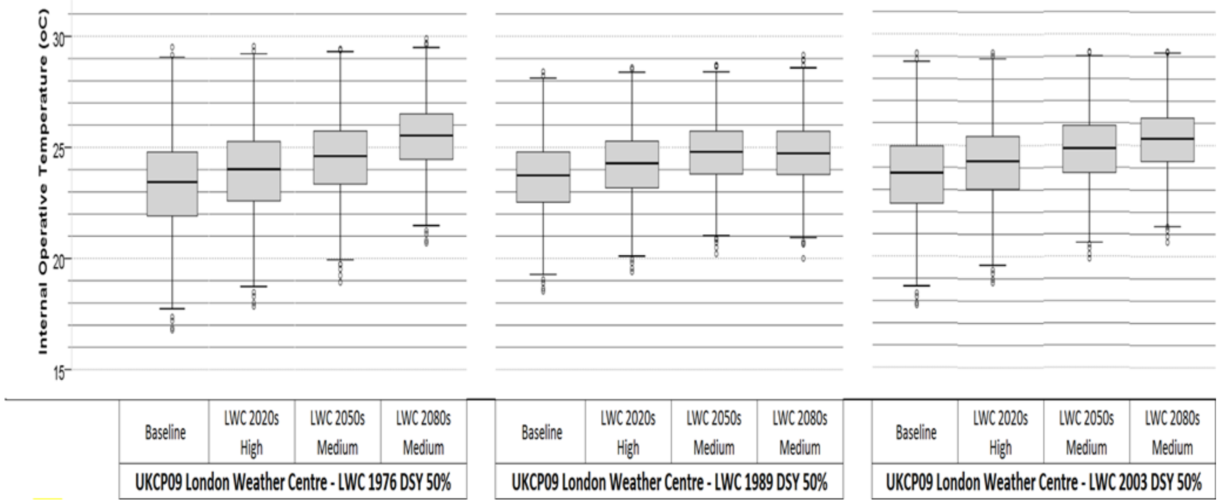


Figure 5.12 Box and whiskers plot comparison of the internal operative temperatures reported in relation to the effect of the design summer year (DSY) medium 50% probabilistic scenarios of the 1976, 1989 and 2003 weather data sets of London Weather Centre

5.3.4 Sensitivity analysis due to climate change alone

5.3.4.1 Tornado plot as deterministic sensitivity analysis

Ranking of the inputs according to individual correlation with the target parameter of internal operative temperature is presented in the form of a tornado chart in figure 5.14. Tornado plots are useful deterministic sensitivity analysis diagrams which compare the relative significance of input variables. The most influential parameters appear at the top of the chart. The plot further shows the relative magnitude and the direction (positive or negative relationship) and further depicts the degree of linear relationship between the target variable and the input variables. The plots show that the dry bulb temperature and the radiant temperature are the most influential inputs affecting the internal operative temperatures. The external temperature and the daily hourly exponential running mean temperature are the next influential parameters. The external humidity parameter and the cloud cover show a negative relationship with the internal operative temperature.

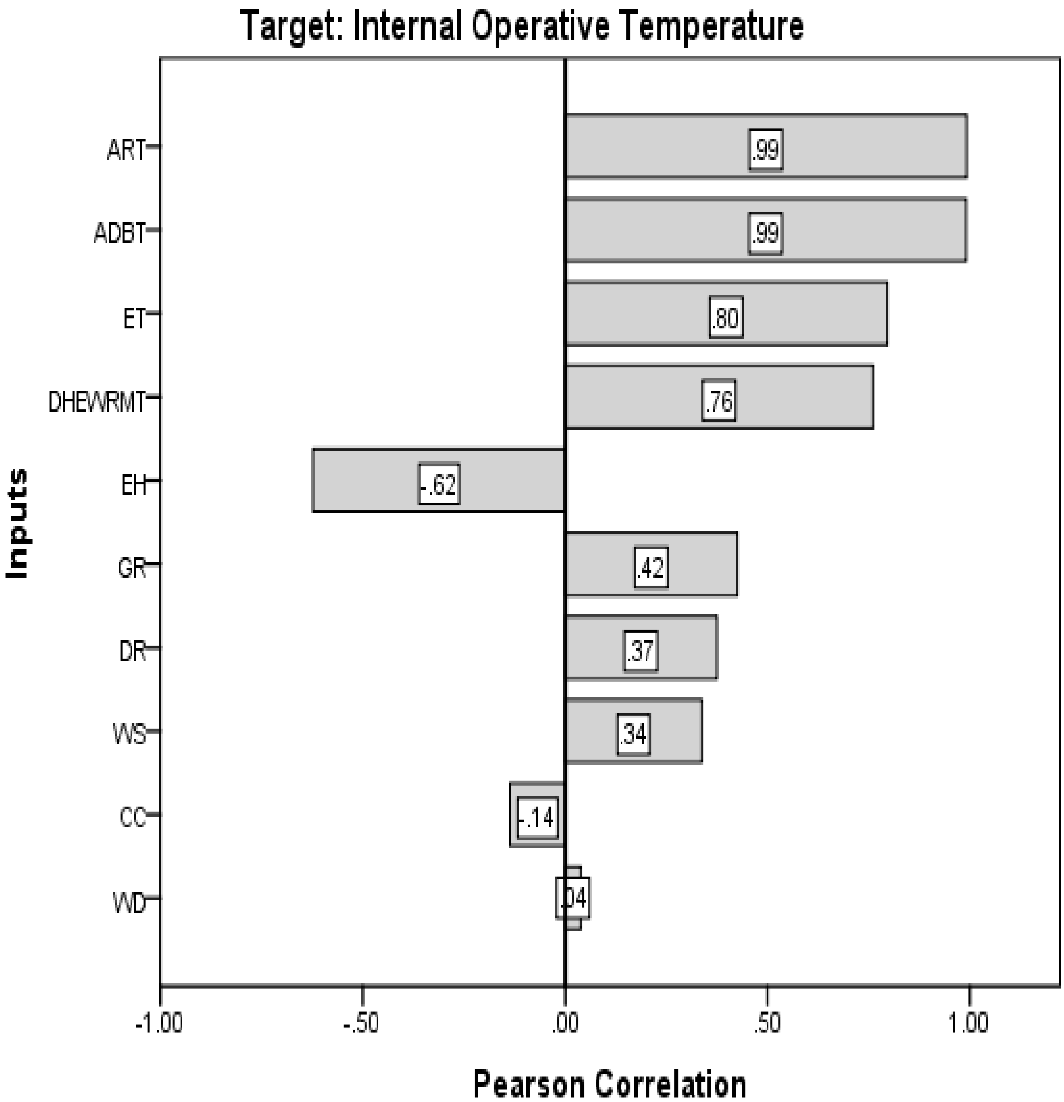


Figure 5.14 Tornado plot as deterministic sensitivity analysis due to climate change alone

5.3.4.2 Sensitivity analysis with SRC and PCC as sensitivity indices

Figure 5.14 illustrates the comparison of the standardized regression coefficient (SRC) and the partial correlation coefficients (PCC) of the weather input variables for the UKCIP02 Heathrow and UKCP09 1989 Heathrow weather data sets. Figures 5.15 to 5.18 depict the sensitivity analysis for the three weather locations of Gatwick, Heathrow and London Weather Centre for the 1976, 1989 and 2003 weather files. A comparison of the SRC and PCC sensitivity indices results shows that they give a similar pattern of results, pointing to the robustness of the analysis and the credibility of the results.

The results of all the sensitivity analysis results when considering the variation of the weather data alone indicate that the internal operative temperature of dwellings is mostly influenced by the radiant temperature and the dry bulb temperature. The other weather variables of wind direction, wind speed, external humidity, external temperature, cloud cover, diffused radiation, global radiation and the daily hourly exponentially weight running mean temperature have a relatively small impact on the internal operative temperature. This observation is in consonance with the formulae used in predicting thermal comfort in CIBSE TM52 and BSI (2007) BS EN 15251 which combine the air and radiant temperatures to obtain the operative temperature.

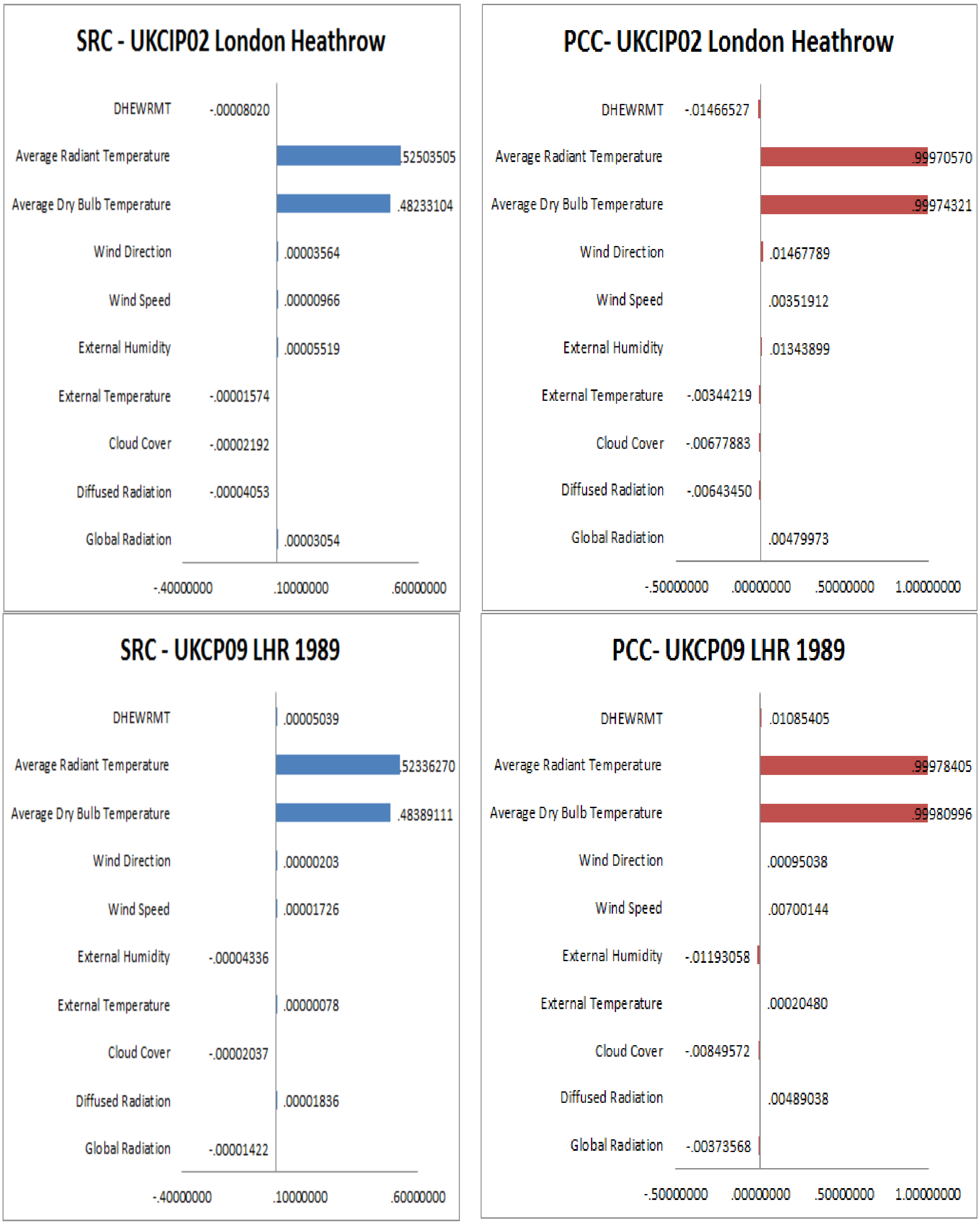


Figure 5.14 Comparison of the standardized regression coefficient (SRC) and the partial correlation coefficients (PCC) of the weather input variables for the UKCIP02 Heathrow and UKCP09 1989 Heathrow weather data sets.

Figure 5.15 Comparison of the standardized regression coefficient (SRC) and the partial correlation coefficients (PCC) of the weather input variables for the UKCP09 1976, 1989 and 2003 Gatwick weather data sets.

Figure 5.16 Comparison of the standardized regression coefficient (SRC) and the partial correlation coefficients (PCC) of the weather input variables for the UKCP09 1976, 1989 and 2003 Heathrow weather data sets.

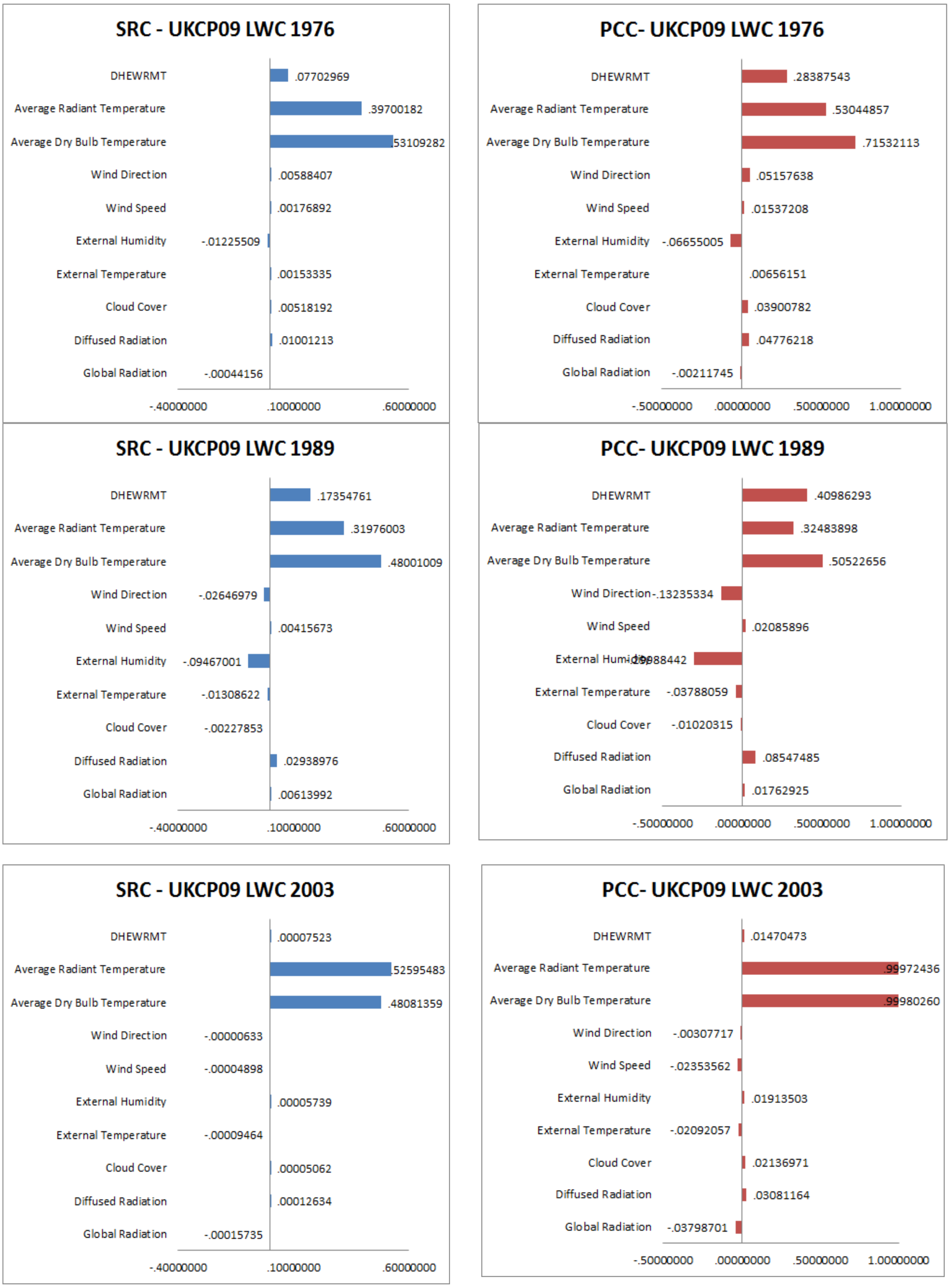


Figure 5.17 Comparison of the standardized regression coefficient (SRC) and the partial correlation coefficients (PCC) of the weather input variables for the UKCP09 1976, 1989 and 2003 London Weather Centre weather data sets.

5.4 Summary and Conclusion

The case study investigated the impact of varying weather patterns on thermal performance of dwellings. The work is underpinned by building simulation modules in TAS coupled with the Monte Carlo global sensitivity analysis method using IBM SPSS to indicate that the proposed method can facilitate the analysis and prediction of sensitive building parameters which influence the thermal comfort of residential buildings.

The deterministic analysis results of the UKCP09 Heathrow DSY Medium 50% probabilistic scenarios for 1976, 1989 and 2003 indicated a progressive increase in maximum internal operative temperatures for the 1976 and 2003 years for all timeline scenarios. Gatwick had the lowest maximum operative temperatures whilst London Weather Centre was observed to have the highest operative temperatures. This affirmed the incorporation of the urban heat island effect of the London Weather Centre weather data sets of CIBSE TM49 as compared to the Heathrow and Gatwick weather files.

The Monte Carlo uncertainty analysis results of the median lines showed that the 50th percentiles of the UKCP09 for the 2020s and 2050s are slightly higher than that of the UKCIP02 weather projections, whilst the opposite is realised with regards to the 2080s weather data set. However, the overall pattern of variability of the two weather data sets seems to be not very different from each other as analysis of the UKCIP02 and UKCP09 results show that the median changes from 23.5 °C to 25.4°C and 23.5°C to 25.3°C respectively. Thus, there is no marked observable effect of change in internal operative temperatures in the two sets of the uncertainty analysis results. However, the deterministic results shows the operative temperatures of the UKCIP02 are slightly higher than those of UKCP09 with the UKCP09 having narrow range of operative temperatures.

The Monte Carlo sensitivity analysis quantified and identified the dry bulb and radiant temperatures as the most influential weather parameters which affect thermal comfort on dwellings. The study results further indicated marginal differences in maximum and minimum operative temperatures for the Heathrow DSY Medium High and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios for the baseline, 2020s and 2050s weather data sets with the former being slightly higher. For the 2080s scenarios, the difference in maximum operative temperature for the two weather data sets was about 0.5 °C. Moreover, the time series analysis of internal operative temperatures using CIBSE TM52 as overheating criteria for the UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow DSY 1989 medium 50% probabilistic scenario weather data sets showed a very strong similarity in the respective timelines for the two weather data sets.

The standardized regression coefficient and the partial correlation coefficients are useful sensitivity indices for determining the relative importance of building parameters which influence the thermal comfort of dwellings. The work stresses the need for climate sensitive design and the knowledge of this could offer insight for efficient designs and retrofitting practice to improve the thermal comfort of dwellings.

It is proposed that for easy analysis and replicable of the methodology used in this work, it is recommended that EDSL TAS incorporate Monte Carlo and global sensitivity analysis as key standard functionalities of its modelling and simulation software to facilitate the analysis and prediction of key thermal performance parameters and further assess different energy conservation measures.

CHAPTER 6: Impact of climate change on building energy performance - consideration of only varying weather data set scenarios

6.0 Case study 3: Deterministic analysis of key building energy performance parameters of ten (10) Persimmon 2-storey residential detached buildings

6.1 Introduction

This deterministic analysis case study investigates the variability of future climatic conditions on newly built detached dwellings in the UK. The study employs an approved thermal analysis building simulator as a tool to perform a series of simulations on ten detached houses and thereby evaluate and predict the extent of the impact of varying future climatic patterns, based on the current CIBSE weather data set morphed from the UK Climate Projection 2002 weather information, on newly built detached dwellings in the UK, based on five (5) key building performance indicators of total annual energy consumption, annual gas consumption, annual electricity grid consumption, building emissions rate and heating and cooling demand. The study identifies and quantifies a consistent declining trend of building performance which is in accordance with current scientific knowledge of prediction for annual temperature change in relation to long term climatic variation. The average percentage decrease for the annual energy consumption for heating when cooling was not applied was predicted to be 2.80, 6.60 and 10.56 for 2020s, 2050s and 2080s time lines respectively. A similar declining trend in the case of annual natural gas consumption was 4.24, 9.98 and 16.1, and that for building emission rate and heating demand were 2.27, 5.49 and

8.72 and 7.82, 18.43 and 29.46 respectively. With the application of cooling, the average percentage increase for heating and cooling demand was predicted to be 0.53, 4.68 and 8.12. The study analyses the future heating and cooling demands of the three warmest months of the year and ascertains future variance in relative humidity and indoor temperature. In addition, overheating risk and its implication to cooling energy demand is quantified. The average cooling energy demand to offset overheating for the ten building prototypes was observed to be 2.7, 12.64, 29.56 and 46.33 MJ/m^2 for the current, 2020s, 2050s and 2080s timelines respectively. This analysis indicates that future predicted temperature rise might necessitate the use of room cooling systems to provide thermal comfort.

6.2 Research Method 3 – For Case Study 3

Detailed method for case study 3 is discussed in chapter 3 section 3.2.5.

6.3 Results and Discussion

The analysis of one building prototype - Persimmon South East Ltd Sheppey General Hospital dwelling 0712 House Type G Private - two-storey residential detached building is presented below. Figures 6.1 to 6.3 represent the outcome of the modelling process.

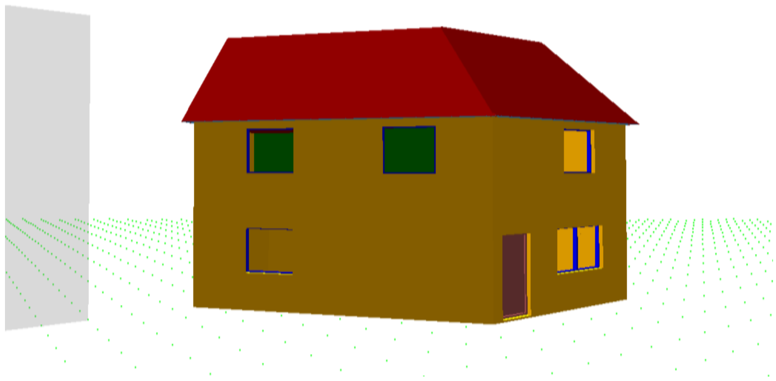


Figure 6.1 Modelling Results Front Elevation

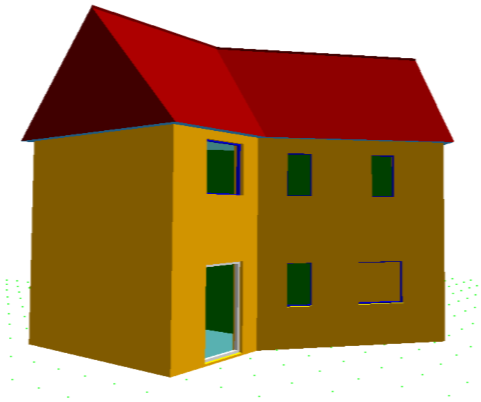


Figure 6.2 Modelling Results Rear and Side Elevation

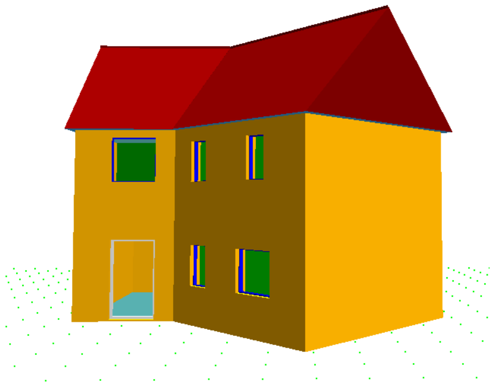
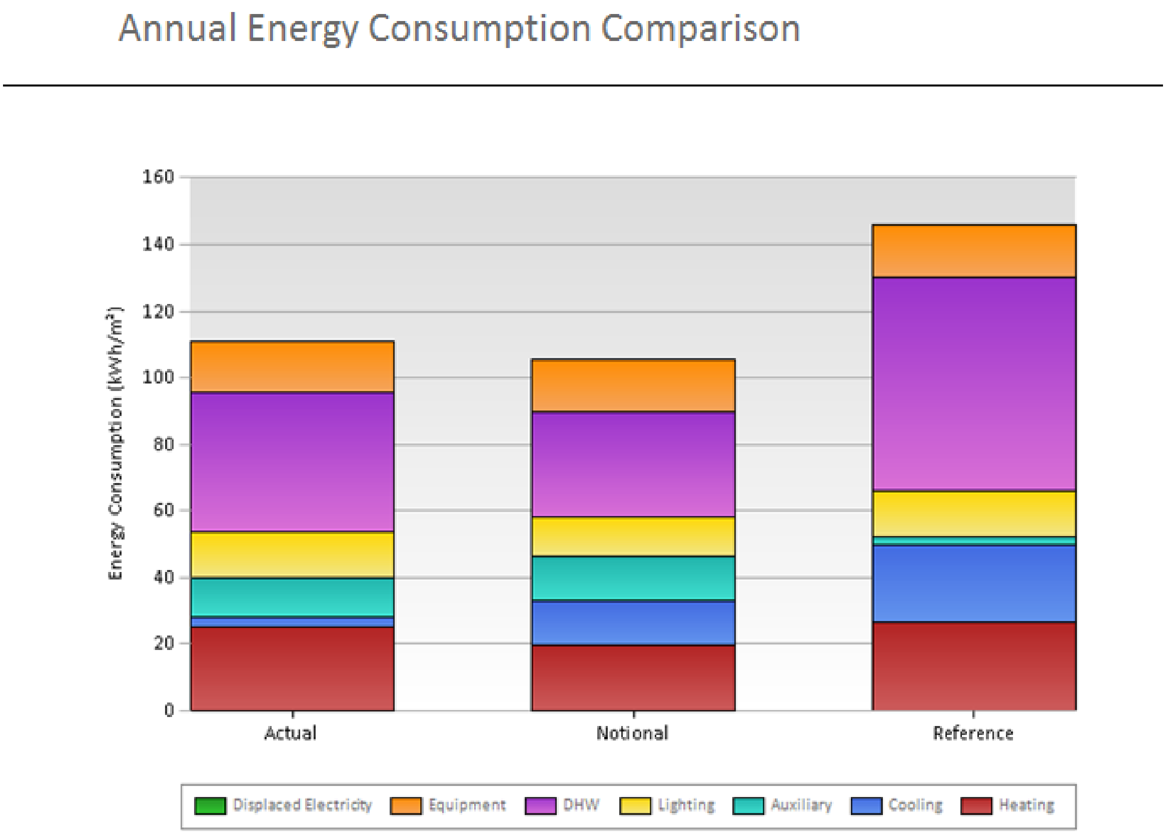


Figure 6.3 Modelling Results Rear and Side Elevation

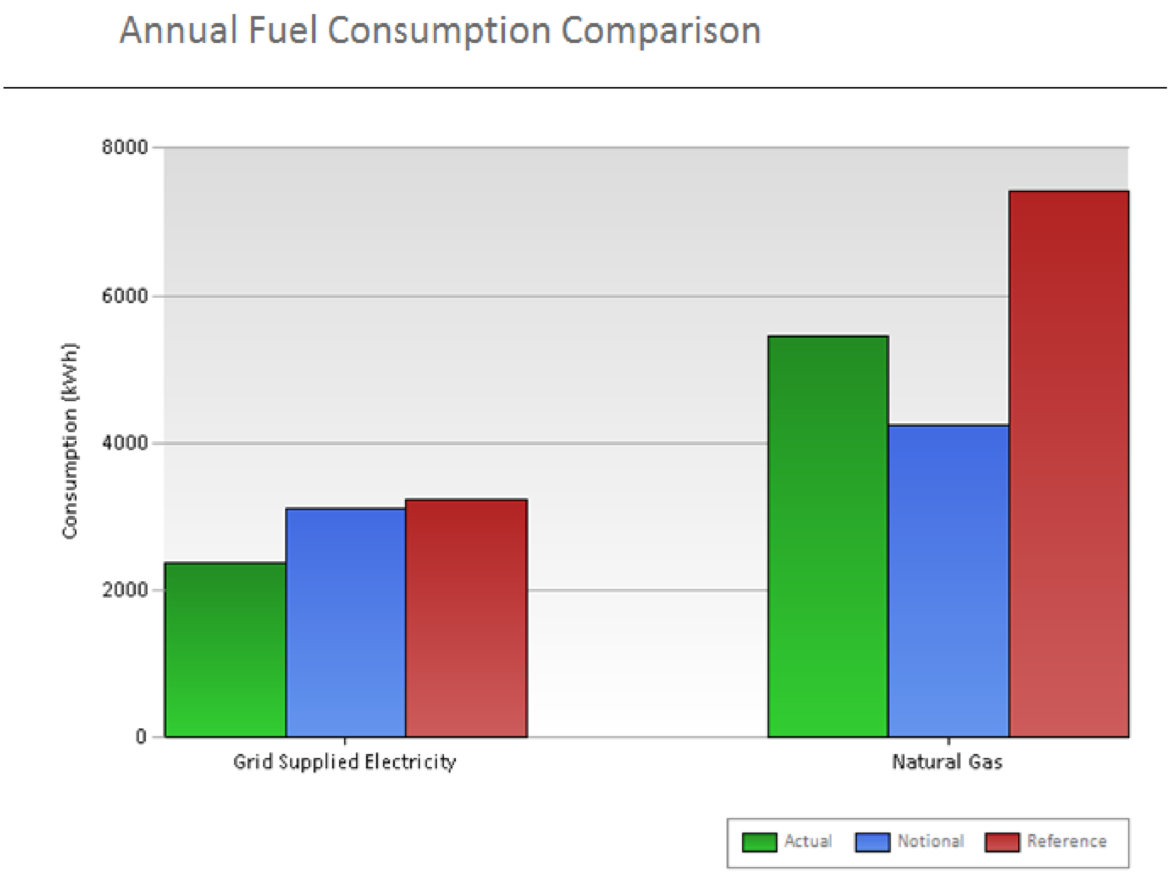
Figures 6.4 to 6.8 show typical TAS results of a simulation information using the UK building Studio 2010 of the building performance indicators earmarked for the study. Figure 6.4 shows the Part L (of the Building Regulations for England and Wales) and Energy Performance Certificate (EPC) reports of total annual energy consumption comparison of actual, notional and reference buildings simulations of the Persimmon building type G, of which information is extracted for statistical analysis. The total annual energy consumption encompasses heating, auxiliary, lighting, domestic hot water (DHW) and equipment energy usage.



	Actual	*Notional*	*Reference*
Heating (kWh/m²)	24.91	19.92	26.39
Cooling (kWh/m²)	3.41	13.03	23.18
Auxiliary (kWh/m²)	11.52	13.16	2.54
Lighting (kWh/m²)	14.06	11.88	13.71
DHW (kWh/m²)	41.57	31.79	64.29
Equipment (kWh/m²)	15.66	15.66	15.66
Displaced Electricity (kWh/m²)	0.00	0.00	0.00
Total (kWh/m²)	111.13	105.44	145.77
Total Floor Area (m²)	81.81	81.81	81.81

Figure 6.4 Annual Energy Consumption Comparison

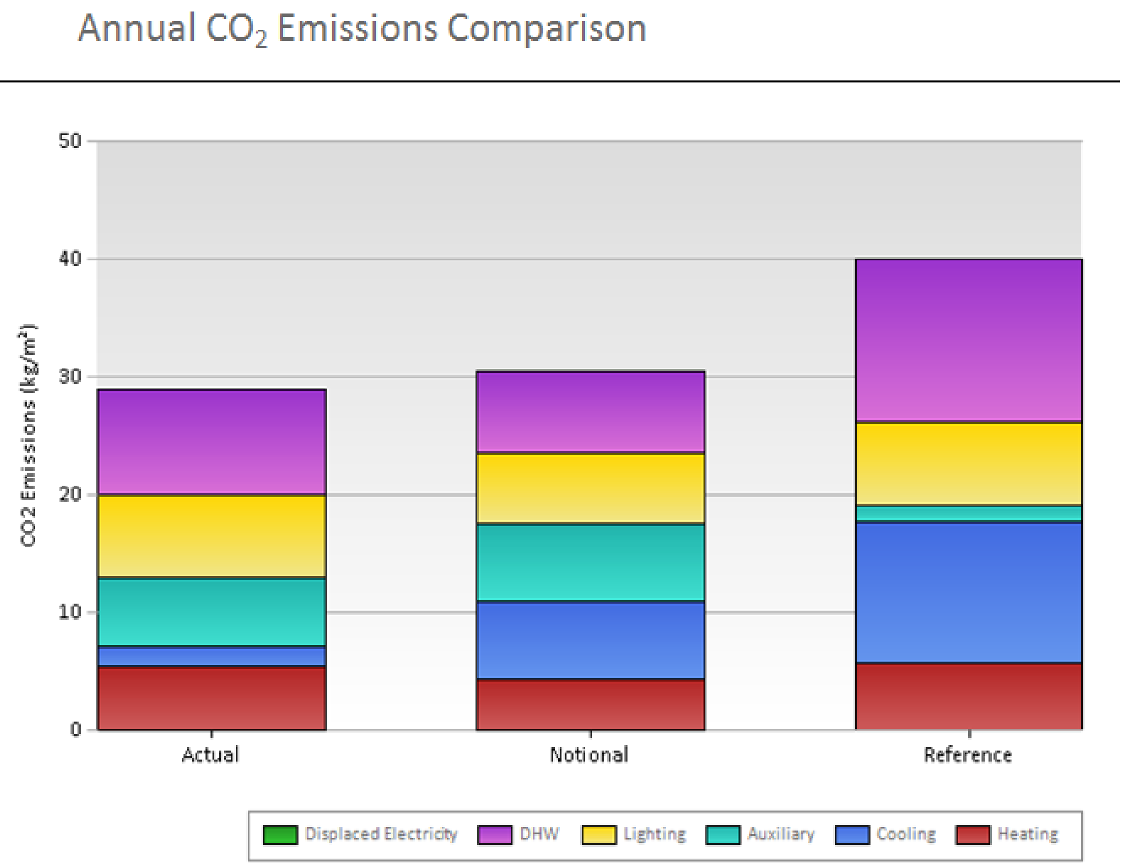
From Figure 6.4, the auxiliary energy is the additional electric energy consumed by fans and pumps of the heat ventilation air-conditioning (HVAC) systems. The domestic hot water (DHW) is basically the hot water consumption rates in relation to each zone activity. The equipment energy is the consumption due to household appliances, whilst the displaced electricity is the renewable energy configuration, for example the use of solar photovoltaic panels to displace the utility power. Figure 6.5 shows the Part L and EPC report on annual fuel (natural gas and grid supplied electricity) consumption comparison of actual, notional and reference buildings simulations of which information is extracted for statistical analysis.



	Actual	*Notional*	*Reference*
Grid Supplied Electricity (kWh)	2371.75	3114.23	3225.56
Natural Gas (kWh)	5439.12	4230.84	7418.81

Figure 6.5 Annual Fuel Consumption Comparison

6.6 shows the Part L and EPC report on carbon dioxide emission comparison of actual, notional and reference buildings simulations of which information is extracted for statistical analysis.



	Actual	*Notional*	*Reference*
Heating (kgCO2/m²)	5.38	4.30	5.70
Cooling (kgCO2/m²)	1.72	6.59	12.03
Auxiliary (kgCO2/m²)	5.83	6.66	1.32
Lighting (kgCO2/m²)	7.12	6.01	7.11
DHW (kgCO2/m²)	8.98	6.87	13.89
Displaced Electricity (kgCO2/m²)	0.00	0.00	0.00
*Equipment (kgCO2/m²) **	*7.92*	*7.92*	*8.13*
Total (kgCO2/m²)	29.03	30.43	40.05
Total Floor Area (m²)	81.81	81.81	81.81

** Energy used by equipment does not contribute to total value - it is presented here for comparison only*

Figure 6.6 Annual CO2 Emissions Comparison

Table 6.1 shows an extract of the Building Regulations United Kingdom part L (BRUKL) output document showing the energy and emission summary of which information is extracted for statistical analysis.

Table 6.1 Energy and CO2 Emissions Summary

	Actual	**Indicative Target**
Heating + Cooling Demand [MJ/m^2]	113.76	121.9
Total Consumption [kWh/m^2]	97.52	103.26
Total emissions [kg/m^2]	25.8	27.1

6.3.1 Statistical Analysis of the key performance indicators

The results of the variations of the key performance indicators of the 13 different sets of simulation of the current and the future weather data of the ten detached dwellings are extracted and tabulated below in table 6.2. The table shows the percentage variations of the building performance indicators using the future weather data timelines scenarios when compared to the current weather data.

Figures 6.7 to 6.11 give the detailed statistical results of the key performance building indicators of total annual energy consumption, annual natural gas comparison, annual electricity grid comparison, building emission rate and building heating demand of Persimmon South East Ltd Sheppey General Hospital dwelling 0712 House Type G Private.

Table 6.2a Timeline variance of Annual Energy, Natural Gas and Electricity

House Type	Total Annual Energy Consumption (kWh/m^2)			Annual Natural Gas Consumption (kWh)			Annual Electricity Grid Consumption (kWh)		
	% Dec 2020	% Dec 2050	% Dec 2080	% Dec 2020	% Dec 2050	% Dec 2080	% Inc 2020	% Inc 2050	% Inc 2080
A	2.73	6.44	10.30	4.40	10.38	16.63	0.53	5.41	18.36
F	2.72	6.46	10.43	4.17	9.94	16.09	0.36	3.67	12.47
E	2.71	6.49	10.47	4.31	10.33	16.70	0.35	3.58	12.15
G	2.75	6.32	10.19	4.35	10.00	16.14	0.36	3.64	12.36
H1	2.84	6.65	10.74	4.31	10.12	16.35	0.34	3.41	11.59
N	2.90	6.85	11.14	4.25	10.03	16.36	0.28	2.86	9.70
H2	2.76	6.60	10.64	4.18	9.98	16.14	0.34	3.41	11.59
K	2.67	6.20	9.88	4.19	9.75	15.63	0.32	3.20	10.87
M	3.08	7.17	10.74	4.46	10.40	15.62	0.31	3.12	10.60
P	2.89	6.85	11.07	3.75	8.90	14.42	0.25	2.49	8.46
Average	2.80	6.60	10.56	4.25	9.98	16.01	0.34	3.48	11.82

Table 6.2b Timeline variance of Building Emission Rate and Heating Demand

House Type	Building Emission Rate (KgCO$_2$/m^2)			Heating Demand (MJ/m^2)			Heating + Cooling Demand (MJ/m^2)		
	% Dec 2020	% Dec 2050	% Dec 2080	% Dec 2020	% Dec 2050	% Dec 2080	% Inc 2020	% Inc 2050	% Inc 2080
A	2.94	5.54	7.04	8.20	19.28	30.58	0.45	3.98	6.90
F	3.50	6.58	8.37	7.77	18.31	29.36	0.54	4.73	8.21
E	3.38	6.37	8.10	8.00	19.11	30.49	0.52	4.57	7.94
G	3.53	6.64	8.44	8.18	18.73	29.87	0.54	4.77	8.28
H1	3.65	6.88	8.75	7.59	17.80	28.41	0.56	4.94	8.58
N	3.09	5.83	7.41	7.90	18.66	30.10	0.47	4.18	7.26
H2	3.65	6.88	8.75	6.82	17.17	27.79	0.56	4.94	8.57
K	3.93	7.41	9.42	8.43	19.48	30.66	0.60	5.32	9.23
M	3.03	5.71	7.26	7.68	17.80	28.48	0.47	4.10	7.12
P	3.87	7.29	9.28	7.60	17.99	28.88	0.59	5.24	9.09
Average	3.46	6.51	8.28	7.82	18.43	29.46	0.53	4.68	8.12

6.3.1.1 Percentage of Total Annual Energy Consumption Reduction

The annual energy consumption for current and the future climate variables at different timelines of 2020s, 2050s and 2080s with their respective four carbon scenarios of high, medium-high, medium-low and low all show a progressive decrease variability. This declining trend is observed in all the ten building prototypes with an average percentage decrease of 2.80, 6.60 and 10.56 for 2020s, 2050s and 2080s time lines respectively. This decline is in consonance with the range of annual average temperature change predicted by the GCM based on the IPCC scenarios (IPCC, 2001) which generally shows an increase in temperature over stipulated timelines.

Total Annual Energy Consumption (kWh/m^2)

	Current	2020s	2050s	2080s		% Dec 2020s	% Dec 2050s	% Dec 2080s
High Try	113.18	109.85	104.17	97.86		2.94	7.96	13.54
Med High Try	113.18	110.05	105.70	100.02		2.77	6.61	11.63
Med Low Try	113.18	110.05	106.69	103.75		2.77	5.73	8.33
Low Try	113.18	110.30	107.53	104.97		2.54	4.99	7.25
					Mean % Dec	2.75	6.32	10.19
					Std. Dev	0.16	1.28	2.91

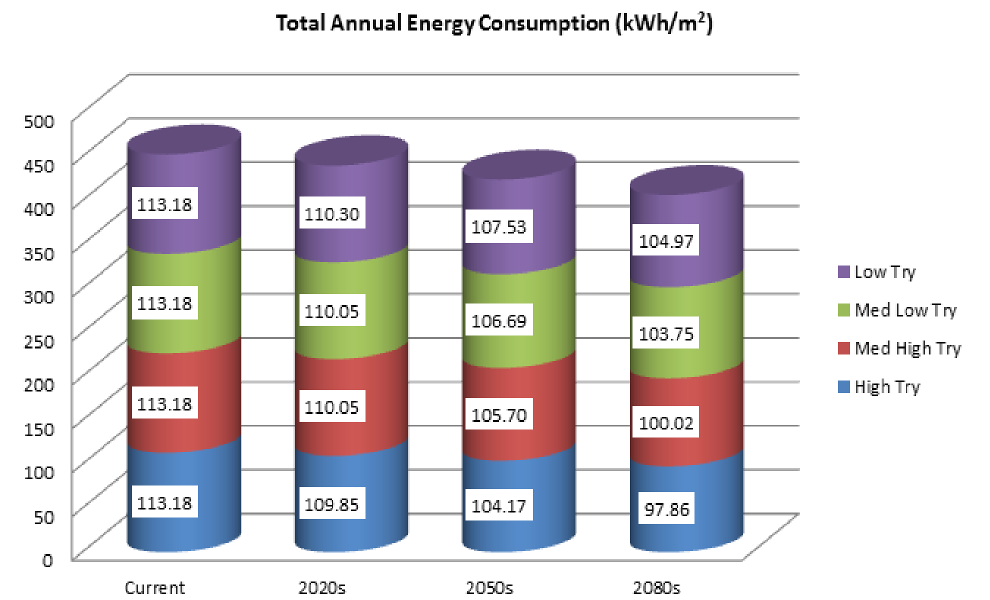


Figure 6.7 Total Annual Energy Consumption Analysis

6.3.1.2 Percentage of Annual Natural Gas Consumption Reduction

The annual natural gas consumption for current and the future climate variables at different timelines of 2020s, 2050s and 2080s with their respective four carbon scenarios of high, medium-high, medium-low and low all also show a progressive decrease variability. This declining trend is also observed in all the ten building prototypes with an average percentage decrease of 4.24, 9.98 and 16.1 for 2020s, 2050s and 2080s timelines respectively. This decline is also seen to be in consonance with the range of annual average temperature change predicted by the GCM based on the IPCC scenarios (IPCC, 2001) which generally shows an increase in temperature over stipulated timelines. Increase in future temperature would obviously lead in the decrease in gas consumption. Gas is mainly used in domestic heating.

Annual Natural Gas Comparison (kWh)

	Current	2020s	2050s	2080s	% Dec 2020s	% Dec 2050s	% Dec 2080s
High Try	5868.59	5595.84	5129.20	4607.71	4.65	12.60	21.49
Med High Try	5868.59	5611.88	5255.95	4786.75	4.37	10.44	18.43
Med Low Try	5868.59	5611.88	5336.93	5094.49	4.37	9.06	13.19
Low Try	5868.59	5632.83	5405.58	5196.36	4.02	7.89	11.45
Mean % Dec					4.35	10.00	16.14
Std. Dev					0.26	2.02	4.64

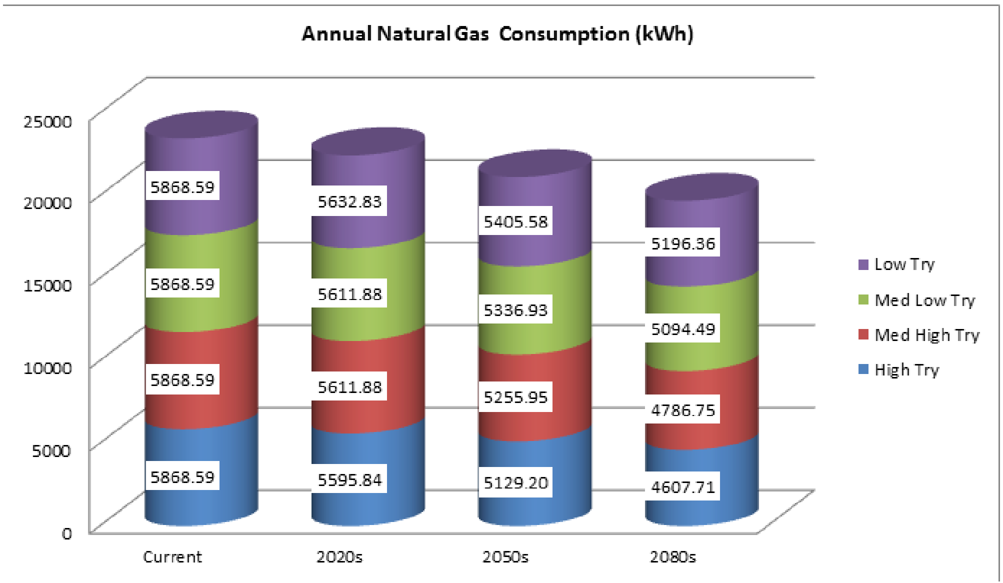


Figure 6.8 Annual Natural Gas Comparison Analysis

6.3.1.3 Annual Electricity Grid Comparison Analysis

The annual electricity grid consumption when cooling is introduced for current and the future climate variables at different timelines of 2020s, 2050s and 2080s with their respective four carbon scenarios of high, medium-high, medium-low and low all also show an observable relatively increase variability in consumption over the stipulated timelines. This increasing trend is observed in all the ten building prototypes with an average percentage increase of 0.34, 3.48 and 11.82 for 2020s, 2050s and 2080s timelines respectively.

Annual Electricity Grid Comparison (kWh)

	Current	2020s	2050s	2080s		% Inc 2020s	% Inc 2050s	% Inc 2080s
High Try	2106.06	2117.27	2188.44	2371.75		0.53	3.91	12.62
Med High Try	2106.06	2115.20	2184.20	2368.84		0.43	3.71	12.48
Med Low Try	2106.06	2112.20	2180.22	2366.10		0.29	3.52	12.35
Low Try	2106.06	2110.20	2177.80	2359.20		0.20	3.41	12.02
					Mean % Inc	0.36	3.64	12.36
					Std. Dev	0.15	0.22	0.25

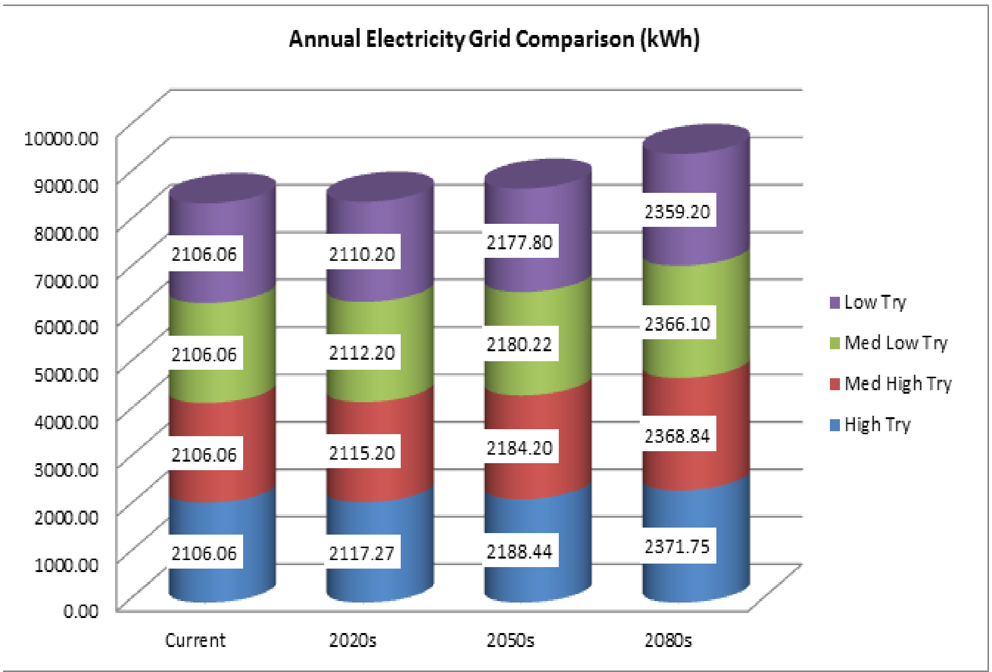


Figure 6.9 Annual Electricity Grid Comparison Analysis

6.3.1.4 Percentage of Building Emission Reduction

The trend of building emission rate for the current and the future climate variables at different timelines of 2020s, 2050s and 2080s with their respective four carbon scenarios of high, medium-high, medium-low and low all also show a progressive decrease variability. This declining trend is also observed in all the ten building prototypes with an average percentage decrease of 3.46, 6.51 and 8.28 for 2020s, 2050s and 2080s time lines respectively. This decline is also seen to be in consonance with the range of annual average temperature change predicted by the GCM based on the IPCC scenarios (IPCC, 2001) which generally shows an increase in temperature over stipulated timelines. Increase in future temperature would obviously lead in less building emission rate.

Building Emission Rate ($KgCO_2/m^2$)

	Current	2020s	2050s	2080s		% Dec 2020s	% Dec 2050s	% Dec 2080s
High Try	31.70	30.30	29.30	29.00		4.42	7.57	8.52
Med High Try	31.70	30.56	29.62	29.37		3.60	6.56	7.35
Med Low Try	31.70	30.66	29.66	29.40		3.28	6.44	7.26
Low Try	31.70	30.81	29.80	29.59		2.81	5.99	6.66
					Mean % Dec	3.53	6.64	7.44
					Std. Dev	0.68	0.67	0.78

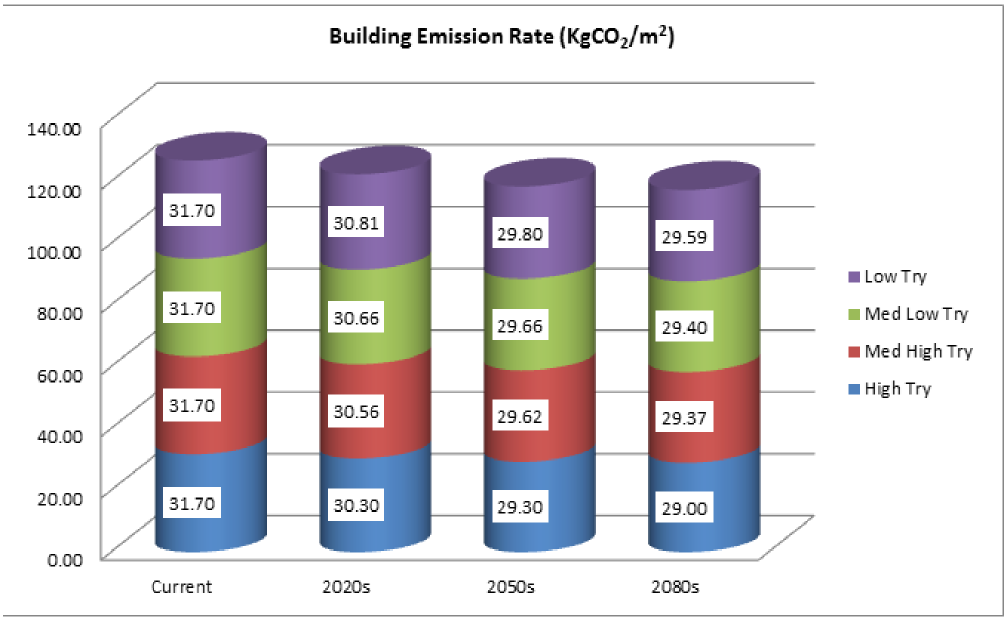


Figure 6.10 Building Emission Rate Analysis

6.3.1.5 Percentage of Energy Demand – Heating and Cooling

The trend of heating demand for the current and the future climate variables at different timelines of 2020s, 2050s and 2080s with their respective four carbon scenarios of high, medium-high, medium-low and low all also show a progressive decrease variability in figure 6.11(a). This declining trend is also observed in all the ten building prototypes with an average percentage decrease of 7.82, 18.43 and 29.46 for 2020s, 2050s and 2080s timelines respectively. This decline is also seen to be in consonance with the range of annual average temperature change predicted by the GCM based on the IPCC scenarios (IPCC, 2001) which generally shows an increase in temperature over stipulated timelines. The study therefore points to the fact that increase in future temperature due to climatic variation would obviously have a significant declining impact on heating demand.

However, with the introduction of cooling to offset overheating risk, the trend of heating and cooling demand for the current and the future climate variables at different timelines of 2020s, 2050s and 2080s with their respective four carbon scenarios of high, medium-high, medium-low and low all shows a progressive increase variability in figure 6.11(b). This declining trend is also observed in all the ten building prototypes with an average percentage increase of 0.53, 4.68 and 8.12 for 2020s, 2050s and 2080s timelines respectively. It is therefore observed that the introduction of cooling cancels out the energy gains related to heating due to future climatic variability. The average cooling energy demand to offset overheating for the ten building prototypes was observed to be 2.7, 12.64, 29.56 and 46.33 MJ/m^2 for the current, 2020s, 2050s and 2080s timelines respectively.

Heating demand (MJ/m^2)

	Current	2020s	2050s	2080s		% Dec 2020s	% Dec 2050s	% Dec 2080s
High Try	113.76	103.82	87.08	68.90		8.74	23.45	39.43
Med High Try	113.76	104.40	91.44	75.06		8.23	19.62	34.02
Med Low Try	113.76	104.40	94.39	85.86		8.23	17.03	24.53
Low Try	113.76	105.19	96.91	89.28		7.53	14.81	21.52
					Mean % Dec	8.18	18.73	29.87
					Std. Dev	0.49	3.71	8.31

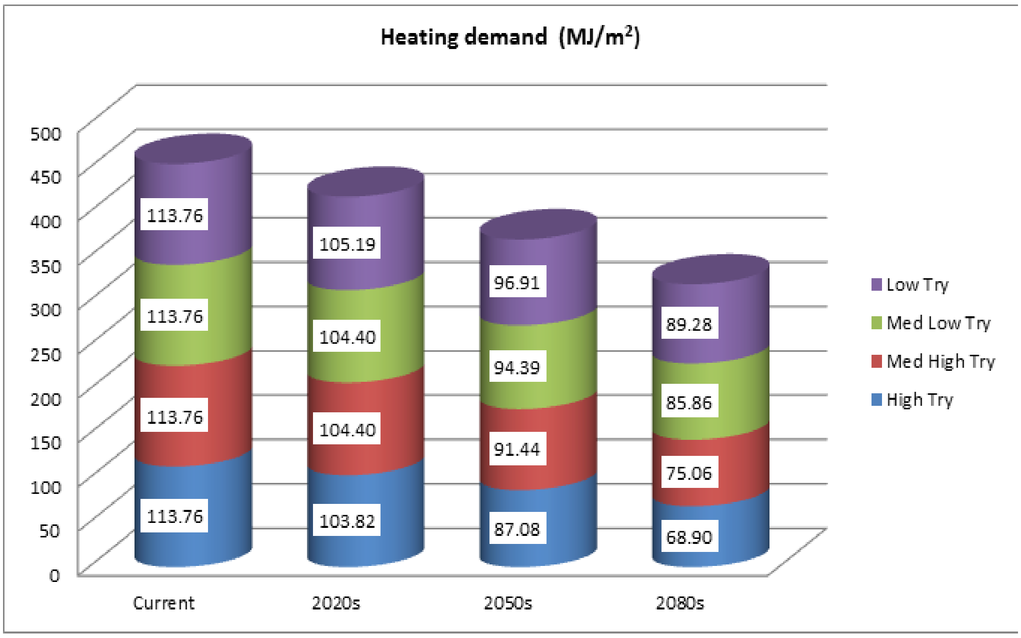


Figure 6.11(a) Heating Demand Analysis

However, this scenario may lead to the influence of increased cooling demand for occupancy comfort. Thermal comfort depends on four basic environmental factors of air temperature, radiant temperature, air velocity and relative humidity. One of the main functions of residential buildings is to provide healthy and comfortable environments to the occupants. Buildings must therefore be designed and built by taking cognisance of the physiological reactions of the occupants due to temperature and humidity tolerance of occupants. The study therefore lends itself to overheating analysis to ascertain the need of cooling demand in the United Kingdom with future prediction of increasing temperature.

Heating & Cooling demand (MJ/m^2)

	Current	2020s	2050s	2080s		% Inc 2020s	% Inc 2050s	% Inc 2080s
High Try	116.46	117.63	123.28	128.87		1.00	5.86	10.66
Med High Try	116.46	117.10	122.44	126.02		0.55	5.13	8.21
Med Low Try	116.46	116.84	121.63	125.30		0.33	4.44	7.59
Low Try	116.46	116.79	120.71	124.21		0.28	3.65	6.65
					Mean % Inc	0.54	4.77	8.28
					Std. Dev	0.33	0.94	1.71

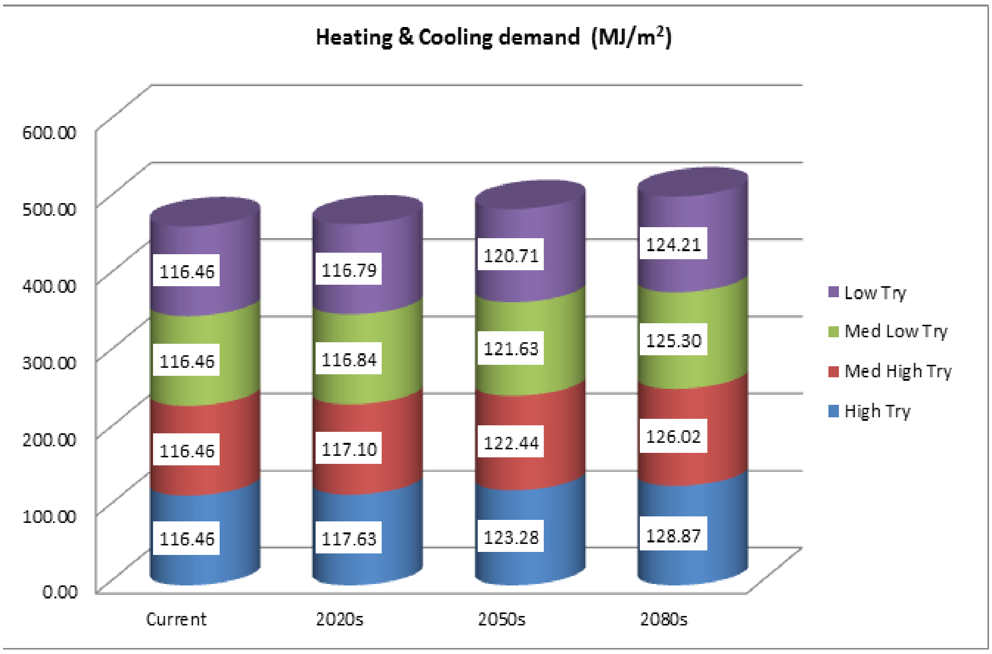


Figure 6.11(b) Heating and Cooling Demand Analysis

6.3.2 Heating and Cooling Demand Analysis

Simulations were therefore run for the current weather data scenario and the worst case scenario of increase temperature of 2080s high DSY. The results are presented in Figures 6.12 to 6.19 which show variations in temperature and loads, radiant temperatures, humidity and loads, and total load profile for all zones between June 1 and August 31 – the three warmest months of the year with clear sky - for the current weather and the 2080s high DSY data sets.

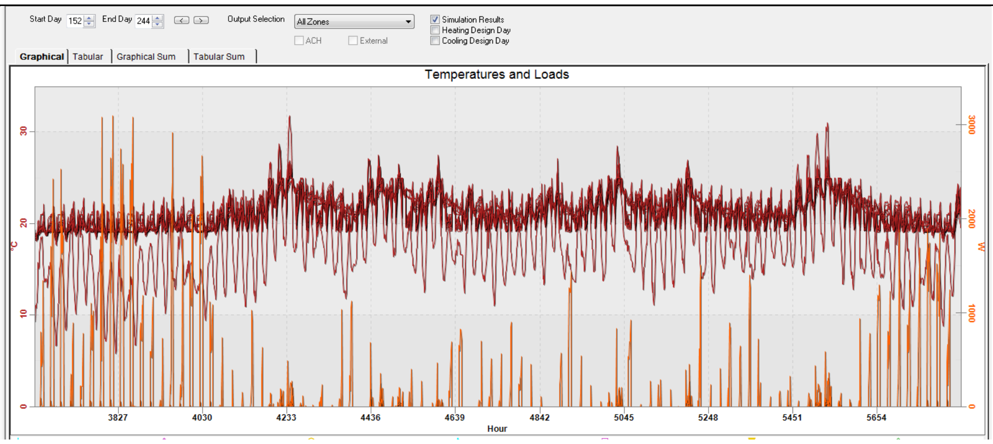


Figure 6.12 Temperature and Loads Analysis - Current weather data All Zones

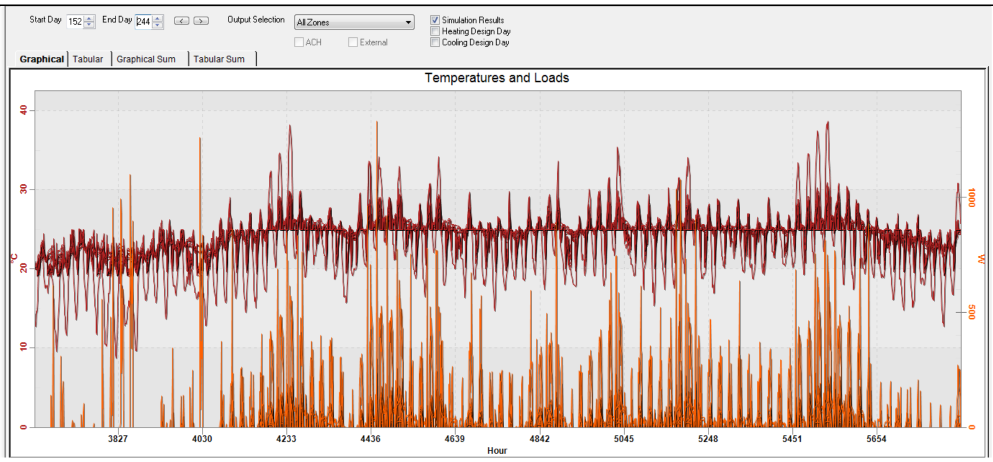


Figure 6.13 Temperature and Load Analysis - 2080s High DSY All Zones

A comparison of the variability of the temperature and loads analysis in Figures 6.12 and 6.13 shows a rise in the radiant temperatures from the current weather data to the worst case scenario, 2080s high DSY. In TAS system, the radiant temperature simulation takes into consideration the external temperature, the mean radiant temperature and the resultant temperature. Radiant temperature has more impact to body temperature variation than air temperature. Figures 6.12 and 6.16 when compared to Figures 6.17 and 6.19 give the ranges of radiant temperatures ranging from $6^{\circ}C$ to $32^{\circ}C$ with relatively few periods going above

28°C mark (CIBSE 'Guide A' (2006) maximum threshold above which majority of people in a building will begin to experience discomfort) for the current weather data set and from 8°C to 38°C with relatively increase in periods for the worst case scenario of 2080s high DSY for the specified period of analysis respectively.

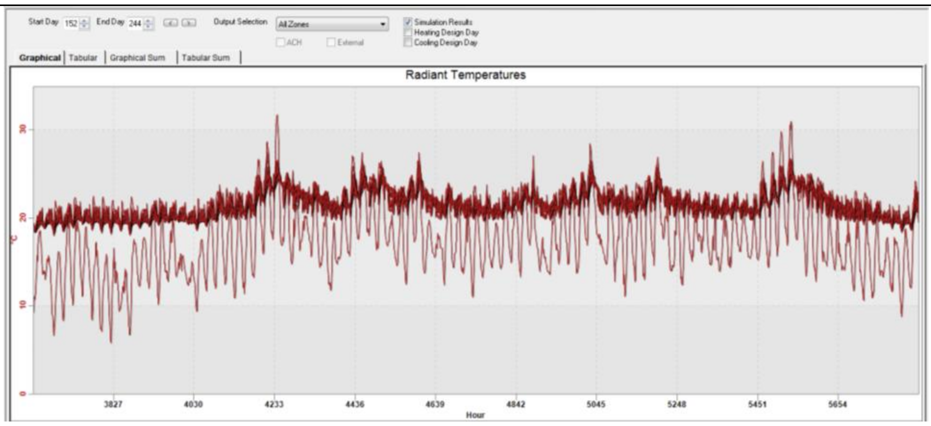


Figure 6.14 Radiant Temperature Analysis - Current weather data All Zones

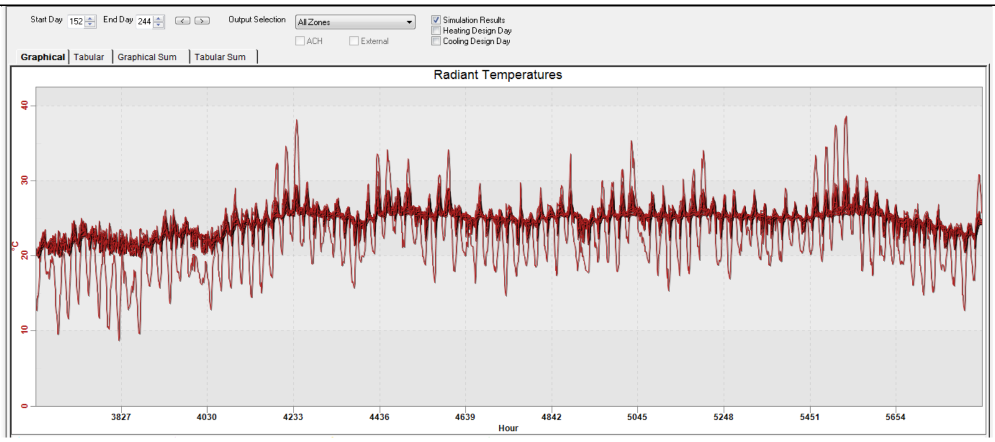


Figure 6.15 Radiant Temperature Analysis - 2080s High DSY All Zones

Climate factors of temperature and relative humidity are keys to determine thermal comfort of building occupants. The thermal environmental conditions for human occupancy standards are set out in the European Committee for Standardization (CEN), the International Organisation for Standardization (ISO) and American

Standards of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (Boduck and Fincher 2009).

Currently, majority of buildings in the United Kingdom are cooled in summer by opening windows. No mechanical cooling is applied in many new dwellings during summer as most naturally ventilated buildings are free-running non air-conditioned buildings. The average monthly maximum temperature range for the three warmest months in the year in England from 1981 to 2010 is observed to be between 18.6^{o}C and 20.7^{o}C, and 20.2^{o}C to 22.6^{o}C for London; temperatures in England being higher than the rest of United Kingdom (Met Office, 2013).

The European Committee for Standardization sets the recommended criteria for the indoor temperature of a dwelling based on a running mean outside temperature as between 18°C to 27°C for all categories of residential buildings and 2 °C to 26°C for normal level of expectation recommended for new buildings and renovations (EN 15251 CEN, 2007). The ASHRAE's Standard 55, Thermal Environmental conditions for Human Occupancy, stipulates the guideline room air temperatures for residences during summer to be in the range of 23°C to 26°C (ASHRAE Standard 55, 1992).

The 2080s high DSY worst case scenario with the temperature range of °C to 38°C and the mean temperature of about 26 °C indicates that the future length of cooling season may slightly increase, which might therefore necessitate the use of room conditioning systems to keep the indoor temperatures at specified levels to provide heat balance or thermal comfort.

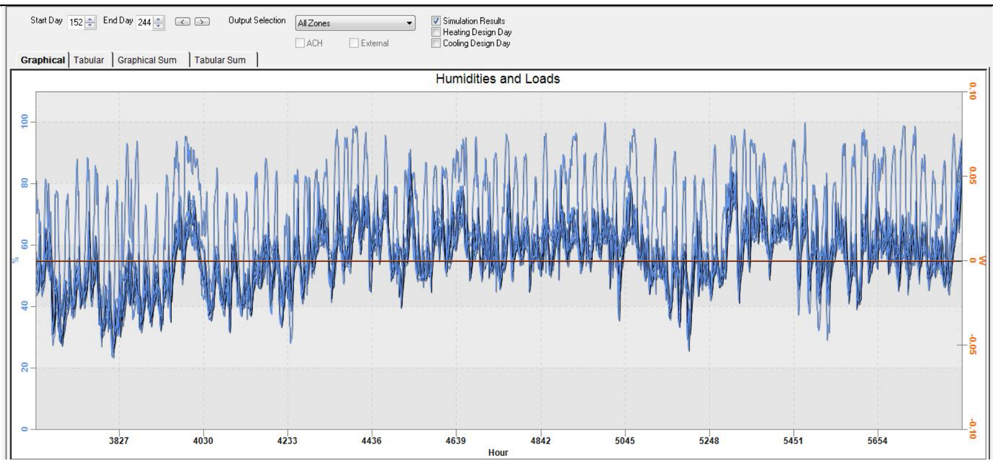


Figure 6.16 Humidity and Load Analysis - Current weather data All Zones

A comparison of figures 6.16 and 6.17 give the variability of humidity and load analysis within the specified period. In the TAS system, simulation of the humidities and loads takes into consideration the external humidity, relative humidity, latent removal load and latent addition load. Figure 6.16 shows humidity range variability between 25% and 98% with most relative humidity between 40% and 60%. Figure 6.17 gives the range variability to be between 20% and 96% with most relative humidity values between 38% and 58%. The higher the humidity the less evaporation of sweat, thus high levels of relative humidity leads to less body evaporation resulting in minimal cooling of the body. The converse leads to skin dryness and dryness and irritation of the eyes, throat and nose (Boduch and Fincher, 2009). Relative humidity between 40% and 70% has little impact on thermal comfort (Thermal Comfort 2013). The base line for thermal comfort with reference to relative humidity is set within the range of 25% and 60% (Boduch and Fincher 2009). The International Organization for Standardization ISO 7730:2005 stipulates that humidity impact is limited at temperatures less than 26 °C considering moderate activity levels (ISO 7730:2005). Unlike temperature effect on heat balance, thermal comfort is expressed over a wide range of relative humidity conditions. With this wide range, variability of relative humidity, unlike temperature, has only a minimal effect on thermal comfort (EN 15251 CEN, 2007). Thus although there is evidence of some reduction in humidity in the worst case scenario of 2080s high DSY, the variability does not suggest a great shift to cooling demands.

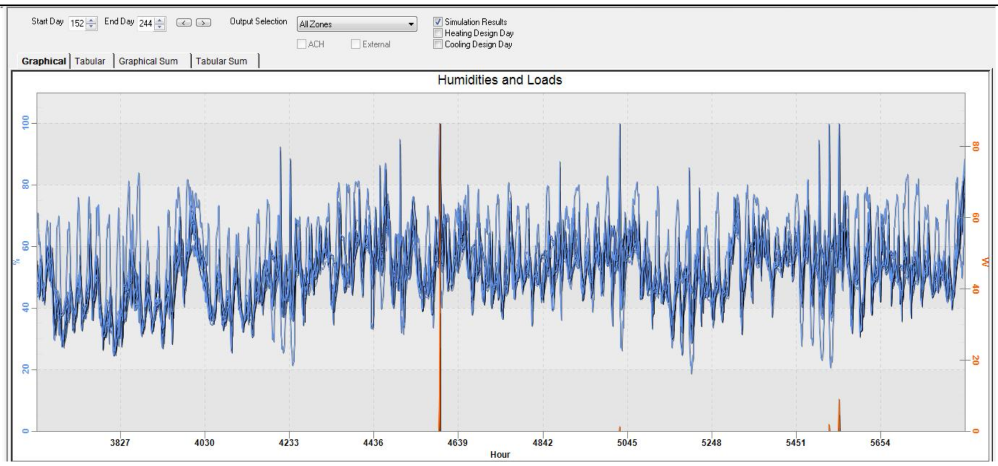


Figure 6.17 Humidity and Load Analysis - 2080s High DSY All Zones

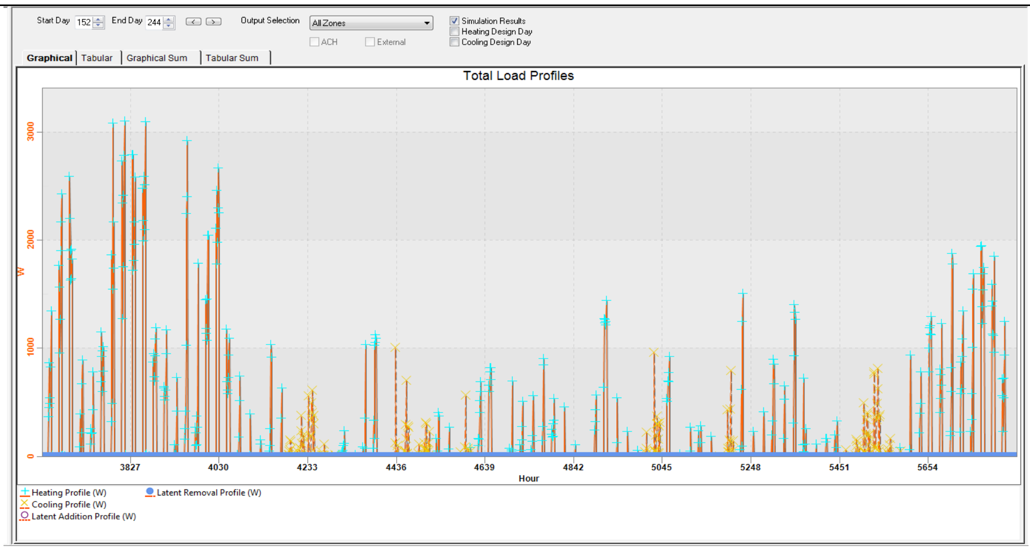


Figure 6.18 Total Load Profiles Analysis - Current weather data All Zones

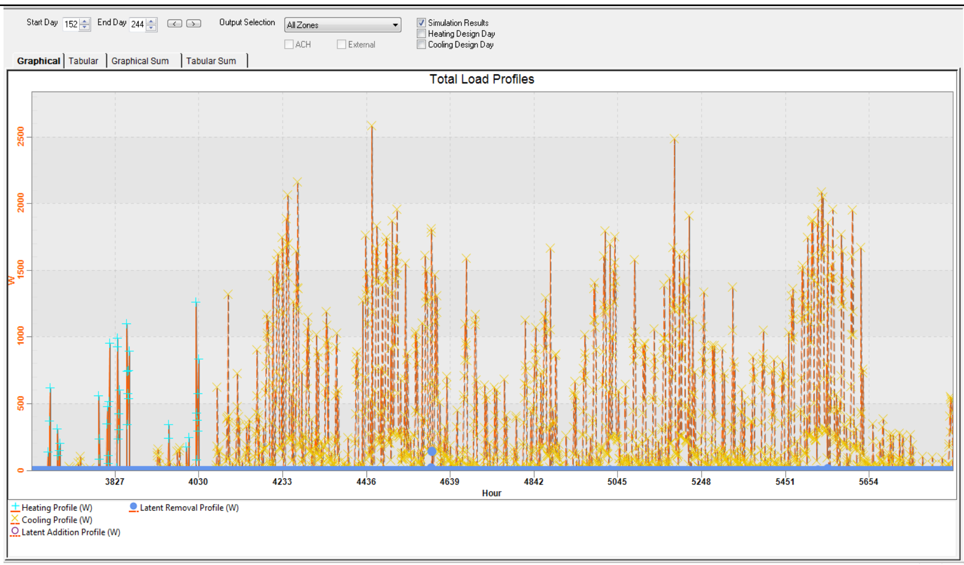


Figure 6.19 Total Load Profiles Analysis - 2080s High DSY All Zones

A comparison of figures 6.18 and 6.19 give the total load profiles of heating and cooling loads for the specified period of analysis. The variability of the total load profiles in the current weather data scenario shows more of heating load profile with relatively little cooling load profile. The converse is observed in the worst case scenario of 2080s high DSY. The TAS system simulates sensible heat but not latent heat. Sensible heating or cooling process of air is related to the dry heat causing change in temperature but does not affect the moisture content of the air. However, latent heating or cooling process of air is the heat supplied or removed from air which leads to a change of moisture content but does not affect the air temperature. Factors which influence the sensible cooling in the TAS system includes gains in solar, lighting, air movement, vent, occupant sensible, equipment sensible and building heat transfer, external conduction opaque and external conduction glazing.

6.4 Summary and Conclusion

The study investigated the variability of future climatic conditions on newly built detached dwellings in the United Kingdom. Analysis of simulation results leads to the predicting of consistent declining trend of annual building energy consumption, annual building natural gas consumption, building emission rate and heating demand but with no change in annual electricity grid consumption over the different timelines of 2020s, 2050s and 2080s used in the simulation.

The average percentage decrease for the annual energy consumption for current and future weather data set in the absence of cooling observed in all the ten building prototypes was 2.80, 6.60 and 10.56 for 2020s, 2050s and 2080s timelines respectively. A similar declining trend in the case of annual natural gas consumption was 4.24, 9.98 and 16.1, and that for building emission rate and heating demand were 2.27, 5.49 and 8.72 and 7.82, 18.43 and 29.46 for 2020s, 2050s and 2080s timelines respectively. These declines are in consonance with the range of annual average temperature change predicted by the GCM based on the IPCC scenarios which generally shows an increase in temperature over stipulated timelines. The average percentage increase for heating and cooling demand was predicted to be 0.53, 4.68 and 8.12. The overheating risk and its implication to cooling energy demand indicate that the average cooling energy demand to offset overheating for the ten building prototypes was observed to be 2.7, 12.64, 29.56 and 46.33 MJ/m^2 for the current, 2020s, 2050s and 2080s timelines respectively.

Analysis of the future heating and cooling demands of the three warmest months of the year with clear sky for the current weather and the worst case scenario data sets showed a reduction in humidity in the worst case scenario. However, the variability does not suggest a shift to cooling demands as the range falls within the thermal comfort relative humidity tolerance associated with the physiological reactions of the building occupants. The worst case scenario analysis of radiant temperature indicated that the future length of cooling season may increase, which might therefore necessitate the use of room conditioning systems to keep the indoor temperatures at specified levels to provide heat balance or thermal comfort.

The study thus establishes the significant impact of variability of climatic patterns on building performance taking cognizance of the future timelines which also coincides with building life span. It further confirms that predicted increase in future temperatures might result in reduction in energy use for space heating and emissions but conversely lead to the increase in cooling demand, thus offsetting the gains in heating demand. Increase in cooling demand has environmental implications as it results in increased electricity consumption leading to higher emissions.

This work has indicated that building performance simulation using variation of future climatic patterns can contribute to the reduction of the environmental implications to the built environment and facilitates the drive towards the attainment of future sustainability requirements. The focus on how to reduce cooling loads and improve building energy efficiency will challenge future innovative design and adapted technological process. These will augur for climatic adaptation and mitigation strategies to effectively meet the future demand in the built environment. The measures would include planning and design options sensitive to varying climatic conditions and resilient building design which incorporates improved and better façade and building envelope, passive design technologies and high efficient HVAC and radiant systems with the aim to eventually reduce future total energy demands in dwellings. In addition emphasis should be placed on behavioural adaptations of building occupants to re-conscientize them in controlling building performance.

This study has currently evaluated and quantified the impact of varying future climatic patterns on five key building performance indicators of newly built detached dwellings in the United Kingdom. It has further showed that future predicted temperature rise might result in the reduction in dwelling heating demand and might necessitate the increasing use of cooling systems.

CHAPTER 7: Impact of four standard construction specifications on thermal comfort in three major cities in the United Kingdom.

7.0 Case study 4: Impact of four standard construction specifications on thermal comfort on three major cities in the United Kingdom – Deterministic analytical approach based on CIBSE TM48 weather files.

7.1 Introduction

The quest for enhanced thermal comfort for dwellings encompasses the holistic utilization of improved building fabric, impact of weather variation and amongst passive cooling design consideration the provision of appropriate ventilation and shading strategy. Whilst thermal comfort is prime to dwellings' considerations, limited research has been done in this area with the attention focused mostly on non-dwellings. This study examines the current and future thermal comfort implications of four different standard construction specifications which show a progressive increase in thermal mass and airtightness and is underpinned by the newly developed CIBSE adaptive thermal comfort method for assessing the risk of overheating in naturally ventilated dwellings. Interactive investigation on the impact of building fabric variation, natural ventilation scenarios, external shading and varying occupants' characteristics to analyse dwellings' thermal comfort based on non-heating season of current and future weather patterns of London, Birmingham and Glasgow is conducted.

Prior to the advent of the new CIBSE overheating criteria, the Zero Carbon Hub in conclusion after their work on overheating on a range of UK dwelling types indicated the need of a more robust tool for assessing overheating in buildings (ZCH, 2012). No research to the author's view has been done using the new CIBSE overheating criteria to holistically assess the thermal comfort of detached dwellings in the UK. This study therefore employed integrated passive cooling strategies of enhanced thermal mass, ventilation scenarios, different building locations and external shading, and a methodology that combines thermal analysis modelling and simulation coupled with the application of the newly developed CIBSE overheating criteria to investigate the thermal comfort in detached dwellings in the UK using the CIBSE high design summer year (DSY) emission scenarios for the current and future (2020s, 2050s and 2080s) climatic change projections.

The overheating analysis focuses on the whole building and individual zones. The findings from the thermal analysis simulation are illustrated graphically, coupled with statistical analysis of data collected from the simulation. The results indicated that the prime factor for the variation of indoor temperatures is the variability of climatic patterns.

In addition, London is observed to likely experience more risk of thermal discomfort than Birmingham and Glasgow over the time period for the analysis. The total number of zones failing 2 or 3 CIBSE TM52 overheating criteria is more in London than in Birmingham and Glasgow. The results further indicated that progressive increase in thermal mass decrease the indoor temperature swings but increase in future operative temperatures and night ventilation coupled with shading offered the best mitigation strategy in reducing indoor temperatures in London and Birmingham. These results indicate that, judicious integrated approach of improved design options could substantially reduce the operative temperatures in dwellings and enhance thermal comfort.

However, the converse is experienced in Glasgow as the effectiveness of optimum thermal mass design coupled with night ventilation and shading scenarios would be realised only when the diurnal variation of external temperatures exceeds 10^{o}C. Glasgow has moderate low summer temperatures when compared to London and Birmingham. This shows that inadequate thermal mass design could aggravate overheating risk.

7.2 Research Method 4 – For Case Study 4

Detailed method for case study 4 is discussed in chapter 3 section 3.2.6.

7.3 Results and Discussion

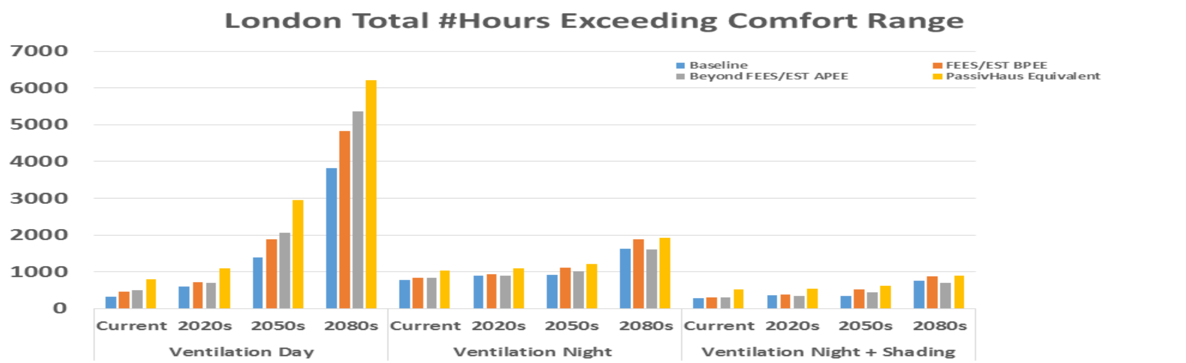
The analysis of building prototype - Persimmon South East Ltd Sheppey General Hospital dwelling 0712 House Type G Private - two-storey residential detached building is presented below. Figures 6.1 to 6.3 represent the outcome of the modelling process.

Appendix 7.1 to 7.12 show the Excel whole building analysis results of the four standardized construction specifications (Baseline, Fabric Energy Efficiency Standard/EST Best Practice Energy Efficiency Standard, Beyond Fabric energy Efficiency Standard/EST Advanced Practice Energy Efficiency Standard and the Passivhaus equivalent standard) effect on thermal comfort using the internal operative temperature as the overheating indicator based on CIBSE TM52 overheating criteria for London, Birmingham and Glasgow respectively, of all the simulation scenarios of progressive improvement of thermal mass, change of building location, different ventilation strategies, provision of external shading and variable occupant behaviour designated to optimize thermal comfort, the set goal for the study.

Figures 7.1 to 7.4 show analysis of operative temperatures in respective zones analysis results for London, Birmingham and Glasgow respectively based on the CIBSE TM52 results. Figures 7.5 to 7.8 show analysis of maximum, minimum, average and range operative temperatures in for the whole building analysis results for London, Birmingham and Glasgow respectively.

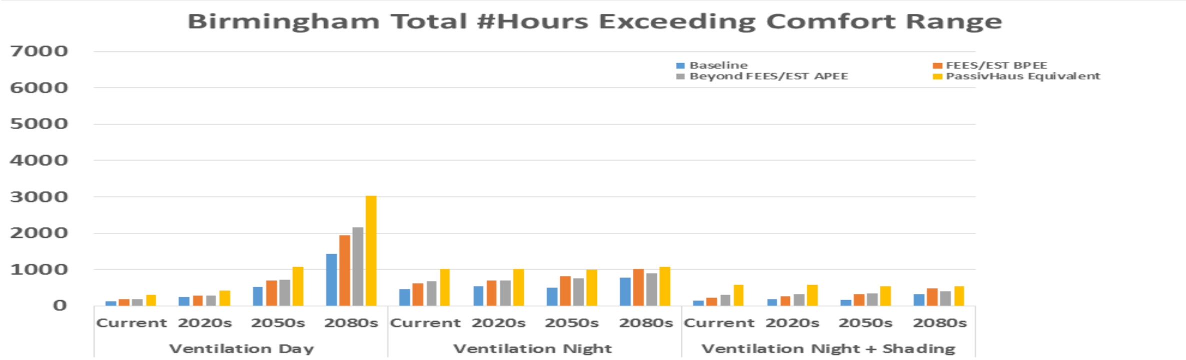
London Total #Hours Exceeding Comfort Range

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	317	586	1392	3821	771	884	911	1621	279	350	332	754
FEES/EST BPEE	464	707	1873	4826	825	925	1110	1883	294	374	510	880
Beyond FEES/EST APEE	502	691	2064	5362	824	889	1012	1606	296	336	429	686
PassivHaus Equivalent	784	1099	2941	6215	1030	1086	1206	1922	509	538	606	886



Birmingham Total #Hours Exceeding Comfort Range

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	126	237	514	1425	461	545	503	783	130	178	167	314
FEES/EST BPEE	187	285	689	1936	620	691	807	1019	215	250	318	467
Beyond FEES/EST APEE	177	276	714	2152	676	700	750	882	306	316	332	392
PassivHaus Equivalent	303	415	1067	3024	1004	1003	996	1070	580	571	539	544



Glasgow Total #Hours Exceeding Comfort Range

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	1	9	20	82	222	281	249	347	26	43	61	120
FEES/EST BPEE	6	16	48	145	388	408	449	526	146	162	208	262
Beyond FEES/EST APEE	1	8	28	110	462	490	504	551	259	257	275	288
PassivHaus Equivalent	10	27	59	153	813	823	784	779	530	527	509	477

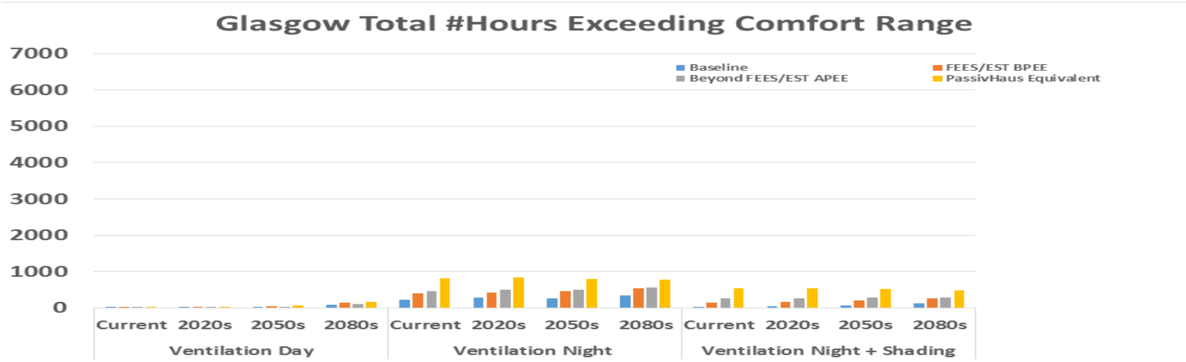
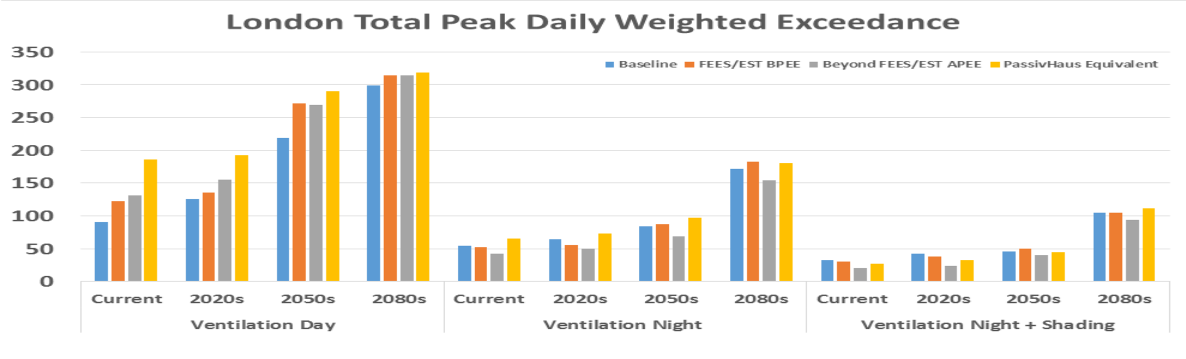


Figure 7.1 A comparison of internal operative temperatures total number of hours exceeding comfort range analysis of respective zone results for London, Birmingham and Glasgow respectively based on CIBSE TM52 adaptive thermal comfort criteria.

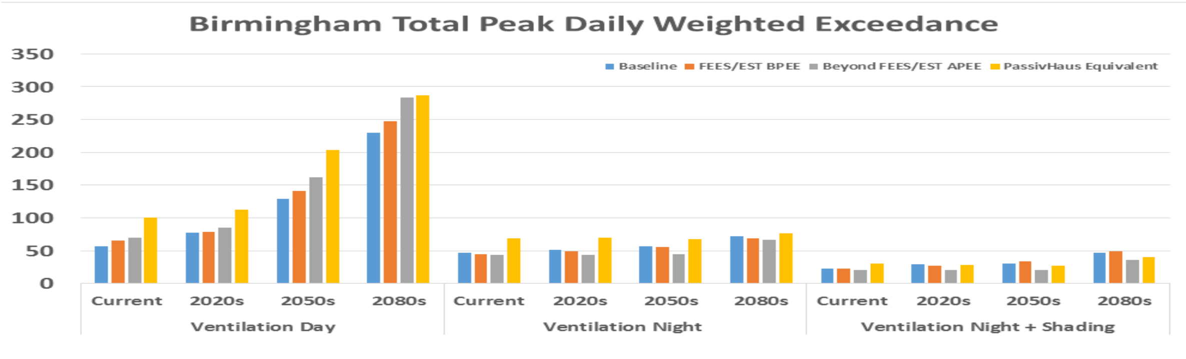
London Total Peak Daily Weighted Exceedance

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	91	126	219	299	54	64	84	172	33	42	46	105
FEES/EST BPEE	122	135	272	314	52	56	87	183	30	38	50	105
Beyond FEES/EST APEE	131	155	269	314	42	50	69	154	20	24	40	94
PassivHaus Equivalent	186	193	290	319	65	73	97	180	27	32	45	111



Birmingham Total Peak Daily Weighted Exceedance

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	57	77	129	230	47	51	57	72	23	29	30	47
FEES/EST BPEE	65	78	141	247	45	49	56	69	23	27	34	49
Beyond FEES/EST APEE	70	85	162	283	43	43	45	67	20	20	20	36
PassivHaus Equivalent	100	113	203	287	69	70	68	76	30	28	27	40



Glasgow Total Peak Daily Weighted Exceedance

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	1	5	8	24	40	44	40	45	11	12	14	16
FEES/EST BPEE	3	6	16	30	45	47	49	49	22	23	24	25
Beyond FEES/EST APEE	1	5	12	22	46	47	48	47	26	25	25	24
PassivHaus Equivalent	6	9	15	33	54	54	52	54	34	33	33	30

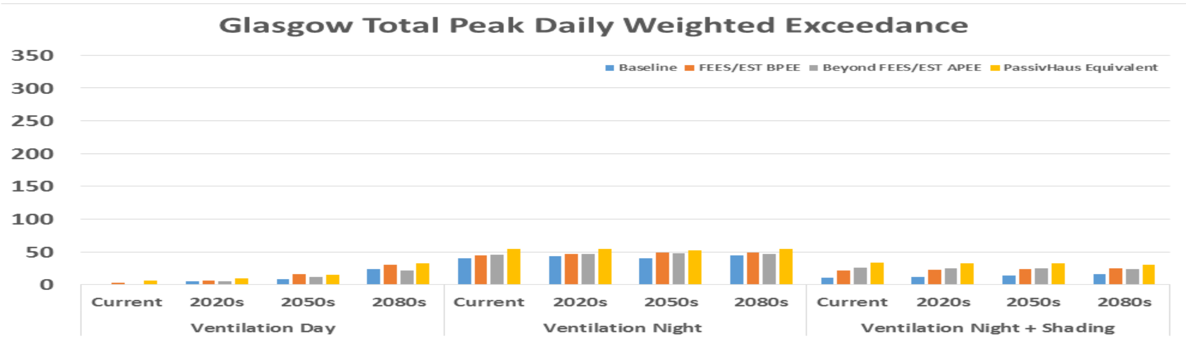
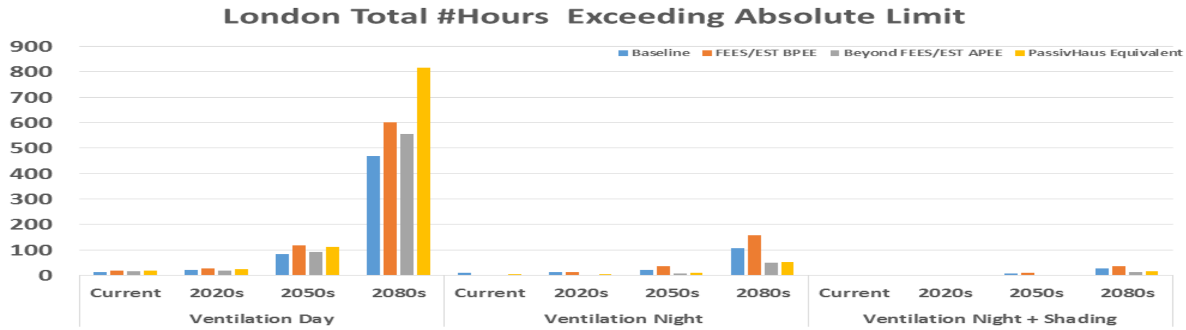


Figure 7.2 A comparison of internal operative temperatures total peak daily weighted exceedance analysis of respective zone results for London, Birmingham and Glasgow respectively based on CIBSE TM52 adaptive thermal comfort criteria.

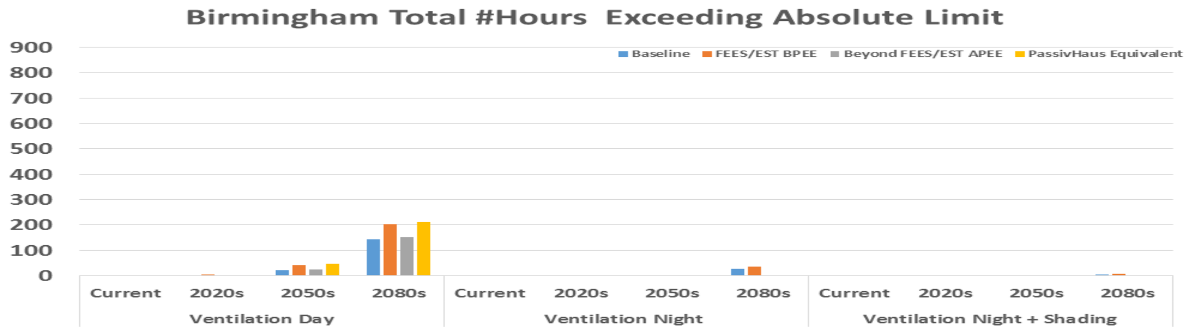
London Total #Hours Exceeding Absolute Limit

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	13	22	83	468	10	13	23	106	0	2	8	28
FEES/EST BPEE	18	27	118	600	3	14	36	158	0	2	9	37
Beyond FEES/EST APEE	15	20	92	556	0	0	8	49	0	0	0	14
PassivHaus Equivalent	18	24	112	817	6	5	10	52	0	0	0	16



Birmingham Total #Hours Exceeding Absolute Limit

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	0	0	21	144	1	0	0	26	0	0	0	6
FEES/EST BPEE	0	5	42	202	0	0	3	35	0	0	0	8
Beyond FEES/EST APEE	0	0	24	153	0	0	0	1	0	0	0	0
PassivHaus Equivalent	0	2	47	211	0	0	0	3	0	0	0	0



Glasgow Total #Hours Exceeding Absolute Limit

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	0	0	0	0	2	2	0	0	0	0	0	0
FEES/EST BPEE	0	0	0	0	6	6	6	5	0	0	0	0
Beyond FEES/EST APEE	0	0	0	0	0	0	0	0	0	0	0	0
PassivHaus Equivalent	0	0	0	0	9	9	7	4	0	0	0	0

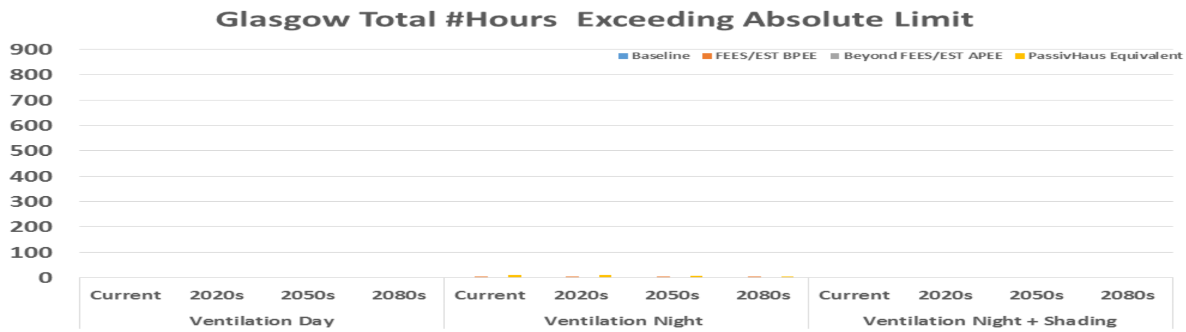
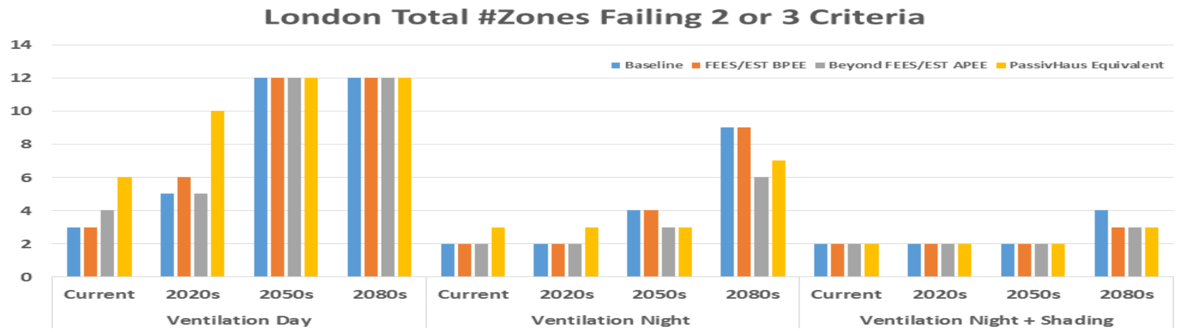


Figure 7.3 A comparison of internal operative temperatures total number of hours exceeding absolute limit analysis of respective zone results for London, Birmingham and Glasgow respectively based on CIBSE TM52 adaptive thermal comfort criteria.

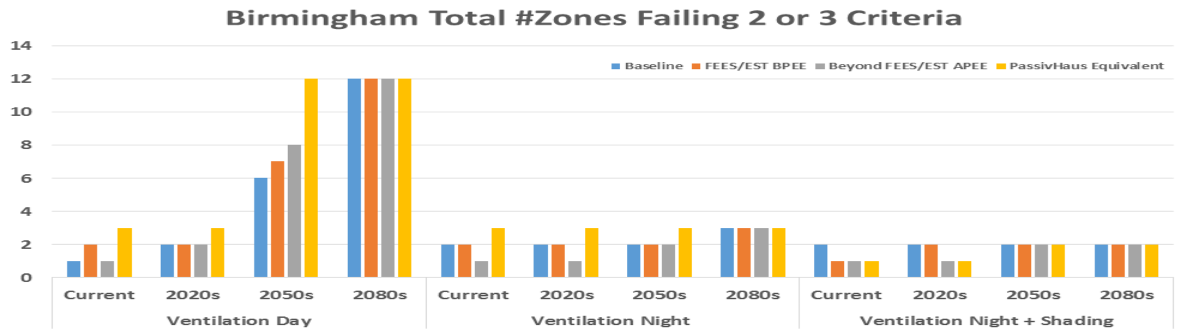
London Total #Zones Failing 2 or 3 Criteria

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	3	5	12	12	2	2	4	9	2	2	2	4
FEES/EST BPEE	3	6	12	12	2	2	4	9	2	2	2	3
Beyond FEES/EST APEE	4	5	12	12	2	2	3	6	2	2	2	3
PassivHaus Equivalent	6	10	12	12	3	3	3	7	2	2	2	3



Birmingham Total #Zones Failing 2 or 3 Criteria

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	1	2	6	12	2	2	2	3	2	2	2	2
FEES/EST BPEE	2	2	7	12	2	2	2	3	1	2	2	2
Beyond FEES/EST APEE	1	2	8	12	1	1	2	3	1	1	2	2
PassivHaus Equivalent	3	3	12	12	3	3	3	3	1	1	2	2



Glasgow Total #Zones Failing 2 or 3 Criteria

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	0	0	0	1	1	1	2	2	0	0	0	1
FEES/EST BPEE	0	0	1	1	1	2	2	2	1	1	2	2
Beyond FEES/EST APEE	0	0	0	1	1	2	2	2	1	1	1	2
PassivHaus Equivalent	0	0	1	1	3	3	3	3	2	2	2	2

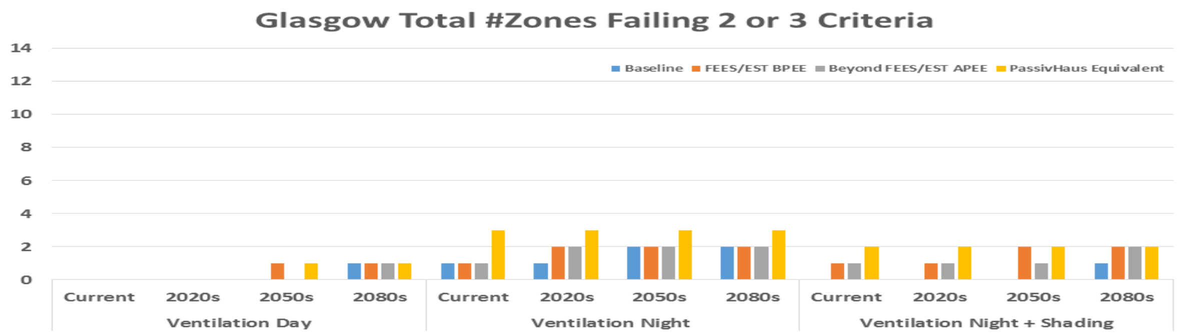
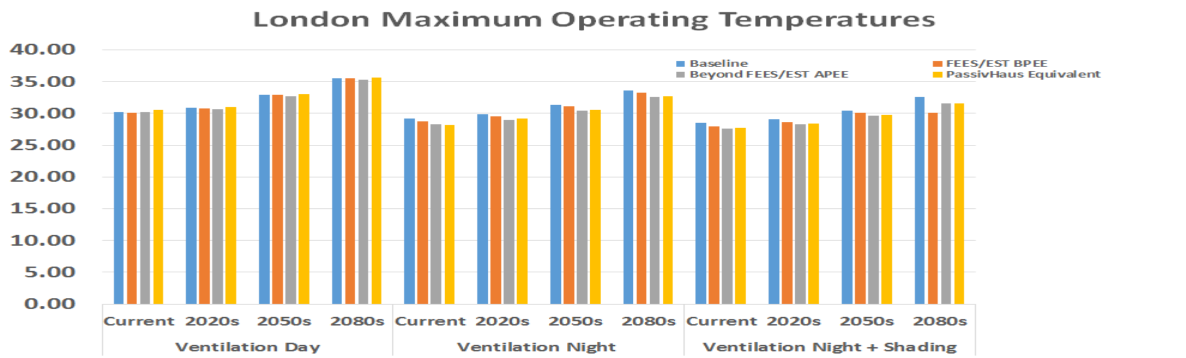


Figure 7.4 A comparison of internal operative temperatures number of zones failing 2 or 3 criteria analysis of respective zone results for London, Birmingham and Glasgow respectively based on CIBSE TM52 adaptive thermal comfort criteria.

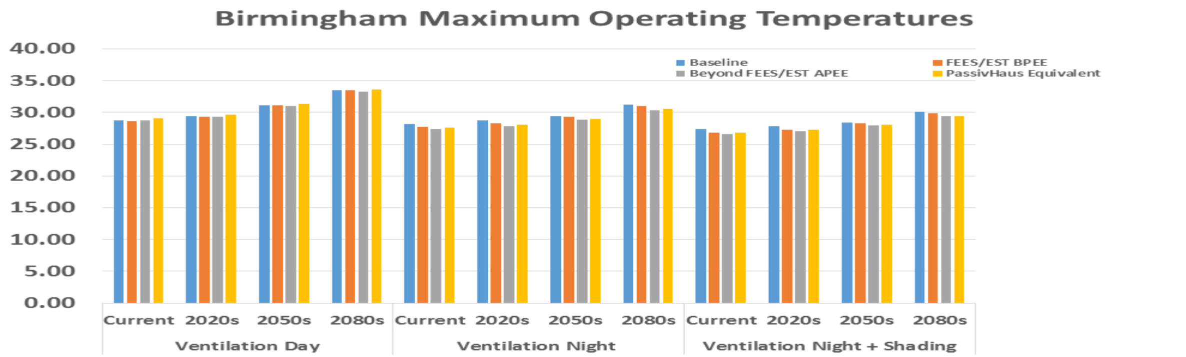
London Maximum Operating Temperatures

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	30.20	30.85	32.87	35.54	29.22	29.87	31.28	33.58	28.49	29.12	30.39	32.55
FEES/EST BPEE	30.13	30.82	32.87	35.48	28.70	29.48	31.09	33.29	27.95	28.64	30.14	30.14
Beyond FEES/EST APEE	30.15	30.71	32.73	35.29	28.23	28.98	30.46	32.57	27.59	28.25	29.64	31.56
PassivHaus Equivalent	30.51	31.04	33.04	35.61	28.14	29.15	30.57	32.68	27.75	28.39	29.71	31.57



Birmingham Maximum Operating Temperatures

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	28.71	29.36	31.10	33.49	28.21	28.74	29.44	31.24	27.33	27.82	28.42	30.09
FEES/EST BPEE	28.67	29.29	31.12	33.46	27.66	28.23	29.32	31.01	26.79	27.28	28.28	29.82
Beyond FEES/EST APEE	28.72	29.25	30.98	33.23	27.35	27.86	28.83	30.37	26.55	27.01	27.90	29.38
PassivHaus Equivalent	29.10	29.59	31.32	33.56	27.59	28.08	28.99	30.50	26.78	27.22	28.04	29.46



Glasgow Maximum Operating Temperatures

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	25.77	26.14	26.76	28.38	26.23	26.52	26.63	27.67	25.69	25.97	26.06	27.09
FEES/EST BPEE	25.67	26.03	27.07	28.66	25.98	26.25	26.88	27.85	25.46	25.70	26.30	27.23
Beyond FEES/EST APEE	25.72	26.03	27.01	28.57	25.90	26.16	26.68	27.55	25.45	25.66	26.21	27.10
PassivHaus Equivalent	26.09	26.39	27.36	28.91	26.30	26.51	26.99	27.81	25.83	26.02	26.48	27.32

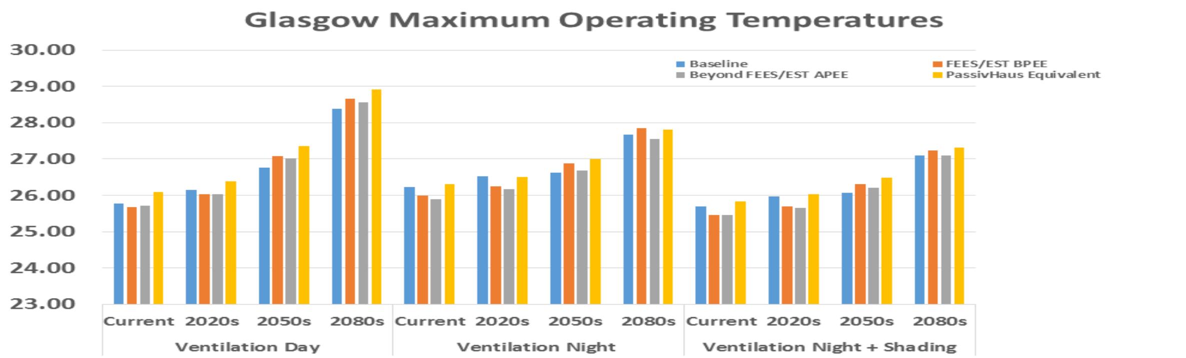
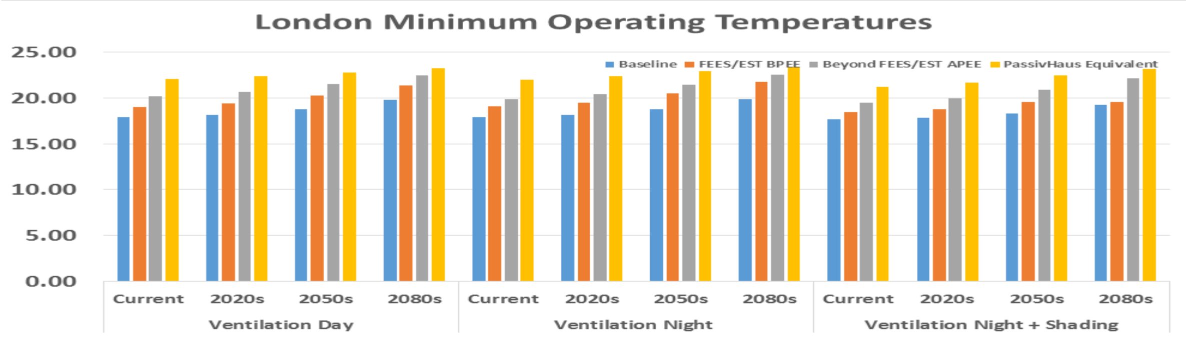


Figure 7.5 A comparison of maximum internal operative temperatures results for London, Birmingham and Glasgow respectively.

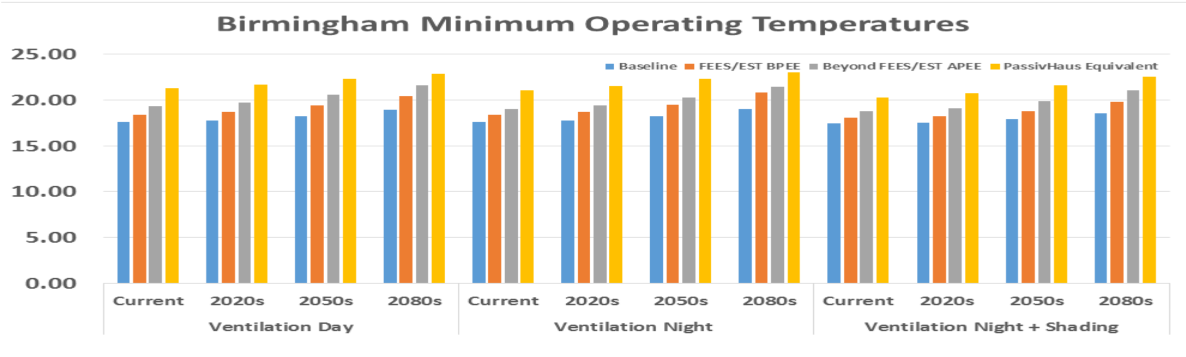
London Minimum Operating Temperatures

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	17.90	18.14	18.76	19.79	17.90	18.14	18.77	19.86	17.66	17.84	18.31	19.20
FEES/EST BPEE	18.98	19.41	20.25	21.37	19.09	19.50	20.46	21.72	18.45	18.74	19.58	19.58
Beyond FEES/EST APEE	20.20	20.68	21.54	22.46	19.88	20.44	21.42	22.52	19.49	19.93	20.91	22.12
PassivHaus Equivalent	22.02	22.34	22.79	23.23	21.98	22.40	22.95	23.36	21.23	21.69	22.47	23.13



Birmingham Minimum Operating Temperatures

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	17.56	17.74	18.18	18.96	17.56	17.74	18.18	18.97	17.40	17.53	17.92	18.55
FEES/EST BPEE	18.40	18.69	19.38	20.38	18.40	18.70	19.44	20.79	18.05	18.23	18.80	19.77
Beyond FEES/EST APEE	19.33	19.73	20.55	21.60	19.03	19.41	20.27	21.46	18.75	19.05	19.84	21.01
PassivHaus Equivalent	21.28	21.66	22.29	22.85	21.07	21.53	22.29	23.01	20.22	20.69	21.58	22.56



Glasgow Minimum Operating Temperatures

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	17.38	17.59	18.11	18.91	17.38	17.59	18.13	18.97	17.12	17.30	17.73	18.44
FEES/EST BPEE	18.71	19.03	19.80	20.76	18.77	19.12	19.99	21.10	18.27	18.53	19.25	20.35
Beyond FEES/EST APEE	20.23	20.58	21.29	22.01	19.80	20.23	21.10	22.02	19.51	19.90	20.76	21.73
PassivHaus Equivalent	21.95	22.14	22.47	22.86	21.94	22.22	22.66	23.08	21.42	21.76	22.34	22.85

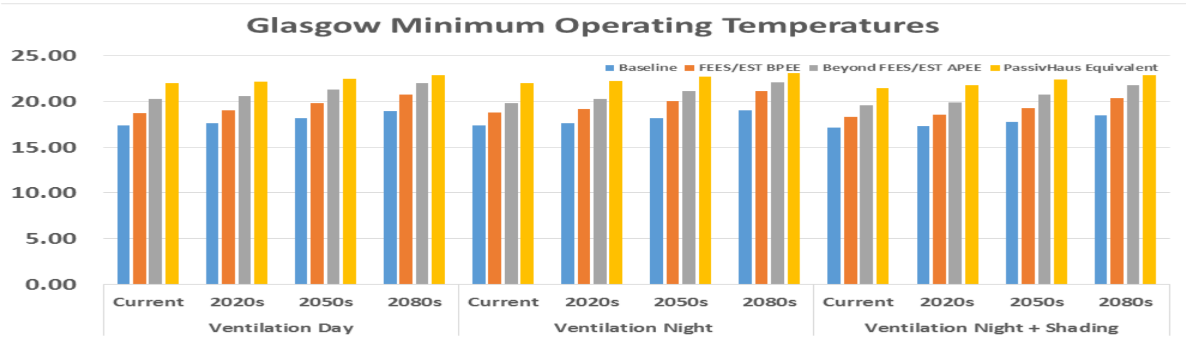
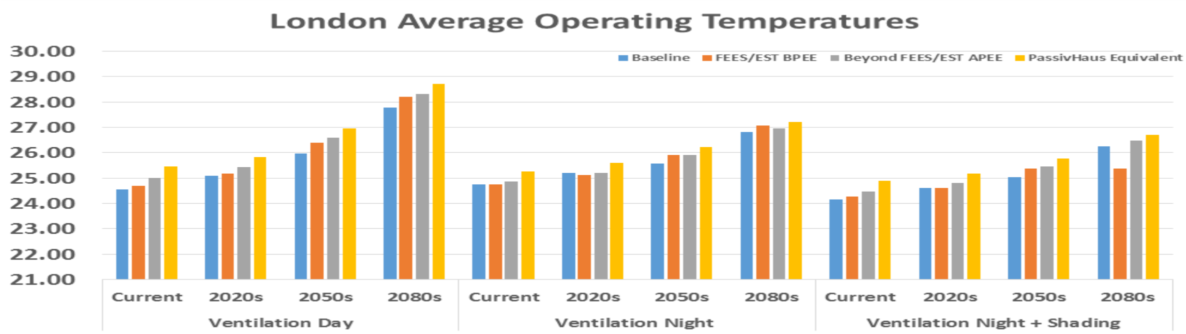


Figure 7.6 A comparison of minimum internal operative temperatures results for London, Birmingham and Glasgow respectively.

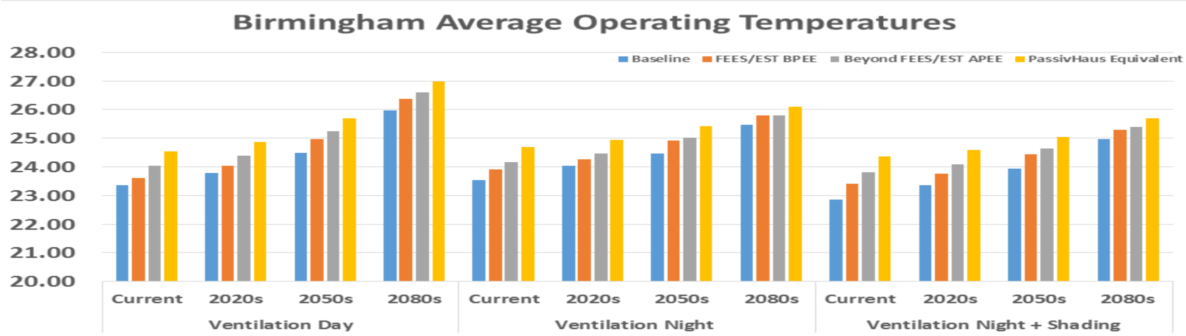
London Average Operating Temperatures

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	24.56	25.10	25.97	27.78	24.75	25.21	25.57	26.81	24.15	24.62	25.04	26.24
FEES/EST BPEE	24.70	25.17	26.39	28.19	24.74	25.12	25.90	27.08	24.26	24.61	25.37	25.37
Beyond FEES/EST APEE	25.01	25.42	26.58	28.32	24.85	25.21	25.90	26.97	24.47	24.80	25.46	26.47
PassivHaus Equivalent	25.46	25.83	26.96	28.70	25.27	25.59	26.21	27.22	24.89	25.18	25.77	26.70



Birmingham Average Operating Temperatures

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	23.35	23.79	24.49	25.97	23.54	24.04	24.46	25.46	22.86	23.37	23.93	24.96
FEES/EST BPEE	23.60	24.03	24.98	26.38	23.92	24.26	24.92	25.79	23.41	23.75	24.45	25.30
Beyond FEES/EST APEE	24.04	24.39	25.25	26.59	24.16	24.46	25.02	25.79	23.81	24.10	24.65	25.39
PassivHaus Equivalent	24.55	24.87	25.69	26.99	24.70	24.95	25.42	26.11	24.36	24.59	25.04	25.69



Glasgow Average Operating Temperatures

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	21.95	22.37	22.78	23.75	22.21	22.64	23.05	23.92	21.62	22.03	22.56	23.46
FEES/EST BPEE	22.51	22.85	23.49	24.34	22.94	23.25	23.85	24.55	22.46	22.75	23.38	24.12
Beyond FEES/EST APEE	23.14	23.41	23.94	24.66	23.39	23.67	24.17	24.74	23.09	23.35	23.86	24.44
PassivHaus Equivalent	23.81	24.01	24.43	25.07	24.19	24.38	24.72	25.16	23.88	24.07	24.43	24.83

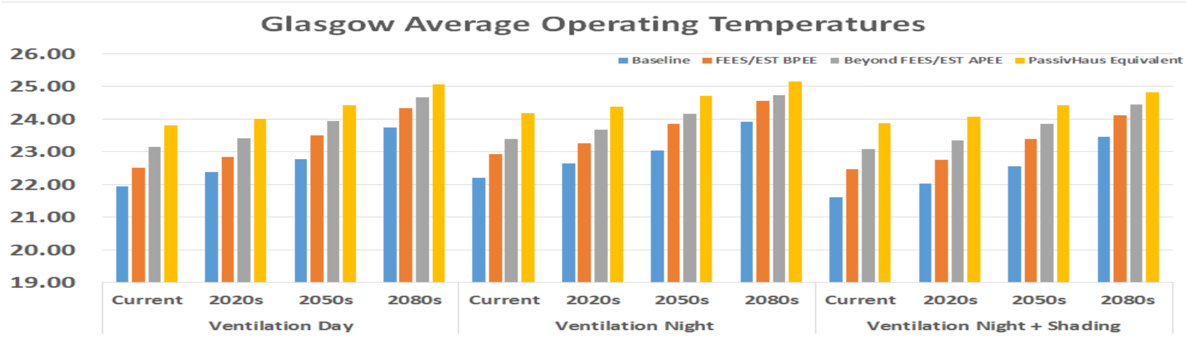
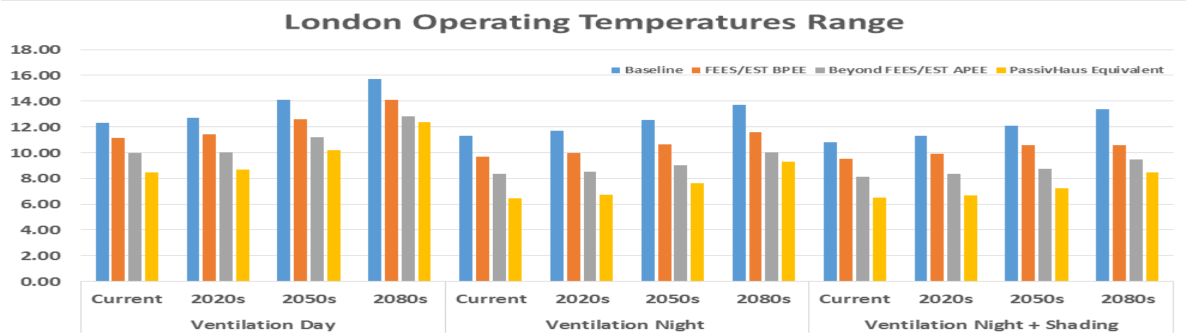


Figure 7.7 A comparison of average internal operative temperatures results for London, Birmingham and Glasgow respectively.

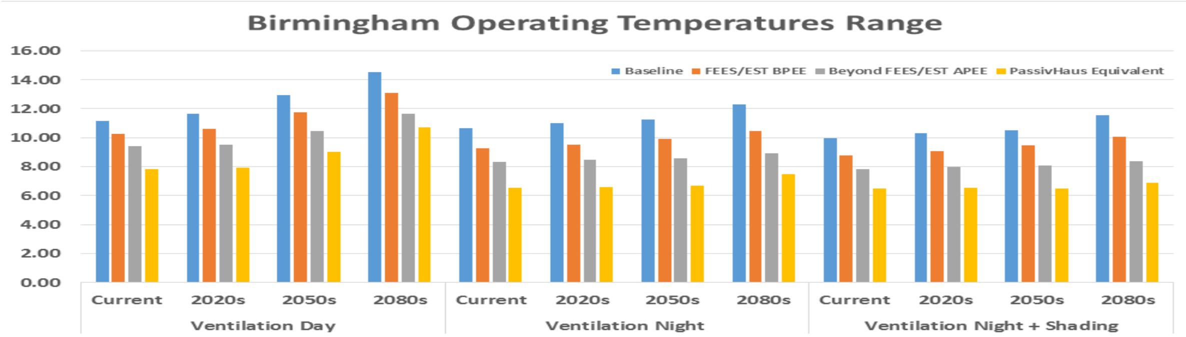
London Operating Temperatures Range

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	12.30	12.71	14.11	15.74	11.32	11.72	12.51	13.72	10.83	11.29	12.08	13.35
FEES/EST BPEE	11.14	11.41	12.62	14.11	9.67	9.98	10.63	11.57	9.50	9.90	10.56	10.56
Beyond FEES/EST APEE	9.95	10.04	11.18	12.83	8.35	8.53	9.04	10.05	8.11	8.33	8.73	9.45
PassivHaus Equivalent	8.49	8.70	10.22	12.38	6.44	6.75	7.62	9.29	6.52	6.70	7.23	8.44



Birmingham Operating Temperatures Range

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	11.15	11.62	12.92	14.53	10.65	11.01	11.26	12.27	9.94	10.28	10.50	11.54
FEES/EST BPEE	10.27	10.60	11.74	13.08	9.27	9.53	9.88	10.43	8.75	9.05	9.48	10.05
Beyond FEES/EST APEE	9.39	9.52	10.43	11.63	8.32	8.45	8.55	8.90	7.80	7.96	8.06	8.37
PassivHaus Equivalent	7.82	7.93	9.03	10.71	6.52	6.56	6.69	7.49	6.49	6.53	6.46	6.89



Glasgow Operating Temperatures Range

	Ventilation Day				Ventilation Night				Ventilation Night + Shading			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
Baseline	8.39	8.55	8.65	9.47	8.85	8.93	8.50	8.70	8.56	8.67	8.35	8.65
FEES/EST BPEE	6.96	7.00	7.27	7.90	7.21	7.13	6.88	6.76	7.19	7.17	7.05	6.88
Beyond FEES/EST APEE	5.48	5.45	5.72	6.56	6.10	5.91	5.58	5.53	5.94	5.76	5.45	5.36
PassivHaus Equivalent	4.14	4.25	4.89	6.04	4.36	4.29	4.33	4.73	4.40	4.26	4.15	4.47

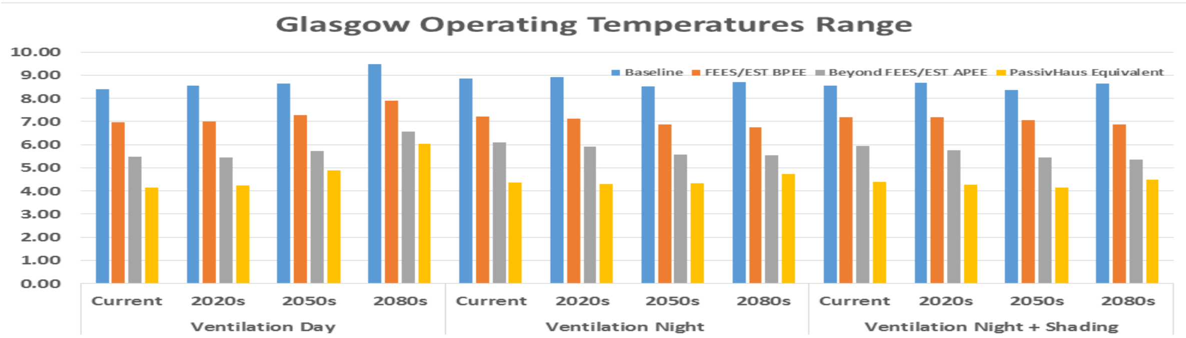


Figure 7.8 A comparison of internal operative temperatures range results for London, Birmingham and Glasgow respectively.

7.3.1 Impact of Weather and location

The whole building simulation scenarios for London, Birmingham and Glasgow results over the current and the three future high Design summer year (DSY) weather data set of 2020s, 2050s and 2080s show a consistence increase in indoor operative temperatures. The prime factor for the variation of indoor operative temperatures is the variability of climatic patterns. The analysis of the average indoor operative temperature for the three locations in figure 7.7 all show a consistent increase variability of operative temperatures for all the current and future weather data set scenarios. This pattern is also observed in the increase in respective maximum and minimum temperatures analysis as shown in figures 7.5 and 7.6 respectively. This observed increase is in consonance with the range of annual average temperature change predicted by the GCM based on the IPCC scenarios (IPCC, 2001) which generally shows an increase in ambient temperature over stipulated timelines.

A comparison of the variability of the indoor operative temperature results in figures 7.5 to 7.7 also shows that London is likely to experience more risk of thermal discomfort than Birmingham and Glasgow over the time period for the analysis. The total number of zones failing two (2) or three (3) CIBSE TM52 overheating criteria is more in London than in Birmingham and Glasgow as shown in figure 7.4. There is observable evidence of all zones in London failing the day ventilation scenarios of all the standard construction specification considered under the CIBSE TM52 assessment criteria in the 2050s and 2080s but this trend is observed only in the 2080s in the case of Birmingham and insignificant in the case of Glasgow.

7.3.2 Effects of Thermal Mass

The role of thermal mass in the provision of thermal comfort is to absorb the internal heat gains during daytime in summer and progressively release it in the night when external temperatures decrease. Its use is more effective when there is marked difference between night and day temperatures. A comparison of the whole building simulation scenarios for London, Birmingham and Glasgow results as indicated in appendix 7.1 through 7.12 shows that the progressive increase in thermal mass for the current and three future high Design summer year (DSY) weather data set decreases the adaptive thermal comfort temperature amplitudes over the non-heating season. The optimum thermal mass design sufficiently de-couples and lessens the heat transfer between the external environment and the building interior. The London, Birmingham and Glasgow operative temperature range analysis presented in figure 7.8 provides evidence that thermal mass improvement effectively reduces and stabilizes the large varying indoor temperature swings and thus leads to the enhancing of thermal comfort over the period. However, it was observed that increasing in thermal mass although providing the advantage of reducing indoor temperature swings led to the progressive increase in indoor operative temperature over the current and future weather data scenarios, as shown in figures 7.5, 7.6 and 7.7 of the maximum, minimum and average operative temperatures respectively and also evident in appendix 7.1 through 7.12 of the whole building simulation analysis underpinned by CIBSE TM52 adaptive thermal comfort overheating criteria. Increasing thermal mass must be augmented with other effective passive design strategies which will cool the building by removing excessive internal heat gains.

In figure 7.1 through 7.4, the benefits of the effectiveness of increasing thermal mass coupled with night ventilation and closing the building during the day are observed in London and Birmingham. The dynamic response of thermal mass design facilitates the storage of heat during the day in the thermal mass, slowing the response to changes in the indoor operative temperatures and reducing their ability to peak during the day. This reduces the extremes in indoor temperature and hence reduces overheating risk without the need of applying cooling systems. The stored heat in the thermal mass is progressive released to the indoor space during the night due to the thermal lag of the fabric energy storage material. Thus, the indoor night time operative temperatures would be slightly higher than if there was low thermal mass design. Night ventilated air dissipates the released thermal energy to the external environment due to lower ambient temperature. The dynamic thermal mass response cycle is repeated for the next day. Application of shading further reduces the overheating risk.

However, the effectiveness of optimum thermal mass design coupled with night ventilation and shading scenarios would be realised only when the diurnal variation of external temperatures exceeds 10^{o}C (Balaras 1996), (Szokolay 1984). Hence, optimum thermal mass design is underpinned by climate with a large diurnal temperature range and is not desirable in climates with lower summer temperatures. In addition, a variable internal operative temperature is essential for the effectiveness of optimal thermal mass design (Balaras 1996).

This explains why the application of thermal mass design is seen to be less effective in Glasgow, where moderate low summer temperatures are experienced, when compared to London and Birmingham. This shows that inadequate thermal mass design could aggravate overheating risk. Analysis of figures 7.1 to 7.4 shows that there is slight increase in the total number of hours exceeding comfort range, the total peak daily weighted exceedance, the total number of hours exceeding absolute limit and the total number of zones failing two or three CIBSE TM52 criteria of overheating during the night ventilation scenarios. However, the extent of these variations is of less significance when compared to those of London and Birmingham due to Glasgow lower summer temperatures.

7.3.3 Ventilation and Shading as Mitigation Strategies

Openable windows significantly contribute to the provision of thermal comfort in dwellings. Effective ventilation dissipates the release internal heat gain by enhanced thermal mass design during the day into the external environment. The daytime ventilation scenario was seen not to be an effective way of mitigating internal heat gains in dwellings in the case of London and Birmingham as shown in figures 7.1 to 7.4. However, an opposite trend is observed in the case of Glasgow which shows a more effective day ventilation scenario in mitigating overheating in dwellings when compared to the night ventilation and night ventilation with shading scenarios. The reason behind this opposite trend is explained in section 7.3.2.

There are noticeable progressive increases in the variability of indoor thermal temperatures from the current to the 2080s' weather data scenarios for London and Birmingham. The alternative night time ventilation strategy offers some improvement in the reduction of indoor operative temperatures. However, the strategic effect of the implementation of night ventilation would only be realised with a good variation in diurnal temperature which facilitates the flow of internal heat gains to the external environment.

Moreover, whilst night ventilation may present security risk, appropriate windows design options could be sought for the implementation of night ventilation strategy. The night ventilation coupled with shading strategy offered the best effective mitigation strategy in reducing indoor operative temperatures in London and Birmingham. Shading decreases the amount of radiant heat penetration during the daytime. Furthermore, since occupant control of windows was used as the means of controlling the indoor temperature it is imperative that variable occupant behaviour should be given more attention in considering the ventilation strategy.

7.3.4 Zones Analysis

It was observed in the zone overheating assessment of both London and Birmingham that most zone failures under the CIBSE TM52 overheating assessment criteria occurred in the kitchen, lounge and the first floor stairs area. The kitchen area generally experiences high internal heat gains because of heating activities related to cooking. The provision of thermal mass in this work was uniformly distributed throughout the building. An uneven distribution of thermal mass with focus on areas most likely to experienced more internal heat gains may improve the cycle of heat storage. It was observed that there was no openable window associated with the first floor stair area leading to unwanted accumulation of internal heat gains with the resulting increase in operative temperatures in the zone. The lounge has only one single sided north-east facing window. This might have contributed to the observed indoor overheating in this zone due to low summer sun angles. Cross-ventilation is more effective in large areas like lounges. A north-south window orientation is also preferable as it has limited solar penetration during the non-heating season. In addition, the fixed external shading due to being adjustable might have contributed to the effectiveness of the shading strategy.

PassiHaus night ventilation with shading scenario presented the most stable short range of adaptive thermal comfort temperature variation over the non-heating season. The variability of the indoor operative temperatures in all-weather scenarios in appendix 7.1 to 7.12 tends to flatten indicating that this design strategy currently offers the most stable effective means in this work consideration to enhance thermal comfort.

7.4 Summary and Conclusion

The study investigated the impact of four standard construction specifications which give a progressive improved thermal mass coupled with passive cooling strategies to optimize the thermal comfort in detached dwellings in London, Birmingham and Glasgow using the CIBSE TM52 criteria for assessing adaptive overheating in free-running dwellings. The CIBSE TM52 criteria proved to be an effective and credible assessment tool as the results obtained in this work are in consonance with what is presented in literature.

Generally, in all scenarios, the indoor temperatures were observed to vary with external temperatures which in turn are related to change in climatic conditions. The findings from the various simulation scenarios coupled with the statistical analysis of the data collected from the simulation present a strong positive correlation between improved building fabric, strategic ventilation scenarios with external shading and indoor adaptive overheating thermal performance. This integrated approach has been verified to result in substantial reduction in indoor operative temperatures leading to enhance thermal comfort environment in London and Birmingham locations. However, the effect of the variability of climate change was clearly observed to impact operative temperature in the 2050s and 2080s in the case of London and 2080s in Birmingham as the future frequency and intensity of heat waves increases. These increases are in consonance with the range of annual average temperature change predicted by the GCM based on the IPCC scenarios which generally shows an increase in temperature over stipulated timelines. It was also observed that the day ventilation scenario for Glasgow was more effective in mitigating internal operative temperatures than the night ventilation and night ventilation with shading scenarios which is contrary to the observable trends in London and Birmingham. The effectiveness of optimum thermal mass design coupled with night ventilation and shading scenarios would be realised only when the diurnal variation of external temperatures exceeds 10^{o}C Optimum thermal mass design must be underpinned by climate with a large diurnal temperature range and is not desirable in climates with lower summer temperatures. Thus, the thermal mass design is less effective in Glasgow, where moderate low summer temperatures are experienced, when compared to London and Birmingham.

The variability of the indoor operative temperature across the progressive increase in thermal mass in the whole building consideration is clearly seen as the swing of the operative temperatures during the non-heating season reduces. The PassiHaus standard construction specification with the incorporation of passive cooling strategies of improved night ventilation with shading offers the best case scenario analysis of the optimization of indoor operative temperatures with relative decrease in the fluctuations of operative temperature during the observed period. However, the progressive increase in thermal mass resulting in the increase in indoor temperatures might necessitate the inclusion of mechanical room conditioning systems in the strategic mix to keep the indoor temperatures at specified levels to provide heat balance or thermal comfort in the future. As heating, ventilation and air conditioning (HVAC) systems have high energy consumption; an alternative strategy could also be the utilization of improved natural ventilation systems.

This study indicates that thermal comfort in dwellings can be enhanced by analysis of future climatic patterns, improved building fabric and provision of passive design consideration of improved ventilation and shading. It also confirms that the utilization of appropriate mitigation strategies to enhance thermal comfort could contribute to the reduction of the environmental implications to the built environment and facilitate the drive towards the attainment of future sustainability requirements. The focus on how to provide enhance thermal comfort will challenge future innovative design and adapt technological process as Building Regulations continuously seek strategies to mitigate carbon dioxide emissions and improve dwelling energy efficiency. The measures would include planning and design options sensitive to varying climatic conditions and resilient building design which incorporates improved and better façade and building envelope and passive design technologies with the aim to eventually reduce future total energy demands in dwellings and at the same time enhance thermal comfort.

CHAPTER 8: Impact of four standard construction specifications on dwellings' thermal comfort of three major weather locations in London.

8.0 Case study 5: Impact of four standard construction specifications on thermal comfort on three weather locations in London – Uncertainty and sensitivity analytical approach based on CIBSE TM49 weather files.

8.1 Introduction

This case study based on Monte Carlo uncertainty and sensitivity analysis seeks to investigate and quantify the variability of impact of climate change of three locations of Gatwick, Heathrow and London Weather Centre on building thermal comfort considering the identified four standardized construction specifications with varying thermal mass and airtightness and passive design solutions. The thermal analysis simulation is underpinned by the CIBSE TM49 weather data set for 2003-2050 medium design summer year with 50% probabilistic scenario timeline and the CIBSE TM52 adaptive thermal comfort criteria for overheating analysis. The sensitivity analysis consideration examines the most influential building envelope and systems parameters and explores their related uncertainty and sensitivity contribution of building adaptation strategies of the four standardized construction specifications which affect thermal comfort. Graphical description in the form of histograms of the results in the three data sets is first presented in the results and analysis section to offer a synopsis of the three data sets. The results show that applying the optimum thermal mass with the appropriate mitigation scenarios of night ventilation and shading have a significant impact on reducing maximum internal operative temperatures of about 1^{o}C to 3^{o}C for respective scenarios, and thus enhancing thermal comfort in dwellings. The PassivHaus equivalent presented the most stable internal operative temperature conditions. The results of the sensitivity analysis indicated that glazing is the most dominant parameter for both the SRC and PCC. The study further shows that more consideration should be given to glazing and internal heat gains than floor and wall construction when seeking to improve the thermal comfort of dwellings.

8.2 Research Method 5 – For Case Study 5

Detailed method for case study 5 is discussed in chapter 3 section 3.2.7.

8.3 Results and Discussion

8.3.1 Results of the Deterministic Analysis

Figures 8.1 to 8.4 illustrates the deterministic analysis results in the form of histogram analysis comparison of the maximum, minimum, average and range of operative temperatures of internal operative temperatures using CIBSE TM52 as overheating criteria and of UKCP09 Gatwick, Heathrow and London Weather Centre 2003_2050 Medium DSY 50% probabilistic scenarios.

UKCP09 London Maximum Operating Temperatures for 2003_2050 Med DSY 50%

	Gatwick				Heathrow				London Weather Centre			
	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus
Day	27.95	27.83	27.47	27.52	28.57	28.35	27.94	27.92	28.79	28.53	28.10	28.06
Night	27.31	27.25	26.81	26.84	28.34	28.12	27.70	27.68	28.72	28.45	28.02	27.98
Night + Shading	25.76	26.26	25.50	25.50	26.70	27.13	26.28	26.23	27.08	27.47	26.62	26.55

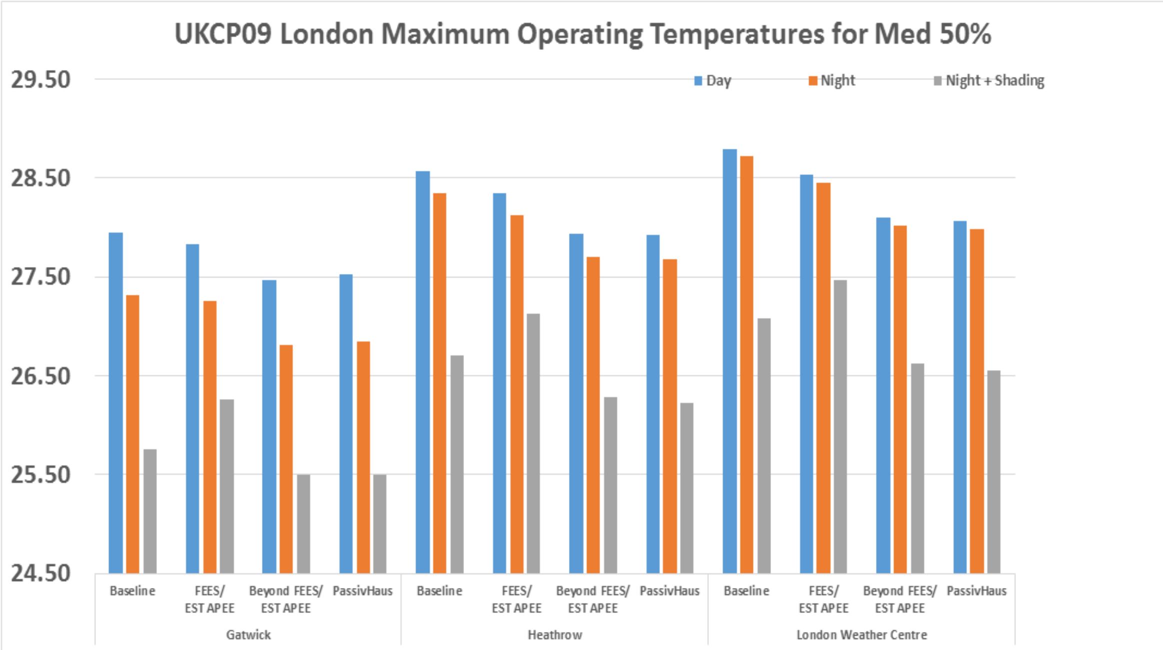


Figure 8.1 Maximum operative temperatures for UKCP09 Gatwick, Heathrow and London Weather Centre 2003_2050 Medium DSY 50% probabilistic scenarios

Figure 8.1 indicates the trend in maximum operative temperatures for the UKCP09 weather data sets of Gatwick, Heathrow and London Weather Centre 2003_2050 medium DSY 50% probabilistic scenarios for the four standard construction specifications. In general temperatures for London Weather Centre are observed to be greater than Heathrow which in turn has temperatures greater than Gatwick. The trends for the respective baseline construction specification for Gatwick, Heathrow and London Weather Centre show a slightly higher maximum operative temperature. A comparison of the day ventilation scenarios for the baseline construction specification shows a maximum temperature difference of about 0.62°C between Heathrow and Gatwick and 0.84°C between London Weather

Centre and Gatwick. Consideration of the night ventilation scenario shows that a maximum temperature difference of about 1.03°C between Heathrow and Gatwick and 1.41°C between London Weather Centre and Gatwick. Application of the night ventilation coupled with shading strategy shows that a maximum temperature difference of about 0.94°C between Heathrow and Gatwick and 1.32°C between London Weather Centre and Gatwick. Similar trends are observed for the other three construction specifications.

In general, there is an observable decrease in maximum operative temperature for all weather centres with the progressive increasing of thermal mass of the standard construction specifications with the PassivHaus construction standard offering the best option in reducing maximum temperatures. The effects of thermal mass on various locations with different data sets consideration is discussed in section 7.3.2 of this work.

Application of the night ventilation and shading scenario offered the best mitigation strategy in reducing the maximum operative temperatures. A maximum temperature difference of about 2.00°C is achieved when comparing the day ventilation and night ventilation coupled with shading scenarios. Detailed explanation of ventilation and shading as overheating mitigation strategies is offered in section 7.3.3 of this work.

UKCP09 London Minimum Operating Temperatures for 2003_2050 Med DSY 50%

	Gatwick				Heathrow				London Weather Centre			
	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus
Day	20.52	21.19	21.33	21.75	21.19	21.75	21.87	22.23	21.68	22.10	22.20	22.50
Night	20.74	21.67	21.64	22.13	21.28	21.95	22.09	22.52	21.82	22.36	22.45	22.79
Night + Shading	17.60	19.35	18.53	18.96	18.38	20.36	19.46	19.93	19.20	20.90	20.07	20.45

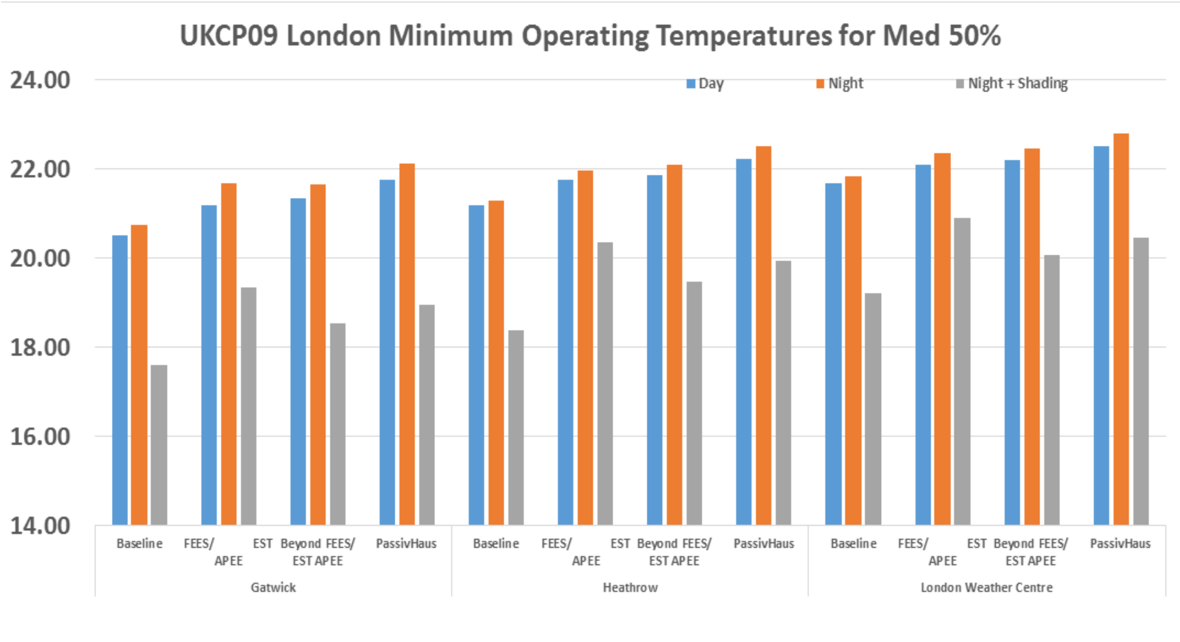


Figure 8.2 Minimum operative temperatures for UKCP09 Gatwick, Heathrow and London Weather Centre 2003_2050 Medium DSY 50% probabilistic scenarios

Figure 8.2, the minimum operative temperature variability, indicates a similar trend of differences to that of figure 8.1. It is observed that the minimum operative temperatures for the night ventilation scenarios show slightly higher temperatures in the range of about 0.3 $^{\circ}$C when compare to the day ventilation scenario for all respective standard construction specifications. The night ventilation coupled with shading scenario variation is the opposite to that with a higher temperature range of about 3 $^{\circ}$C when comparing the day ventilation scenario to the night ventilation coupled with shading scenario. This observation shows that the effectiveness of the use of optimum thermal mass must be integrated with appropriate passive design techniques of combined night ventilation and daytime glazing shading from excessive solar radiation

UKCP09 London Average Operating Temperatures for 2003_2050 Med DSY 50%

	Gatwick				Heathrow				London Weather Centre			
	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus
Day	24.10	24.23	24.15	24.31	24.58	24.66	24.56	24.68	24.77	24.82	24.71	24.81
Night	24.03	24.28	24.10	24.27	24.52	24.61	24.50	24.62	24.73	24.79	24.67	24.77
Night + Shading	22.13	23.20	22.51	22.72	22.88	23.77	23.16	23.32	23.21	24.02	23.44	23.57

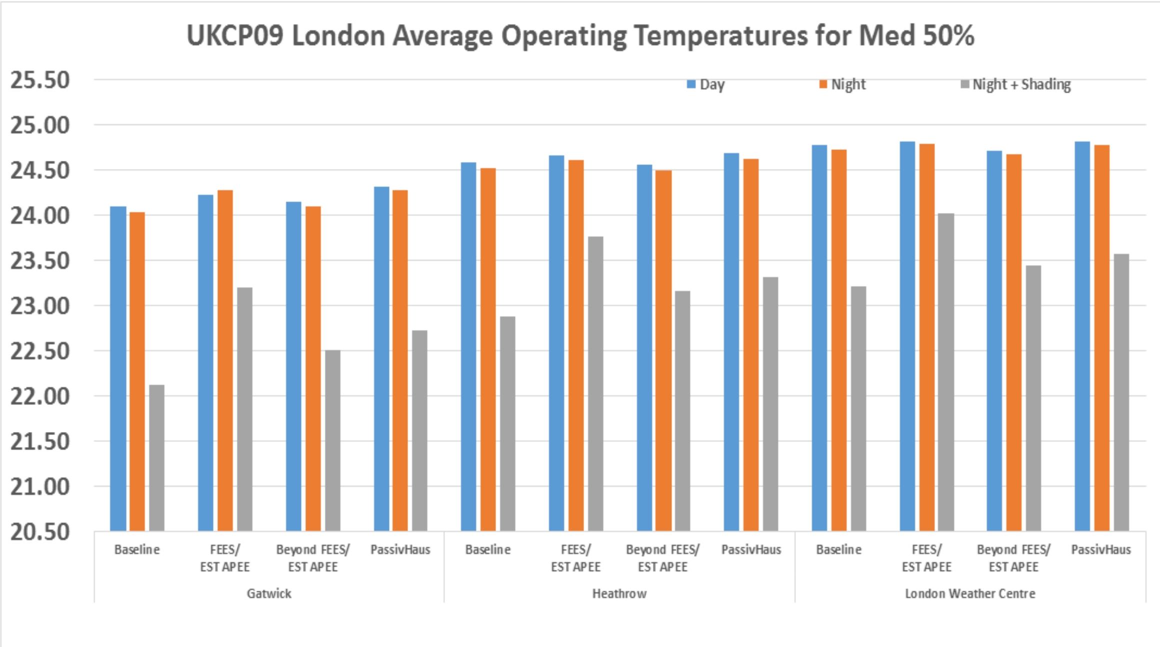


Figure 8.3 Average operative temperatures for UKCP09 Gatwick, Heathrow and London Weather Centre 2003_2050 Medium DSY 50% probabilistic scenarios

Figure 8.3 shows the average internal operative temperatures for the three weather locations and the four different standard construction specifications with increasing thermal mass and airtightness. The day and night ventilation scenarios for the respective standard construction specification show a strong similarity in the trend of average operative temperatures. The effectiveness of thermal mass coupled with night ventilation and shading is observed in all situations as there is about 1.0 ˚C to 2.0 ˚C. As expected, the average temperatures for London Weather

Centre location are greater than Heathrow, whose average temperatures are in turn greater than Gatwick

UKCP09 London Range Operating Temperatures for 2003_2050 Med DSY 50%

	Gatwick				Heathrow				London Weather Centre			
	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus	Baseline	FEES/ EST APEE	Beyond FEES/ EST APEE	PassivHaus
Day	7.43	6.64	6.14	5.77	7.38	6.60	6.07	5.70	7.10	6.43	5.91	5.56
Night	6.56	5.59	5.17	4.71	7.06	6.16	5.61	5.15	6.90	6.10	5.58	5.19
Night + Shading	8.16	6.92	6.97	6.54	8.32	6.77	6.81	6.30	7.89	6.57	6.55	6.10

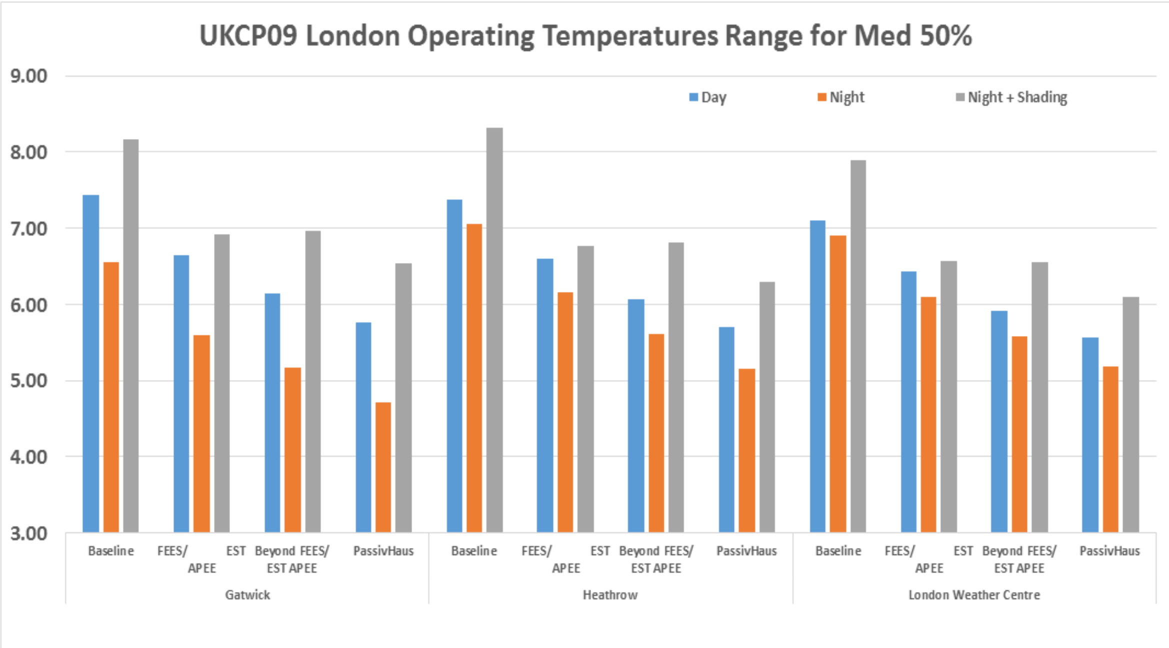


Figure 8.4 Range operative temperatures for UKCP09 Gatwick, Heathrow and London Weather Centre 2003_2050 Medium DSY 50% probabilistic scenarios

In figure 8.4, the range operative temperatures for London Weather Centre location for the progressive increase in thermal mass of the standard construction specifications shows a slight variability decrease in the range operative temperature with PassivHaus standard construction showing the minimum range. This variability could be attributed to the effectiveness of thermal mass couple with appropriate mitigation strategies as discussed in sections 7.3.2 and 7.3.3.

8.3.2 Results of the multivariate linear regression analysis due to climate change and future building adaptation measures

The linear regression analysis shown in the table of model summary box table 8.1 and table of coefficients table 8.3 of the London Weather Centre night ventilation regression model for example indicated that total transmittance, equipment sensible gain, aperture opening, external conduction glazing, internal solar gain, wall u-value, floor u-value, sensible load, occupancy sensible gain, infiltration and ventilation gain, lightning gain, equipment latent gain, solar gain, external conduction opaque, thermal bridging and occupant latent gain are the input parameters with most significant factors. Thus these identified parameters can be used as good indicators for the sensitivity analysis of the weather data and future adaptation measures based on the four standardized construction specifications.

To check for the viability of the multivariate linear regression analysis for the uncertainty and sensitivity analysis, the following results from the model output were examined. The adjusted R square value of 0.773 which gives 77.3% of variability of the target variable of the internal operative temperature accounted by the selected input variables gives an indication of a very good model. The results summary is shown in table 8.1 below.

The ANOVA table; table 2, below gives the assessment of the overall significance of the model. The p value for the output parameters of internal operative temperatures is less than 0.05 indicating the statistical significance of the model. Moreover, the F-test values show that the models are a good fit for the data with p values less than 0.05.

Table 8.1 Table of Model Summary Box for London Weather Centre night ventilation 2003-2050 medium design summer year with 50% probabilistic scenario timeline results

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.880[a]	.774	.773	.47264

a. Predictors: (Constant), Total Transmitance, Equipment Sensible Gain, Aperture Opening, External Conduction Glazing, Internal Solar Gain, Wall U value, Sensible Load, Occupancy Sensible Gain, Inf Vent Gain, Floor U value, Lighting Gain, Equipment Latent Gain, Solar Gain, External Conduction Opaque, Thermal Bridging, Occupancy Latent Gain

b. Dependent Variable: Internal Operating Temperature

The examinations of the standardized beta coefficients, which give the measure of contribution of each variable to the models, indicate those key parameters which might influence internal operative temperature model external conduction glazing, occupancy sensible gain and occupancy latent gain. These parameters had the largest of the standardized beta coefficients. Moreover, the t-test also showed higher values for these parameters with p values less than 0.05, all pointing to the identified parameters having significant influence on the output variable.

Table 8.2 ANOVA table of outputs for London Weather Centre night ventilation 2003-2050 medium design summer year with 50% probabilistic scenario timeline results

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	11205.867	16	700.367	3135.260	.000[b]
	Residual	3277.265	14671	.223		
	Total	14483.132	14687			

a. Dependent Variable: Internal Operating Temperature

b. Predictors: (Constant), Total Transmitance, Equipment Sensible Gain, Aperture Opening, External Conduction Glazing, Internal Solar Gain, Wall U value, Sensible Load, Occupancy Sensible Gain, Inf Vent Gain, Floor U value, Lighting Gain, Equipment Latent Gain, Solar Gain, External Conduction Opaque, Thermal Bridging, Occupancy Latent Gain

Table 8.3 Table of Coefficients for London Weather Centre night ventilation 2003-2050 medium design summer year with 50% probabilistic scenario timeline results

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.	Correlations Zero-order	Correlations Partial	Correlations Part
1	(Constant)	23.768	.054		438.292	.000			
	Sensible Load	-.005	.001	-.158	-8.150	.000	-.509	-.067	-.032
	Solar Gain	.003	.001	.174	5.922	.000	.401	.049	.023
	Lighting Gain	-.013	.001	-.264	-16.814	.000	.063	-.138	-.066
	Inf Vent Gain	.000	.001	.006	.317	.751	.315	.003	.001
	External Conduction Opaque	.012	.001	.399	12.154	.000	-.227	.100	.048
	External Conduction Glazing	.074	.001	.597	91.147	.000	.787	.601	.358
	Occupancy Sensible Gain	-.358	.013	-.550	-27.814	.000	-.298	-.224	-.109
	Equipment Sensible Gain	-.006	.003	-.080	-2.546	.011	.090	-.021	-.010
	Occupancy Latent Gain	.470	.027	.801	17.586	.000	-.018	.144	.069
	Equipment Latent Gain	-.012	.003	-.082	-4.299	.000	.052	-.035	-.017
	Internal Solar Gain	.075	.005	.255	15.835	.000	.388	.130	.062
	Aperture Opening	.703	.023	.205	30.304	.000	.079	.243	.119
	Wall U value	5.563	.795	.327	7.001	.000	-.009	.058	.027
	Floor U value	-8.222	.943	-.222	-8.723	.000	-.006	-.072	-.034
	Thermal Bridging	-15.514	2.339	-.258	-6.634	.000	-.002	-.055	-.026
	Total Transmitance	5.193	.275	.326	18.889	.000	.020	.154	.074

a. Dependent Variable: Internal Operating Temperature

8.3.3 Uncertainty analysis due to climate change and building adaptation measures specified in the four (4) standardised construction specification.

8.3.3.1 Scatter Plots

Appendices 8.1 through 8.3 illustrate the scatter plots of the input building adaptation variables for the sensitivity analysis module. Analysis of the parameters shows that the glazing (external conduction glazing and total transmittance (G-Value) is strongly positive correlated to the internal operative temperatures for the day, night and night with shading scenarios. The external conduction opaque shows fairly positive correlation with the internal operative temperature with occupancy sensible gain being negatively correlated with the internal operative temperature.

8.3.2.2 Box and whiskers plots

Figures 8.4 to 8.6 illustrate the comparison of the four standardized construction specifications (Baseline, Fabric Energy Efficiency Standard/EST Best Practice Energy Efficiency Standard, Beyond Fabric energy Efficiency Standard/EST Advanced Practice Energy Efficiency Standard and the Passivhaus equivalent standard) effect on thermal comfort using the internal operative temperature as the overheating indicator based on CIBSE TM52 overheating criteria. Three different ventilation scenarios are used in the analysis. The plots show the uncertainty associated with Monte Carlo simulation of overheating analysis with the 2003-2050 DSY Medium 50% probabilistic weather scenarios for Gatwick, Heathrow and London Weather Centre, with reference to variations due to the intervention of the designated standard construction specifications with their changes to the 22 parameters such as U-values of the building envelope, the total transmittance (G-value) and the internal heat gains.

In general, there is a uniform variability of the day and night ventilation scenarios with decreasing interquartile ranges, outer ranges and median values across the four standard construction specifications which shows increasing thermal mass and air tightness. The night ventilation coupled with shading scenario for the three weather locations shows irregular variability of the plots with the Fabric Energy Efficiency Standard (FEES) having larger medians in all the three weather locations coupled with comparatively small interquartile range and the outer range of dispersion.

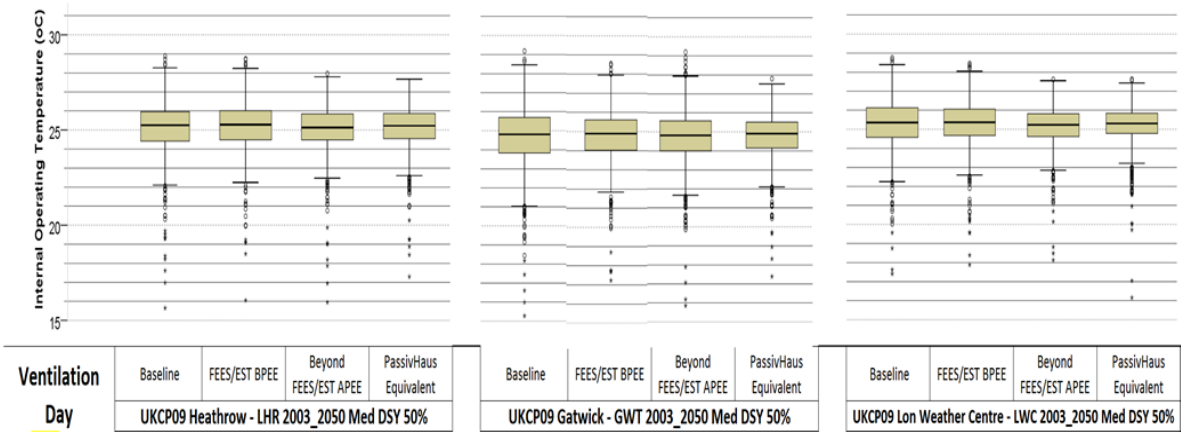


Figure 8.4 Box and whiskers plots for day ventilation scenario comparison of the internal operative temperatures effect of four standardized construction specifications based on 2003-2050 DSY Medium 50% probabilistic weather scenarios for Gatwick, Heathrow and London Weather Centre

The medians for the day ventilation scenarios are generally higher than those of the night ventilation and further higher than the night ventilation with shading scenarios. This observation points to the fact that applying the mitigation scenarios of night ventilation and shading have a significant impact on reducing internal operative temperatures, and thus enhancing thermal comfort in dwellings.

In figure 8.4, there are very significant extreme outliers below the lower whisker's (25^{th} percentile) end. This observation points to marked difference in extreme low internal operative temperature for the day ventilation scenario. The opposite effect is realised in figure 8.5, which shows fairly significant outliers from the upper whisker's (75^{th} percentile) end indicating marked extreme comparatively high internal operative temperatures using the night ventilation scenario. Figure 8.6 shows that that the night ventilation coupled with shading scenario results in relatively fewer outliers lying close to the ends of the whiskers. This point to a measure of relative dispersion of the data set around the interquartile and the outer ranges. This may suggest a relative stability of the internal operative temperatures, thus enhancing thermal comfort as expected with the night ventilation coupled with shading scenario. In figures 8.4 and 8.5, there is a decrease in the interquartile ranges and the outer ranges pointing to the progressively comparatively small dispersion. This suggests a middle clustering of data about the median, thus indicating progressive stable internal operative temperatures with the Passivhaus equivalent offering the most stable internal operative temperature conditions as its plot shows less uncertainty.

In figure 8.6, the interquartile range of all the standard construction specifications are relatively larger under the night ventilation coupled with shading scenario than the day ventilation and night ventilation scenarios in figures 8.4 and 8.5 respectively. This could be interpreted that there is higher spread of the inner 50% of the ranked data. Again, it is pointing to more stable internal operative temperatures with enhanced thermal comfort.

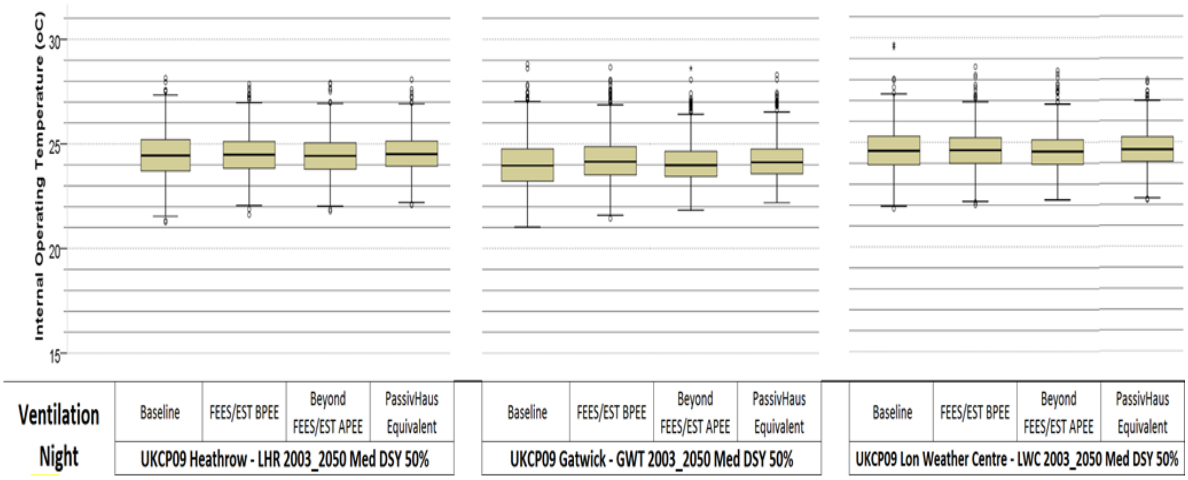


Figure 8.5 Box and whiskers plots for night ventilation scenario comparison of the internal operative temperatures effect of four standardized construction specifications based on 2003-2050 DSY Medium 50% probabilistic weather scenarios for Gatwick, Heathrow and London Weather Centre

The medians of the locations of the day ventilation and night ventilation scenarios across the four standardized construction specifications are roughly the same. In figure 8.4, the median values of 25.2°C, 24.6°C and 25.4°C are observed in the Heathrow, Gatwick and London Weather Centre respectively. Similar patterns of 24.5 °C, 24.0 °C and 24.5 °C are observed in the Heathrow, Gatwick and London Weather Centre respectively for figure 8.5. An observable effect of night ventilation strategy is realised in about 1°C decrease of the median temperatures when the day and night ventilation scenarios of figure 8.4 and 8.5 respectively are compared.

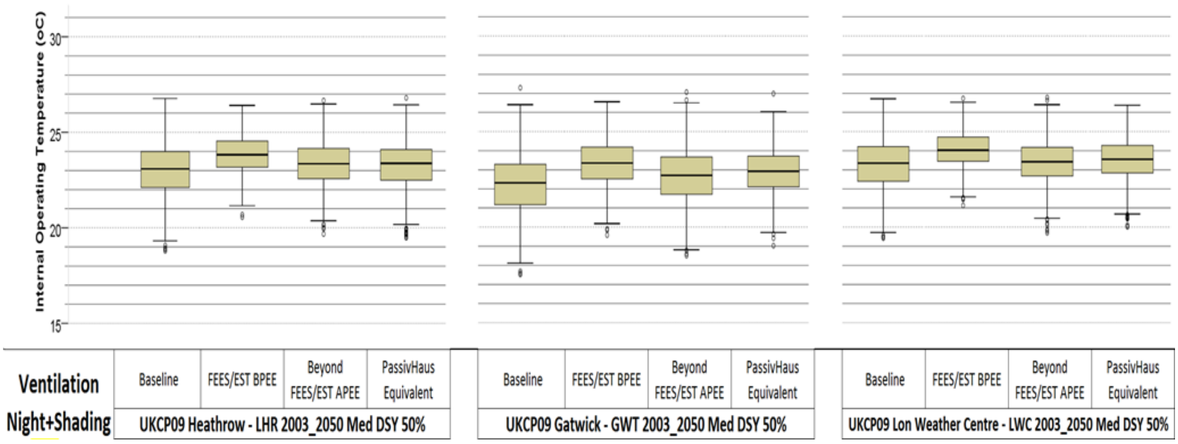


Figure 8.6 Box and whiskers plots for night ventilation with shading scenario comparison of the internal operative temperatures effect of four standardized construction specifications based on 2003-2050 DSY Medium 50% probabilistic weather scenarios for Gatwick, Heathrow and London Weather Centre

A comparison of the medians of figures 8.4 and 8.5 of Heathrow scenarios shows an internal operative temperature decrease of about 8.3% and 6.7% of the baseline and PassivHaus equivalent scenarios respectively. Similar comparison for the Gatwick scenario shows a decrease of 6.7% and 7.3% and that of London

Weather Centre of 7.8% and 7.5% respectively. This observation is similar when comparing the FEES and Beyond FEES scenarios. The findings indicate that the night ventilation coupled with shading offers an enhancement of thermal comfort in all the four standardized construction specifications.

Moreover, the baseline uncertainties in all the scenarios indicated by larger dispersion of the interquartile range are relatively higher than all the other standardized construction specifications indicating greater variability of uncertainty and pointing to a fairly unstable thermal comfort when compared to the rest.

8.3.4 Sensitivity analysis due to climate change and building adaptation measures specified in the four (4) standardised construction specification

8.3.4.1 Tornado plot as deterministic sensitivity analysis

Figure 8.7 to 8.9 show the tornado plots for various building adaptation parameters and their influence on internal operative temperatures. The external conduction glazing is observed to be the most influential parameter affecting the internal operative temperatures in the day and night scenarios, and appearing the second most influential parameter in the night with shading scenario. The sensible load parameter shows a negative relationship with the internal operative temperature for all the three scenarios.

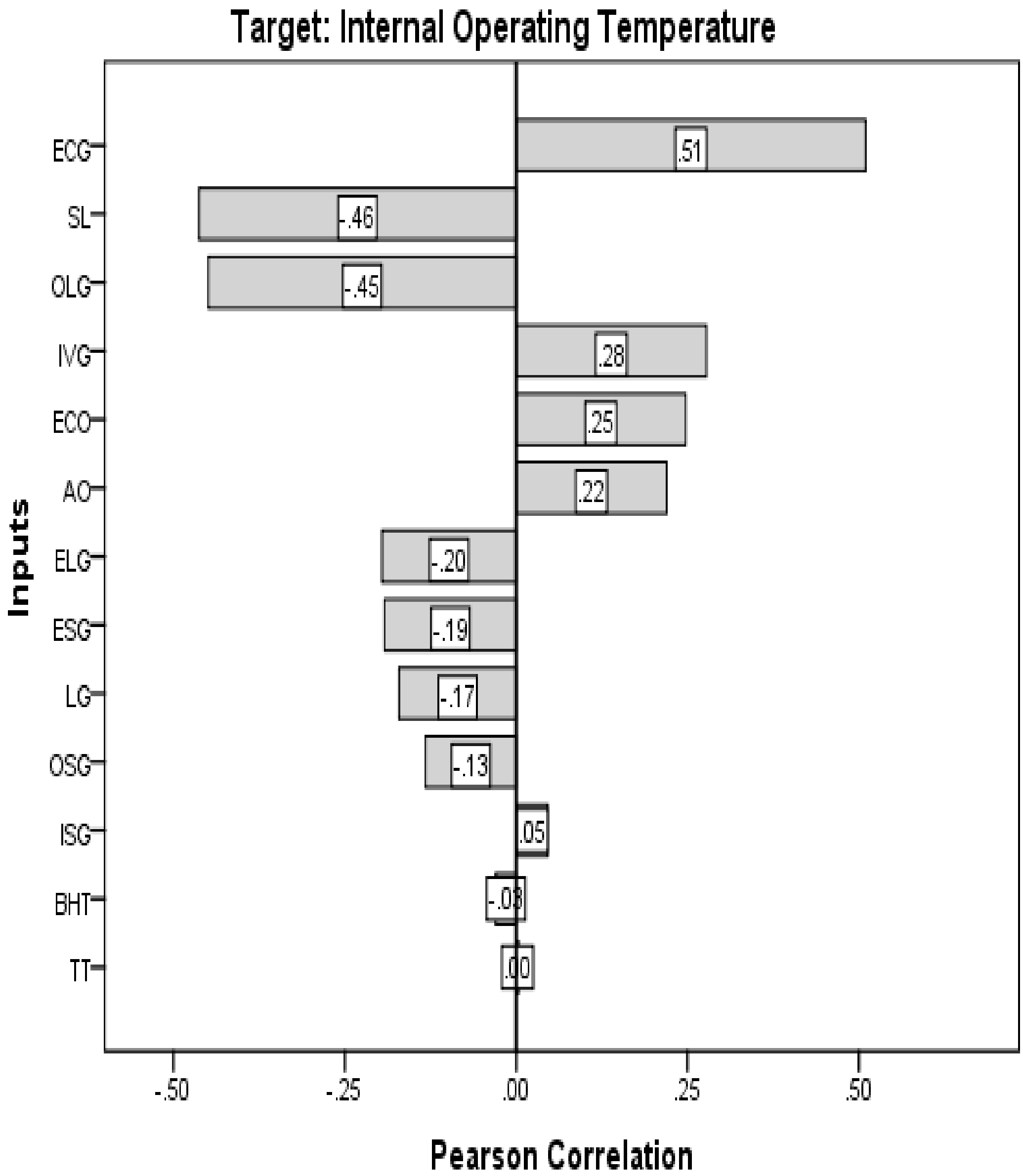


Figure 8.7 Tornado plot for baseline scenario UKCP09 GTW 2003-2050 Med 50% Day

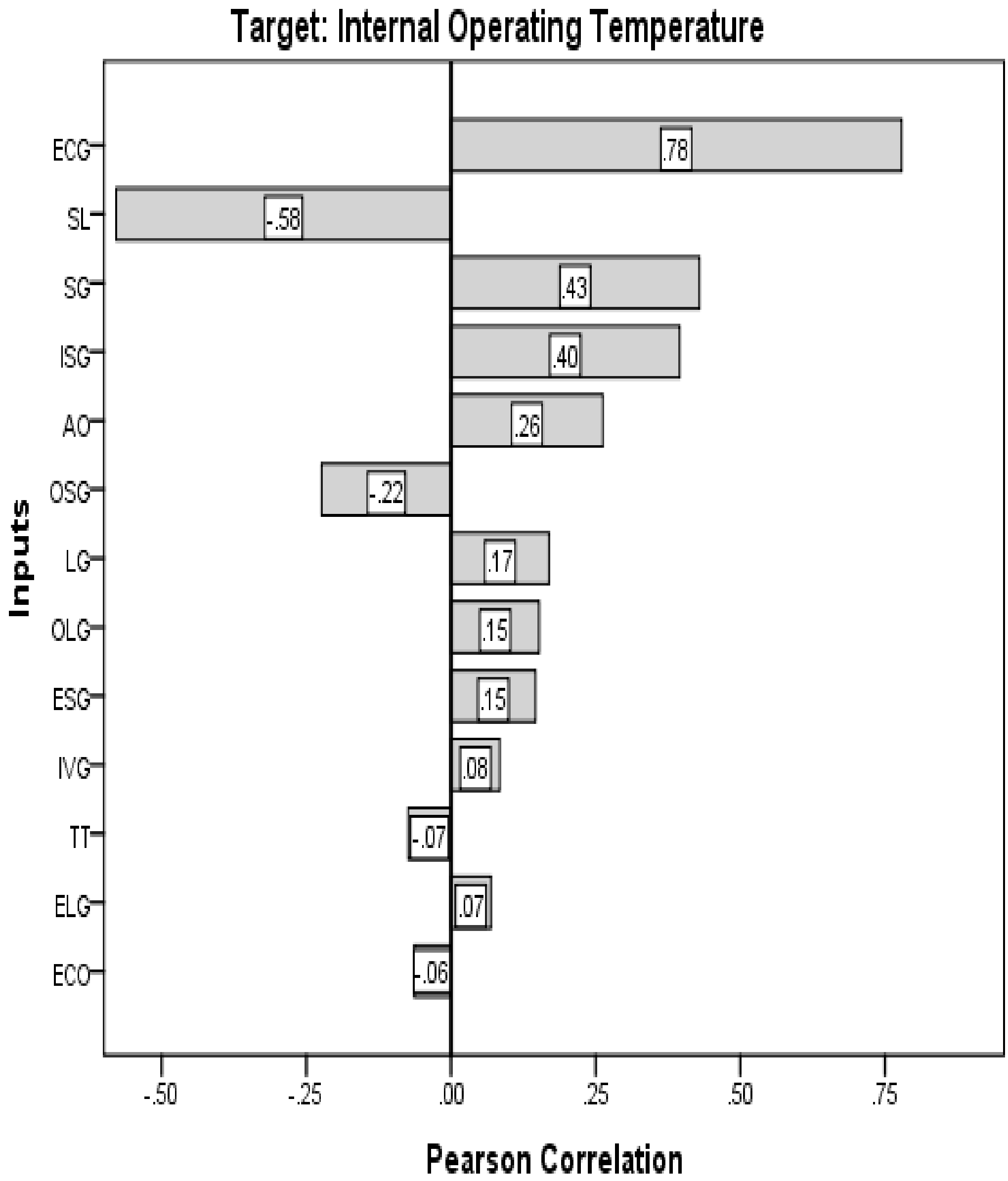


Figure 8.8 Tornado plot for baseline scenario UKCP09 GTW 2003-2050 Med 50% Night

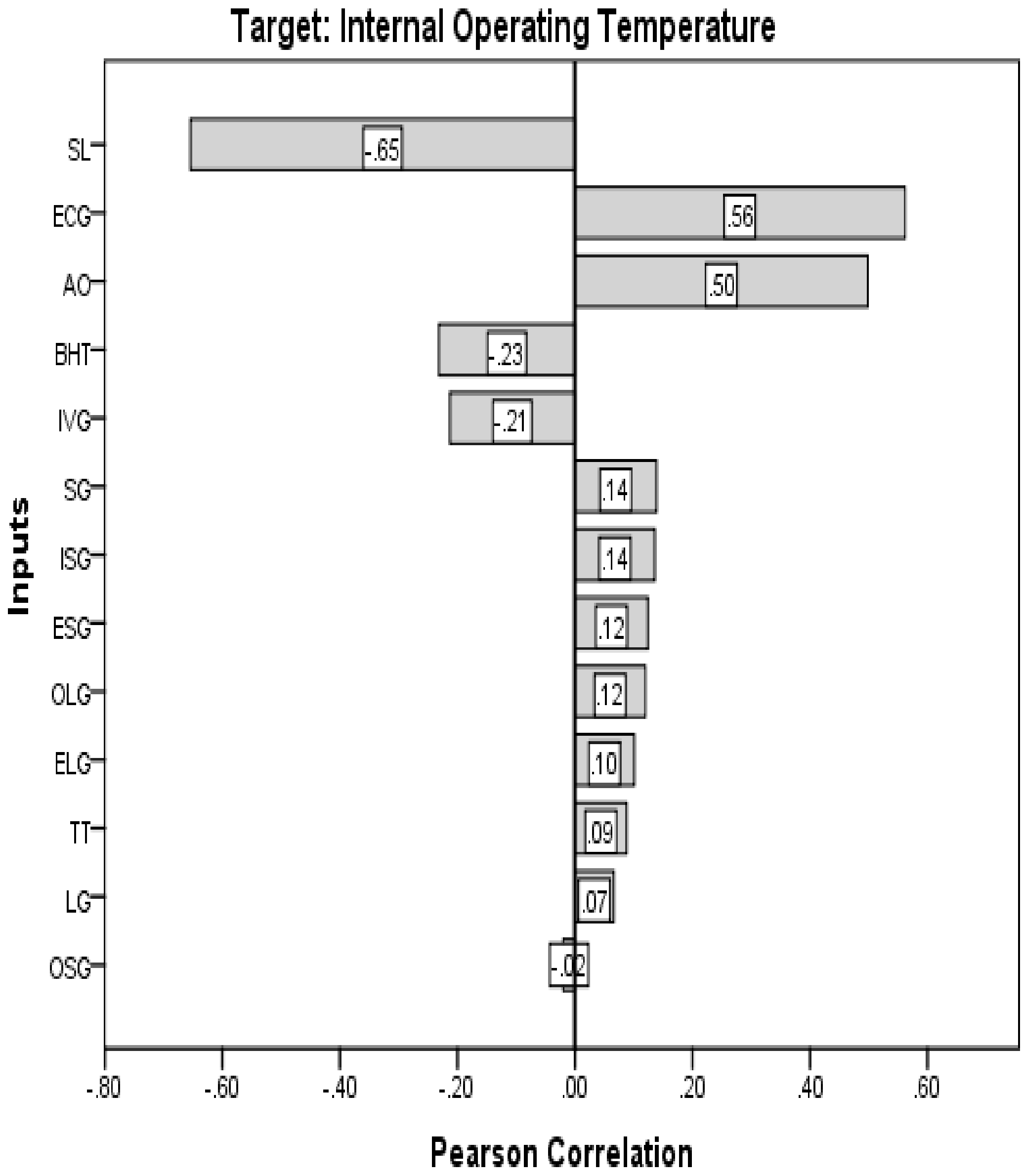


Figure 8.9 Tornado plot for baseline scenario UKCP09 GTW 2003-2050 Med 50% Night & Shading

8.3.4.2 Sensitivity analysis with SRC and PCC as sensitivity index

Figure 8.10 to 8.12 give the results of the two sensitivity methods of the standardized regression coefficient and the partial correlation coefficient as sensitivity analysis indices which assess the relative importance of the building parameters such as the U-values of the building façade, glazing and the internal heat gains, factors which influence the internal operative temperatures of dwellings, thus affecting thermal comfort. The results are presented for the Gatwick, Heathrow and London Weather Centre locations under day, night, and night with shading ventilation scenarios. The two sensitivity methods give similar results for all the scenarios and this confirms the robustness of the sensitivity analysis inspiring confidence in both the methodology and the results.

Similar variability of sensitivity indices is observed for particular ventilation scenarios for the three weather data sets. However, different variability is observed for the day, night and night with shading scenarios. For the day ventilation scenario for each of the three weather locations, the four most important parameters which influence the internal operative temperatures of dwellings are observed to be the glazing (designated as external conducting glazing and total transmittance or G-value), occupancy sensible gain, occupancy latent gain and equipment latent gain.

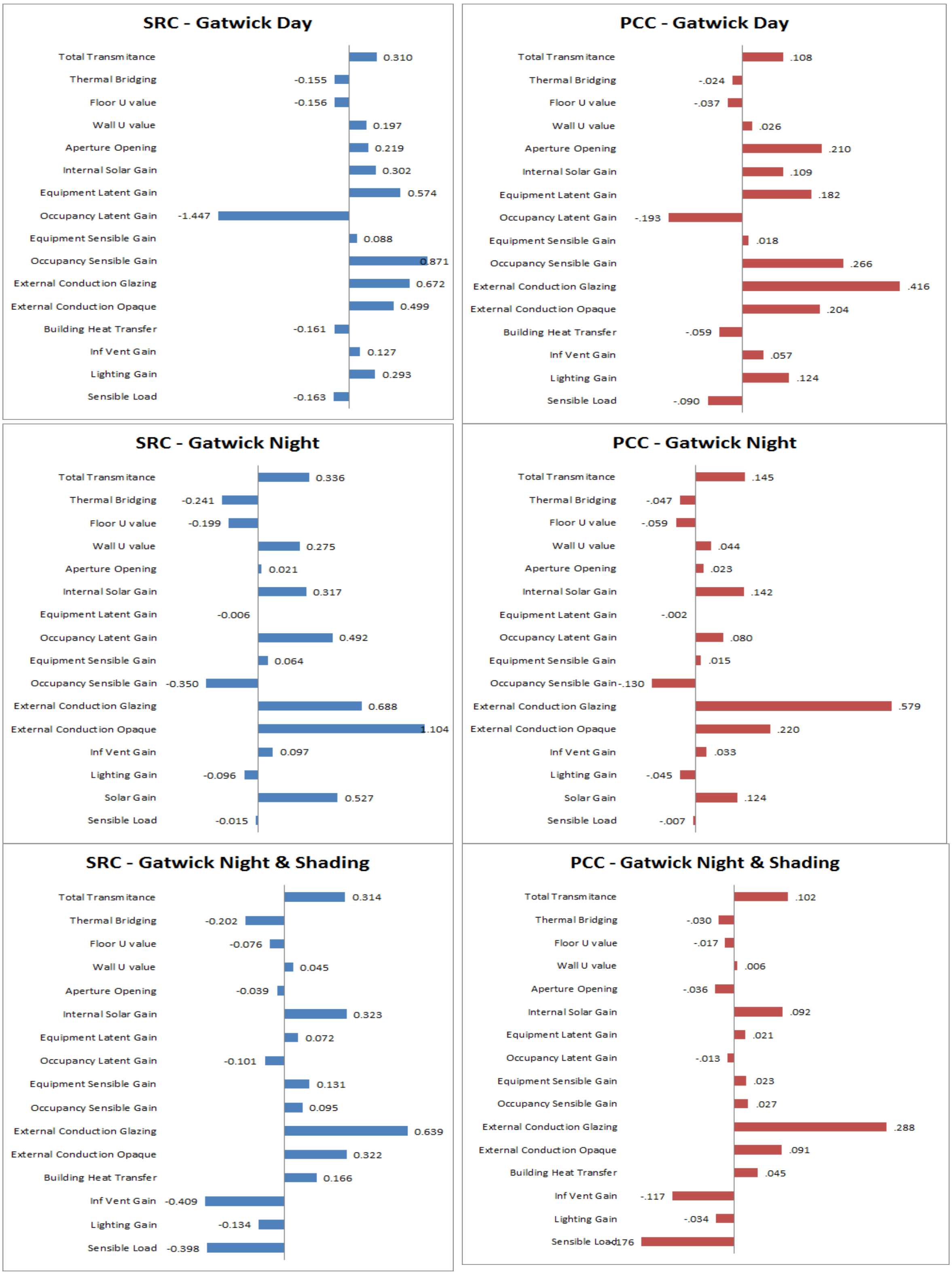


Figure 8.10 Comparison of the standardized regression coefficient (SRC) and the partial correlation coefficients (PCC) of the future building adaptation measures input variables for the standardized construction specifications based on UKCP09 GTW 2003-2050 Med 50% weather data for Gatwick under day, night and night with shading ventilation scenarios.

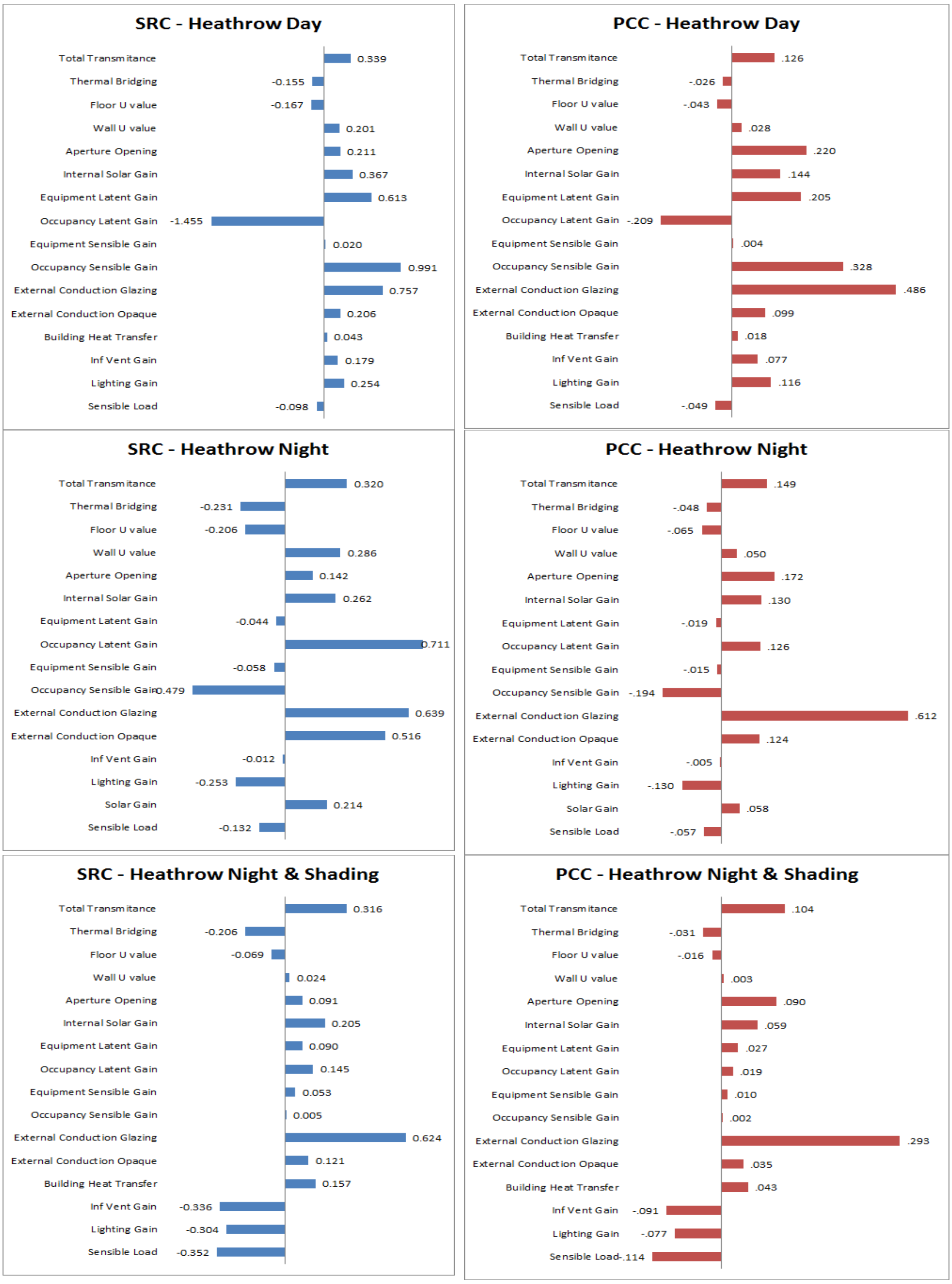


Figure 8.11 Comparison of the standardized regression coefficient (SRC) and the partial correlation coefficients (PCC) of the future building adaptation measures input variables for the standardized construction specifications based on UKCP09 LHR 2003-2050 Med 50% weather data for Heathrow under day, night and night with shading ventilation scenarios.

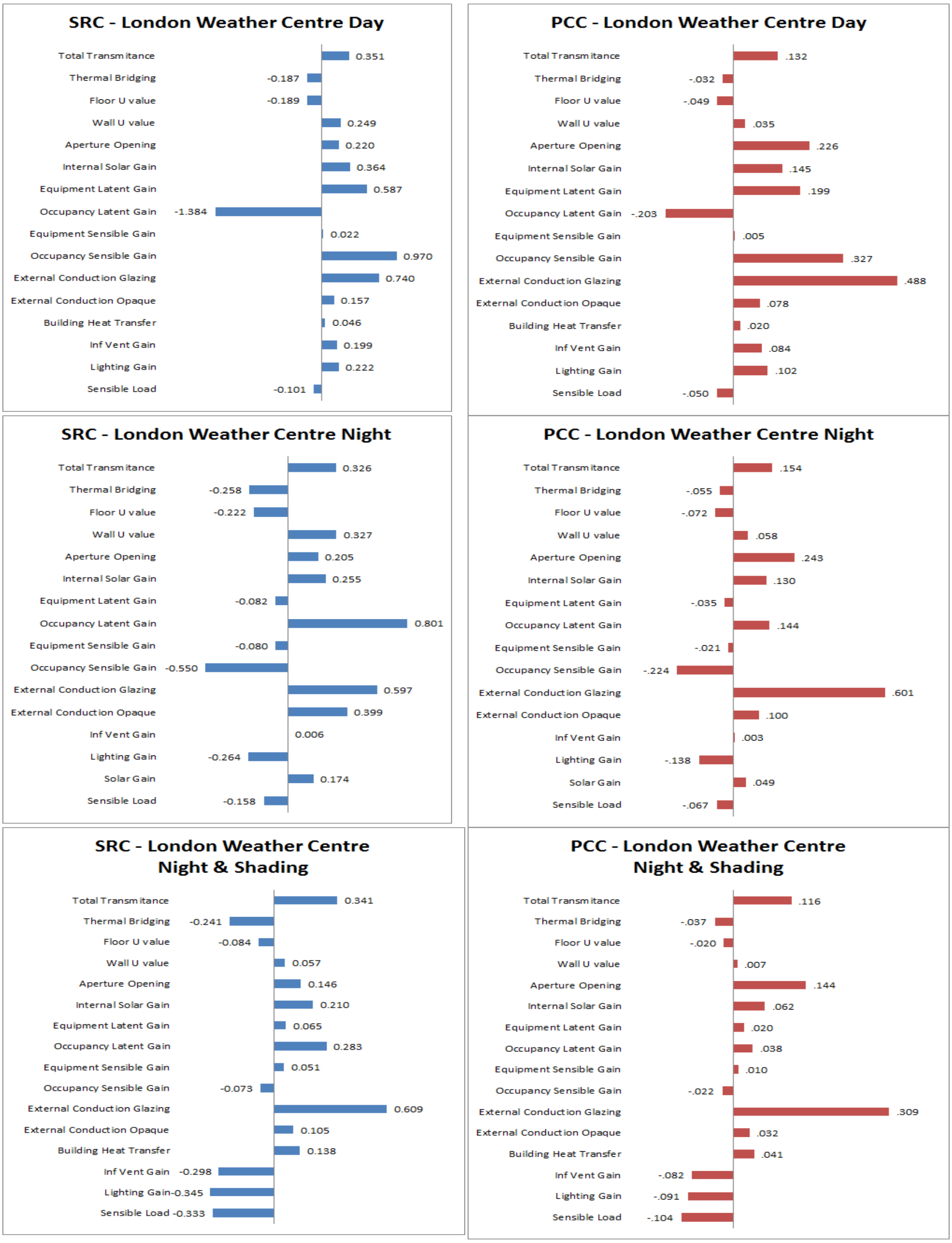


Figure 8.12 Comparison of the standardized regression coefficient (SRC) and the partial correlation coefficients (PCC) of the future building adaptation measures input variables for the standardized construction specifications based on UKCP09 LWC 2003-2050 Med 50% weather data for London Weather Centre under day, night and night with shading ventilation scenarios.

The sensitivity of glazing to thermal comfort increases from Gatwick, with London Weather Centre having the highest sensitivity index. This could be attributed to the urban heat island effect of central London, leading to higher internal operative temperatures.

For the night ventilation and night with shading ventilation scenarios, the glazing is the most dominant parameter for both the SRC and PCC, pointing to the high significance of glazing in enhancing thermal comfort. As expected, increasing the external conducting glazing and the total transmittance has a direct bearing on increasing the internal operative temperatures.

The occupancy latent gain has a significant opposite effect on internal operative temperatures for the day and night ventilation scenarios for all the three locations. The analysis also confirms the expectation that increasing thermal bridging has the opposite effect on the internal operative temperatures which could be observed in all the three ventilation scenarios.

It is observed in all the locations analysis that the U-values (for floor and wall) and the thermal bridging have relatively little variability with the internal operative temperature for all the day ventilation scenarios, with increasing importance in the night and night with shading ventilation scenarios.

Thus the study shows that more consideration should be given to glazing and internal heat gains than floor and wall construction when seeking to improve the thermal comfort of dwellings.

8.4 Summary and Conclusion

The case study presents a Monte Carlo uncertainty and sensitivity analysis in quantifying and predicting the most influential building envelope and systems parameters which affect dwellings' thermal comfort. The analysis was based on the four standardized construction specifications as building adaptation strategy. The thermal analysis simulation was underpinned by the CIBSE TM49 weather data set for 2003-2050 medium design summer year with 50% probabilistic scenario timeline and the CIBSE TM52 adaptive thermal comfort criteria for overheating analysis.

The deterministic analysis of the three data sets indicated that the optimum thermal mass with the appropriate mitigation scenarios of night ventilation and shading have a significant impact on reducing maximum internal operative temperatures of about 1^{o}C to 3^{o}C for respective scenarios. This could enhance thermal comfort in dwellings. The PassivHaus equivalent presented the most stable internal operative temperature conditions as already concluded in case study 4 of chapter 7.

The Monte Carlo uncertainty simulation of overheating analysis was performed for Gatwick, Heathrow and London Weather Centre, with reference to variations due to the intervention of the designated standard construction specifications with their changes to the 22 parameters such as U-values of the building envelope, the total transmittance (G-value) and the internal heat gains.

The uncertainty analysis results indicate a uniform variability of the day and night ventilation scenarios with decreasing interquartile ranges, outer ranges and median values across the four standard construction specifications. The irregular variability of the Fabric Energy Efficiency Standard (FEES) standard having larger medians in all the three weather locations coupled with comparatively small interquartile range and the outer range of dispersion may suggest higher internal operative temperatures under the night ventilation with shading scenario.
The medians for the day ventilation scenarios are generally higher than those of the night ventilation and further higher than the night ventilation with shading scenarios. This observation points to the fact that applying the mitigation scenarios of night ventilation and shading have a significant impact on reducing internal operative temperatures, and thus enhancing thermal comfort in dwellings. The PassivHaus equivalent presented the most stable internal operative temperature conditions as its plot showed less uncertainty. This is in consonance with the conclusions made in case study 4 of chapter 7.

The Monte Carlo sensitivity analysis results focused on two sensitivity methods of standardized regression coefficient and the partial correlation coefficient as sensitivity analysis indices. Two indices are used to ascertain the robustness of the sensitivity analysis inspiring confidence in both the methodology and the results. The sensitivity analysis results indicated that glazing is the most dominant parameter for both the SRC and PCC. This indicates that glazing may be the most significant parameter to influence thermal comfort. In addition to glazing, total transmittance was also observed to have a positive effect in increasing the internal operative temperatures. However, the occupancy latent gain has a significant opposite effect on internal operative temperature. The study indicated that more consideration should be given to glazing and internal heat gains than floor and wall construction when seeking to improve the thermal comfort of dwellings.

CHAPTER 9: Conservatory as a passive design solution

9.0 Case study 6 - Impact of Conservatory on dwelling energy performance and internal temperatures with application of integrated passive design strategies to optimize the energy performance and thermal comfort of dwellings using CIBSE TM52 adaptive thermal comfort criteria as an assessment tool

9.1 Introduction

This chapter focuses on the viability of passive solar design strategies of UK conservatories and shows that passive solar energy utilization in building design can contribute to the reduction of dwelling energy consumption and enhancement of indoor thermal comfort. In general there is absence of modelling and simulation research/current publication into the use of conservatories as passive design solution in the UK. A review of over 70 simulation-based optimization of passive design strategies research publications since 2000 by Sanja Stevanovic made no mention of conservatories as a passive design solution in UK (Stevanovic 2013).

Synergetic passive design strategies that seek to optimize solar energy gains through thermal simulation analysis of design criteria of varying future climatic conditions, variable occupant behaviour, building orientation, adequate provision of thermal mass, advance glazing, appropriate ventilation and sufficient level of shading which influence the potential thermal performance of conservatory is performed. The balance energy benefits of reduction of energy consumption through the application of these principles of passive solar design for space heating in winter and the challenge of reducing excessive solar gains in summer is analysed using the CIBSE adaptive thermal comfort criteria and statistical methods of the data collected from the thermal simulation. Deterministic analysis and optimisation investigation are performed to determine the impact of system parameters such as floor area, aspect ratio and surface to volume ratio on thermal performance of conservatories. The results show that the judicious integration of the passive solar design strategies in conservatories with increasing conservatory size in elongated south facing orientation with an aspect ratio of at least 1.67 could on an average decrease annual energy consumption (by 5 kWh/m^2), building emission rate (by 2.0 $KgCO_2/m^2$) and annual gas consumption (by 7 kWh/m^2) when the conservatory is neither heated nor air-conditioned. Moreover, the CIBSE TM52 overheating analysis showed that the provision of optimum ventilation strategy depending on the period of the year coupled with the efficient design of awnings/overhangs and the provision of external adjustable shading on the east and west facades of the conservatory could significantly enhance the thermal comfort of conservatories.

9.2 Research Method 6 – For Case Study 6

Detailed method for case study 6 is discussed in chapter 3 section 3.2.8.

9.3 Results and Discussion

The analysis of case study building , 49 Carnation Drive; a 1995 three-bedroom two-storey residential detached building located at Bracknell, Berkshire, with the three conservatory designs is presented below. Figures 9.1 (a) - (d) represent the outcome of the modelling process. The entire major façade of the conservatories was southerly orientated with an aspect ratio of at least 1.67.

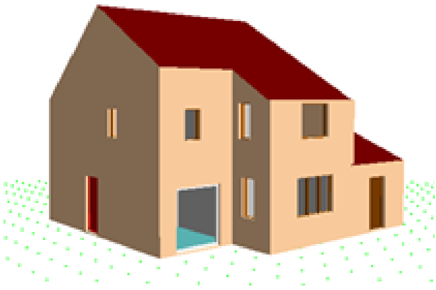


Figure. 9.1(a) 49 Carnation Drive – South facing orientation

Figure. 9.1(b) 49 Carnation Drive and Conservatory 1

Figure 9.1(c) 49 Carnation Drive and Conservatory 2

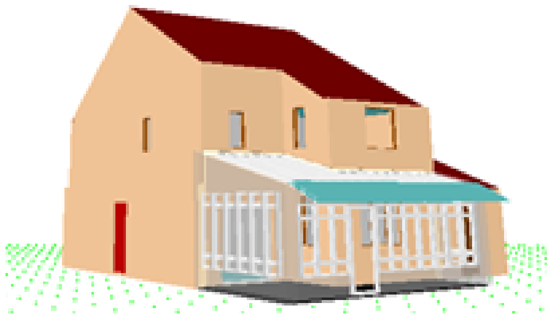


Figure 9.1(d) 49 Carnation Drive and Conservatory 3

Figure 9.1 Modelling Results

9.3.1 Energy performance results and analysis

Figures 9.2 to 9.4 give the statistical results of energy performance of annual energy consumption, building emission rate and annual natural gas consumption for the current and future weather data set for all three conservatory design scenarios. The analysis further considers quantification of overheating impact on energy performance when the conservatories are heated and cooled during the respective seasons.

The annual energy consumption results indicated in figures 9.2(a) – 9.2(c) show an observable decrease in energy consumption for all the three conservatory designs in scenario 2; when the attached conservatory to the main building is neither heated nor cooled throughout the heating and non-heating seasons. A declining trend is observed in the respective climate change progression timelines of current, 2020s, 2050s and 2080s for all conservatory designs. The mean percentage decrease of annual energy consumptions for conservatory 1 to 3 was 12.17, 14.23 and 21.45 respectively and this amount to 3.98, 4.72 and 7.13 kWh/m^2 respectively. This declining trend points to a general decrease in annual energy consumption with progressive increase in conservatory floor area/surface area and indicates a significant contribution to dwelling energy consumption when a conservatory is attached to it.

At periods of low air temperatures coupled with high solar radiation, pre-heated air in the conservatory is transferred to the main dwelling. This convective heat gain leads to the reduction of the main building heat load contribution from a mechanical heating system. In addition, increasing the conservatory dimension along the southern orientation contributes to the provision of additional insulation of the main dwelling. This increasing buffer effect results in a decrease in heat loss from the main dwelling and hence reducing its heating load. At the same time, the progressive increase of the elongated south façade of the conservatory with its coated low emissivity double glazing coupled with the effective design of awnings/overhang which maximize the incident solar radiation collection during the heating season, low level ventilation and the provision of adequate thermal mass for the conservatory floor and dwarf walls all contribute to the passive design consideration leading to the reduction of heating load of the main dwelling.

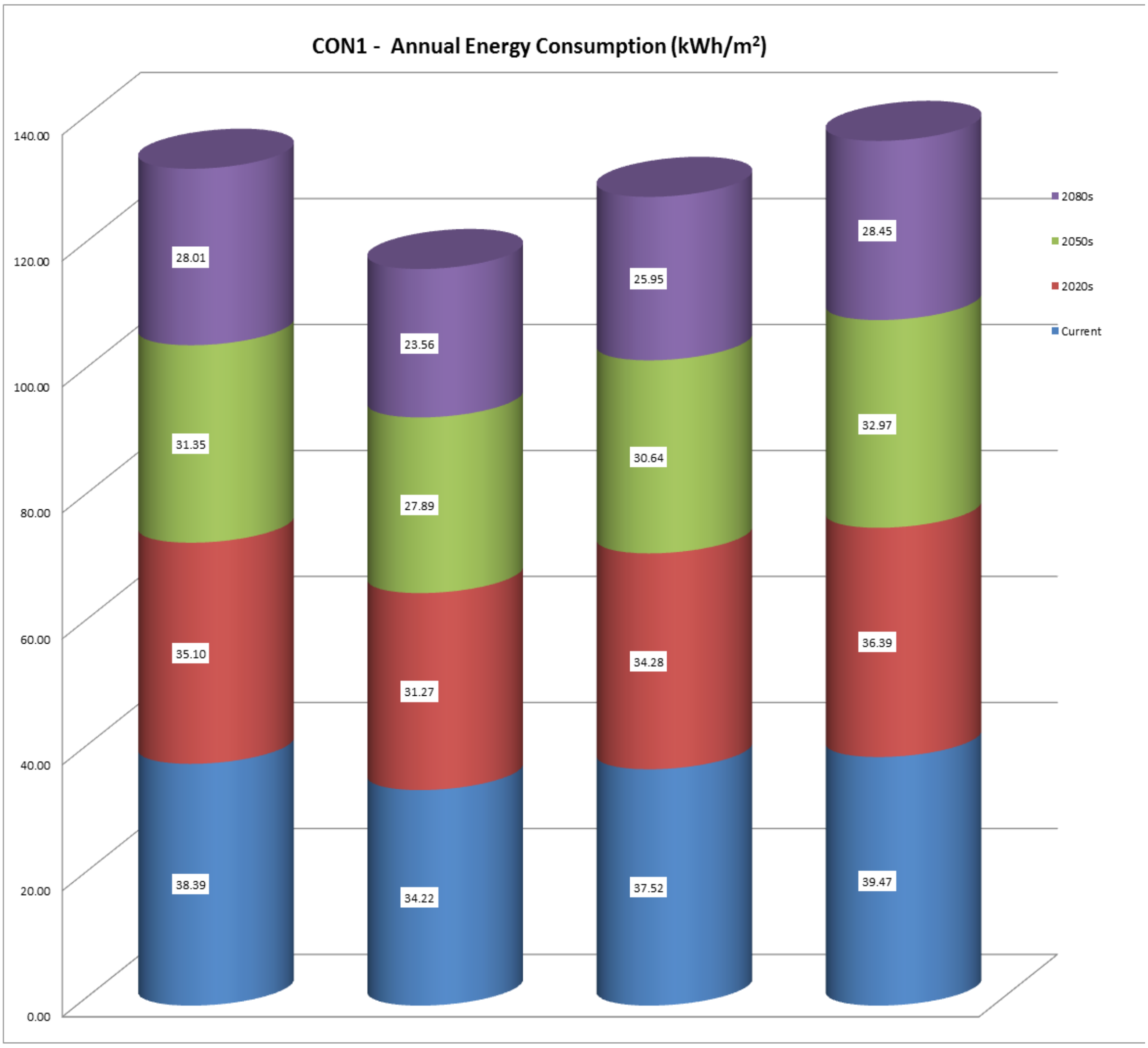
However, the annual energy consumption gains are negated in scenario 3 when the conservatories are heated during the heating season. The mean percentage of annual energy consumption lost due to the heating of the three conservatories was observed to be 9.82, 16.63 and 29.99 for the current and future weather data set. This trend points to increasing loss of overall annual energy consumption with increasing conservatory dimensions when the conservatories are heated during the heating season.

In scenario 4, when the attached conservatories to the main building are heated during the heating season and cooling is applied during the non-heating season, a further lost in annual energy consumption gains is realised. The mean percentage annual energy consumption lost due to the heating and cooling of the three conservatories was observed to be 17.67, 30.42 and 55.06 for the current and future weather data sets. This trend further point to the increasing loss of overall annual energy consumption with increasing conservatory dimensions when the conservatories are heated and cooled during the respective heating and non-heating seasons of the year.

The potential overheating impact on energy consumption due to the introduction of air-conditioning for cooling in the three conservatories amount to an average of 1.67, 2.95 and 5.00 kWh/m^2 for the three conservatories with increasing size respectively.

CON1 - Annual Energy Consumption (kWh/m^2)

	S1	S2	S3	S4		%Dec Con1 Unheated & Uncooled	%Dec Con1 Heated but Uncooled	% Lost due to Con1 Heated but Uncooled	% Lost due to Con1 Heated & Cooled	Cooling Demand
Current	38.39	34.22	37.52	39.47		10.86	2.27	9.64	15.34	1.35
2020s	35.10	31.27	34.28	36.39		10.91	2.34	9.63	16.37	1.54
2050s	31.35	27.89	30.64	32.97		11.04	2.26	9.86	18.21	1.78
2080s	28.01	23.56	25.95	28.45		15.89	7.35	10.14	20.76	2.01
					Mean %Dec	12.17	3.56	9.82	17.67	1.67
					Std. Dev	2.48	2.53	0.24	2.37	0.29

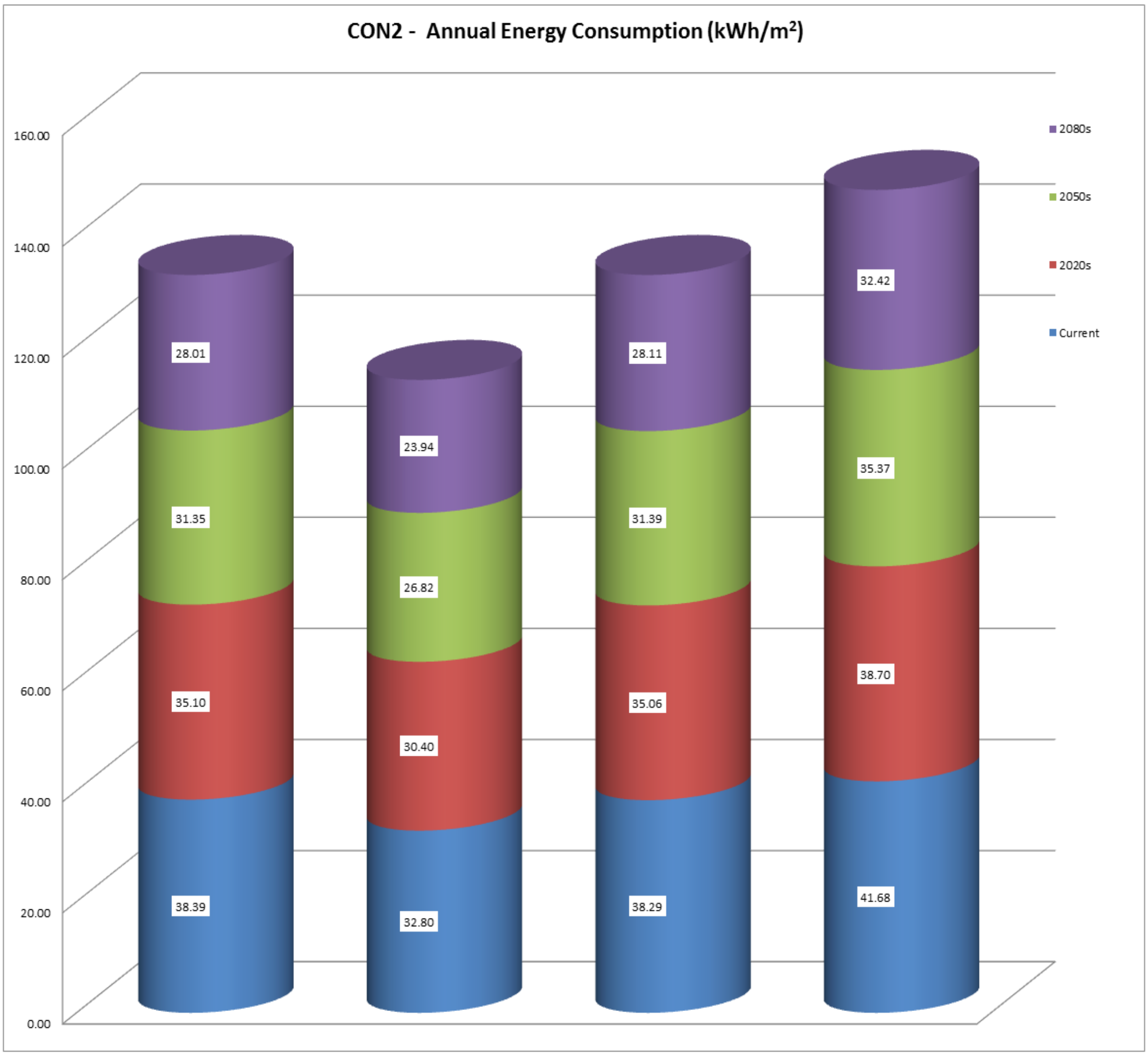


S1 - Senario 1 - Main building heating in the absence of conservatory
S2 - Senario 2- Main building heating with conservatory attached but conservatory is not heated and cooled
S3 - Senario 3- Main building heating with conservatory attached and conservatory is heated but not cooled
S4 - Senario 4- Main building heating with conservatory attached and conservatory is heated and cooled

Figure 9.2 (a) Conservatory 1 – Annual Energy Consumption (kWh/m^2)

CON2 - Annual Energy Consumption (kWh/m^2)

	S1	S2	S3	S4		%Dec Con2 Unheated & Uncooled	%Dec Con2 Heated but Uncooled	% Lost due to Con2 Heated but Uncooled	% Lost due to Con2 Heated & Cooled	Cooling Demand
Current	38.39	32.80	38.29	41.68		14.56	0.26	16.74	27.07	2.44
2020s	35.10	30.40	35.06	38.70		13.39	0.11	15.33	27.30	2.74
2050s	31.35	26.82	31.39	35.37		14.45	-0.13	17.04	31.88	3.12
2080s	28.01	23.94	28.11	32.42		14.53	-0.36	17.42	35.42	3.49
					Mean %Dec	14.23	-0.03	16.63	30.42	2.95
					Std. Dev	0.56	0.27	0.91	4.00	0.46

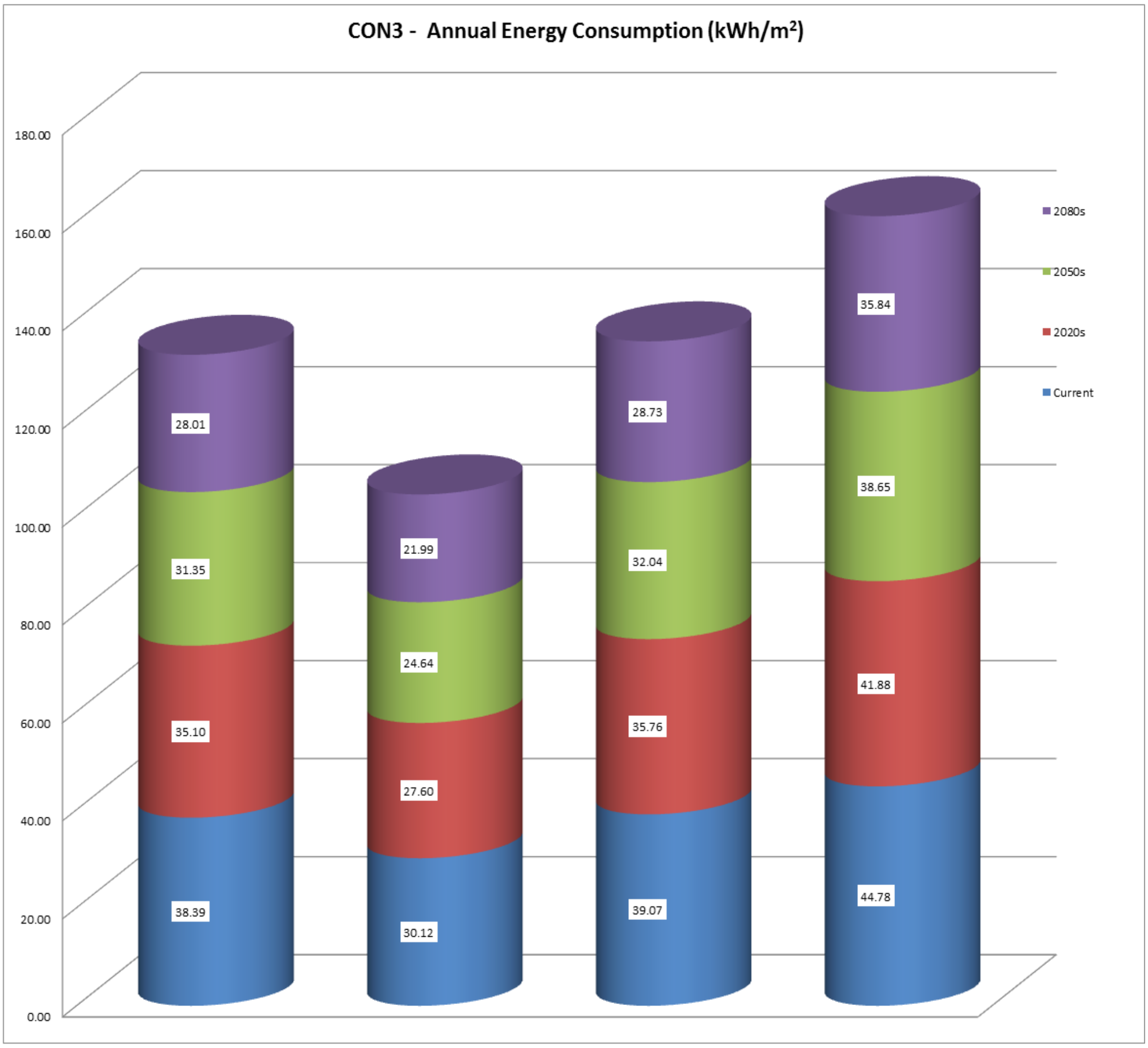


S1 - Senario 1 - Main building heating in the absence of conservatory
S2 - Senario 2- Main building heating with conservatory attached but conservatory is not heated and cooled
S3 - Senario 3- Main building heating with conservatory attached and conservatory is heated but not cooled
S4 - Senario 4- Main building heating with conservatory attached and conservatory is heated and cooled

Figure 9.2 (b) Conservatory 2 – Annual Energy Consumption (kWh/m^2)

CON3 - Annual Energy Consumption (kWh/m^2)

	S1	S2	S3	S4		%Dec Con3 Unheated & Uncooled	%Dec Con3 Heated but Uncooled	% Lost due to Con3 Heated but Uncooled	% Lost due to Con3 Heated & Cooled	Cooling Demand
Current	38.39	30.12	39.07	44.78		21.54	-1.77	29.71	48.67	4.23
2020s	35.10	27.60	35.76	41.88		21.37	-1.88	29.57	51.74	4.70
2050s	31.35	24.64	32.04	38.65		21.40	-2.20	30.03	56.86	5.25
2080s	28.01	21.99	28.73	35.84		21.49	-2.57	30.65	62.98	5.83
					Mean %Dec	21.45	-2.11	29.99	55.06	5.00
					Std. Dev	0.08	0.36	0.48	6.27	0.69



S1 - Senario 1 - Main building heating in the absence of conservatory
S2 - Senario 2- Main building heating with conservatory attached but conservatory is not heated and cooled
S3 - Senario 3- Main building heating with conservatory attached and conservatory is heated but not cooled
S4 - Senario 4- Main building heating with conservatory attached and conservatory is heated and cooled

Figure 9.2 (c) Conservatory 3 – Annual Energy Consumption (kWh/m^2)

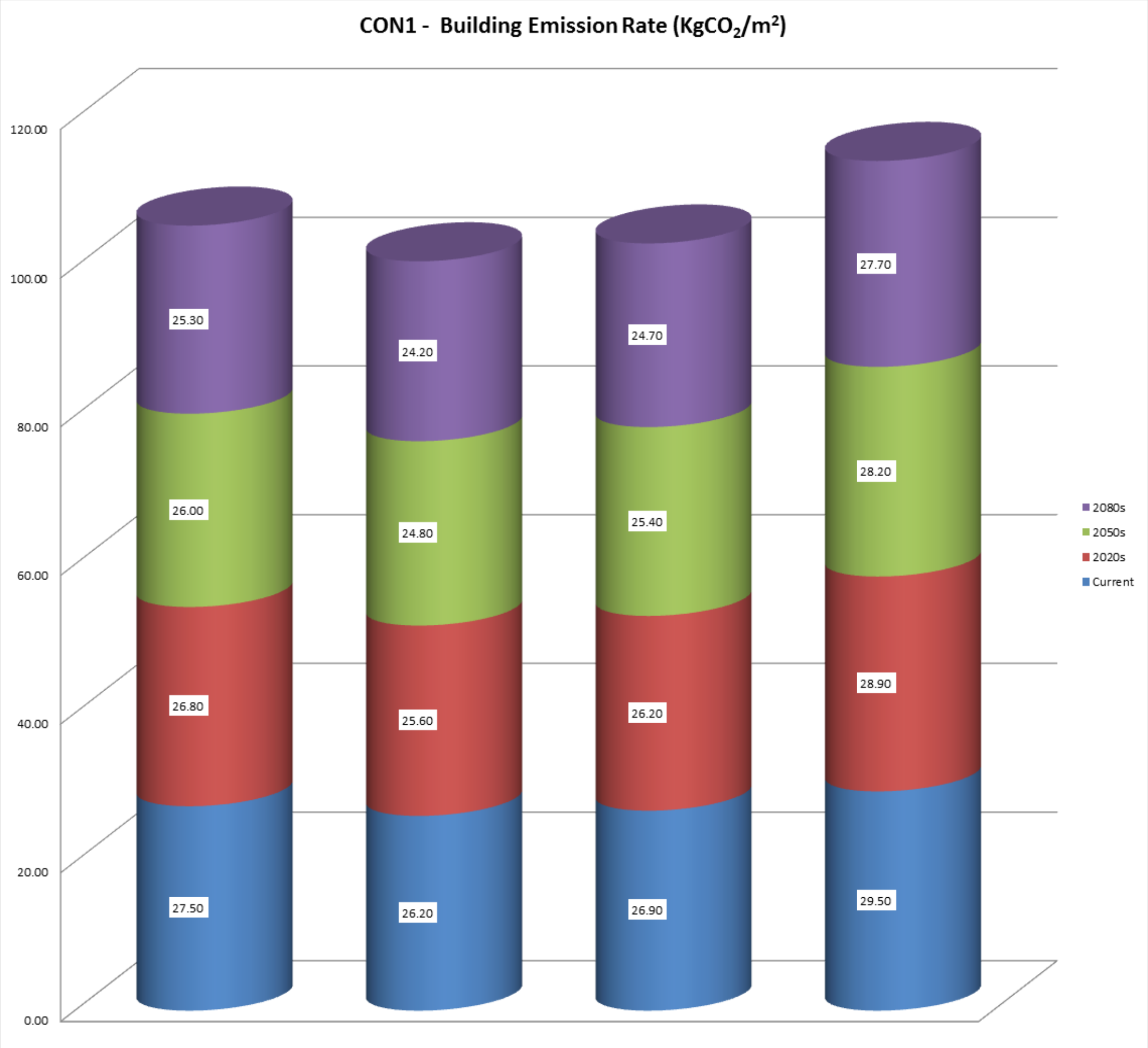
The building emission rate results indicated in figures 9.3(a) – 9.3(c) show an observable decrease in emission rate for all the three conservatory designs in scenario 2; when the attached conservatory to the main building is unheated throughout the heating season. The declining trend is observed in the respective climate change progression timelines of current, 2020s, 2050s and 2080s for all conservatory designs. The mean percentage decrease of building emission rate for conservatory 1 to 3 was 4.54, 6.62 and 11.07 respectively and these amount to 1.20, 1.75 and 2.93 $KgCO_2/m^2$ respectively. This declining trend points to a general decrease in building emission rate with progressive increase in conservatory floor area/surface area and indicate a significant contribution to dwelling emission rate when an unheated and uncooled conservatory is attached to it. The reasons for the declining trend could also be ascribed to the reasons outlined earlier on in relation to the declining trend associated with the annual energy consumptions.

Nevertheless, the building emission rate gains are also negated in considering scenario 3 when the conservatories are heated during the heating season. The mean percentage of building emission rate lost due to the heating of the three conservatories was observed to be 2.38, 4.25 and 7.22 for the current and future weather data set.

Again, a further negative impact is observed in scenario 4, when the conservatories are heated and cooled during the respective heating and non-heating seasons of the year. The mean percentage building emission rate lost due to the application of heating and cooling to the three conservatories was observed to be 13.41, 22.65 and 38.70 for the current and future weather data sets.

CON1 - Building Emission Rate ($KgCO_2/m^2$)

	S1	S2	S3	S4		%Dec Con1 Unheated & Uncooled	%Dec Con1 Heated but Uncooled	% Lost due to Con1 Heated but Uncooled	% Lost due to Con1 Heated & Cooled
Current	27.50	26.20	26.90	29.50		4.73	2.18	2.67	12.60
2020s	26.80	25.60	26.20	28.90		4.48	2.24	2.34	12.89
2050s	26.00	24.80	25.40	28.20		4.62	2.31	2.42	13.71
2080s	25.30	24.20	24.70	27.70		4.35	2.37	2.07	14.46
					Mean %Dec	4.54	2.27	2.38	13.41
					Std. Dev	0.16	0.08	0.25	0.84



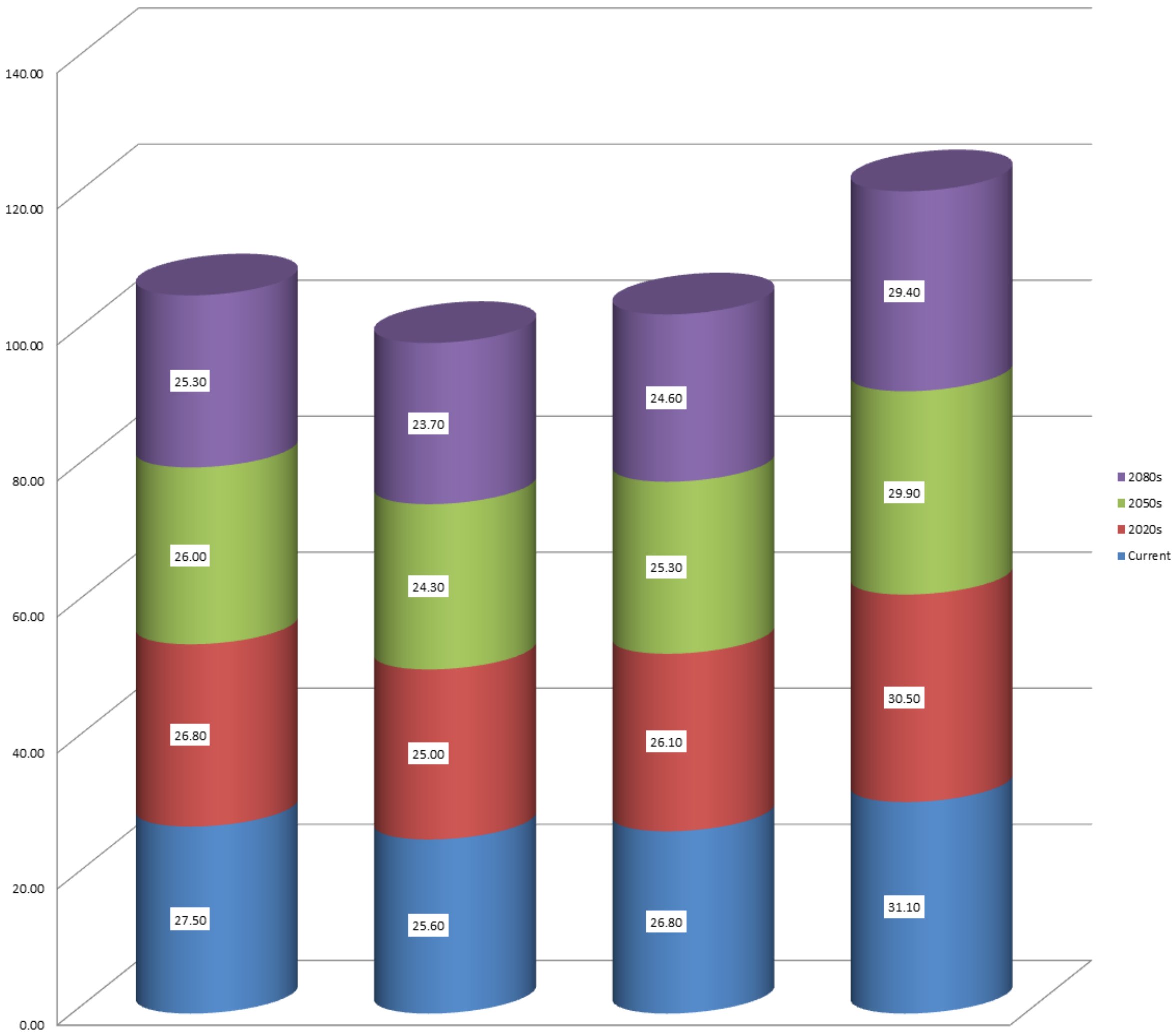
S1 - Senario 1 - Main building heating in the absence of conservatory
S2 - Senario 2- Main building heating with conservatory attached but conservatory is not heated and cooled
S3 - Senario 3- Main building heating with conservatory attached and conservatory is heated but not cooled
S4 - Senario 4- Main building heating with conservatory attached and conservatory is heated and cooled

Figure 9.3 (a) Conservatory 1 – Building Emission Rate ($KgCO_2/m^2$)

CON2 - Building Emission Rate ($KgCO_2/m^2$)

	S1	S2	S3	S4		%Dec Con2 Unheated & Uncooled	%Dec Con2 Heated but Uncooled	% Lost due to Con2 Heated but Uncooled	% Lost due to Con2 Heated & Cooled
Current	27.50	25.60	26.80	31.10		6.91	2.55	4.69	21.48
2020s	26.80	25.00	26.10	30.50		6.72	2.61	4.40	22.00
2050s	26.00	24.30	25.30	29.90		6.54	2.69	4.12	23.05
2080s	25.30	23.70	24.60	29.40		6.32	2.77	3.80	24.05
					Mean %Dec	6.62	2.65	4.25	22.65
					Std. Dev	0.25	0.10	0.38	1.14

CON2 - Building Emission Rate ($KgCO_2/m^2$)

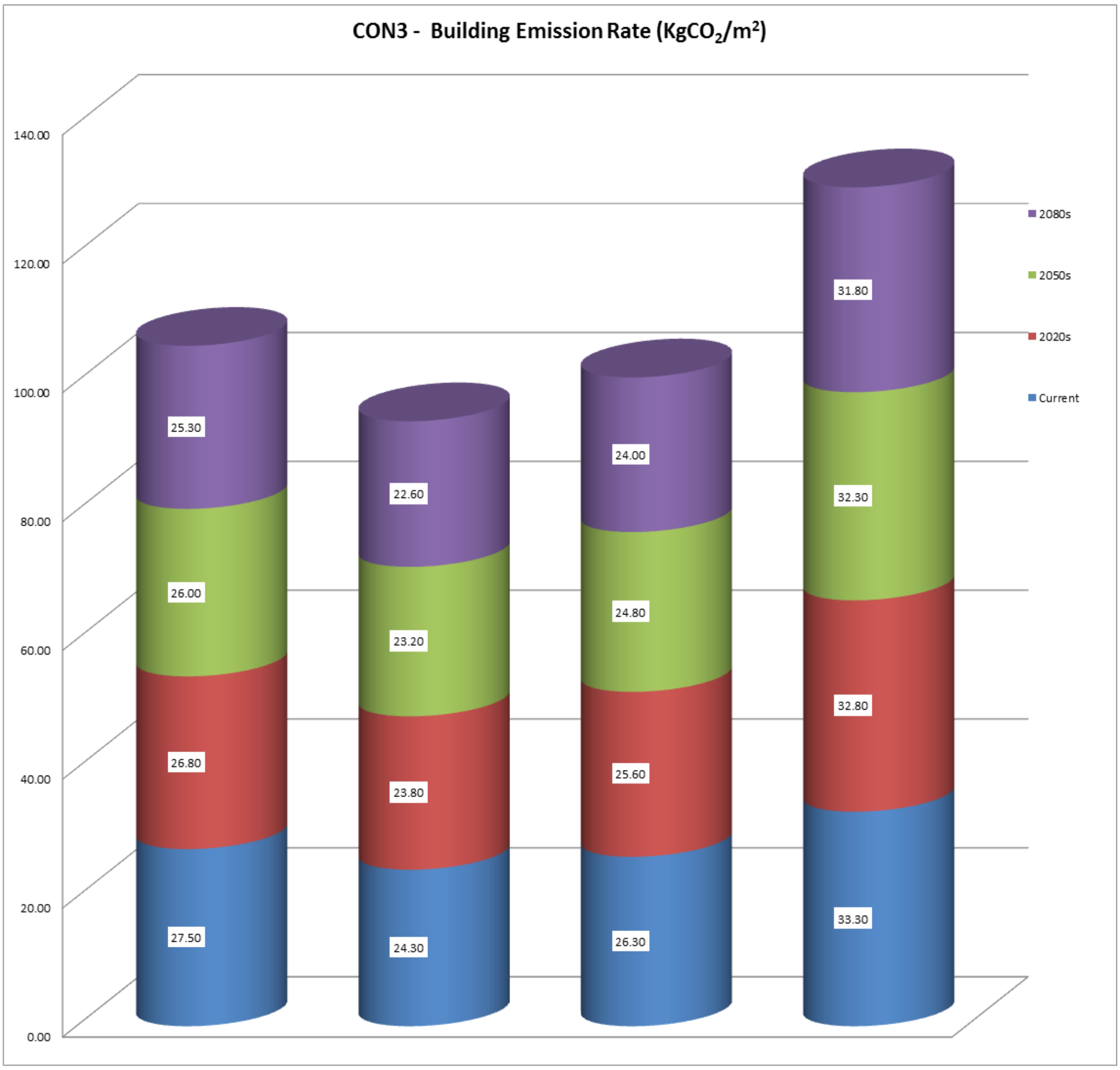


S1 - Senario 1 - Main building heating in the absence of conservatory
S2 - Senario 2- Main building heating with conservatory attached but conservatory is not heated and cooled
S3 - Senario 3- Main building heating with conservatory attached and conservatory is heated but not cooled
S4 - Senario 4- Main building heating with conservatory attached and conservatory is heated and cooled

Figure 9.3 (b) Conservatory 2 – Building Emission Rate ($KgCO_2/m^2$)

CON3 - Building Emission Rate ($KgCO_2/m^2$)

	S1	S2	S3	S4		%Dec Con3 Unheated & Uncooled	%Dec Con3 Heated but Uncooled	% Lost due to Con3 Heated but Uncooled	% Lost due to Con3 Heated & Cooled
Current	27.50	24.30	26.30	33.30		11.64	4.36	8.23	37.04
2020s	26.80	23.80	25.60	32.80		11.19	4.48	7.56	37.82
2050s	26.00	23.20	24.80	32.30		10.77	4.62	6.90	39.22
2080s	25.30	22.60	24.00	31.80		10.67	5.14	6.19	40.71
					Mean %Dec	11.07	4.65	7.22	38.70
					Std. Dev	0.44	0.34	0.87	1.62



S1 - Senario 1 - Main building heating in the absence of conservatory
S2 - Senario 2- Main building heating with conservatory attached but conservatory is not heated and cooled
S3 - Senario 3- Main building heating with conservatory attached and conservatory is heated but not cooled
S4 - Senario 4- Main building heating with conservatory attached and conservatory is heated and cooled

Fig 9.3 (c) Conservatory 3 – Building Emission Rate ($KgCO_2/m^2$)

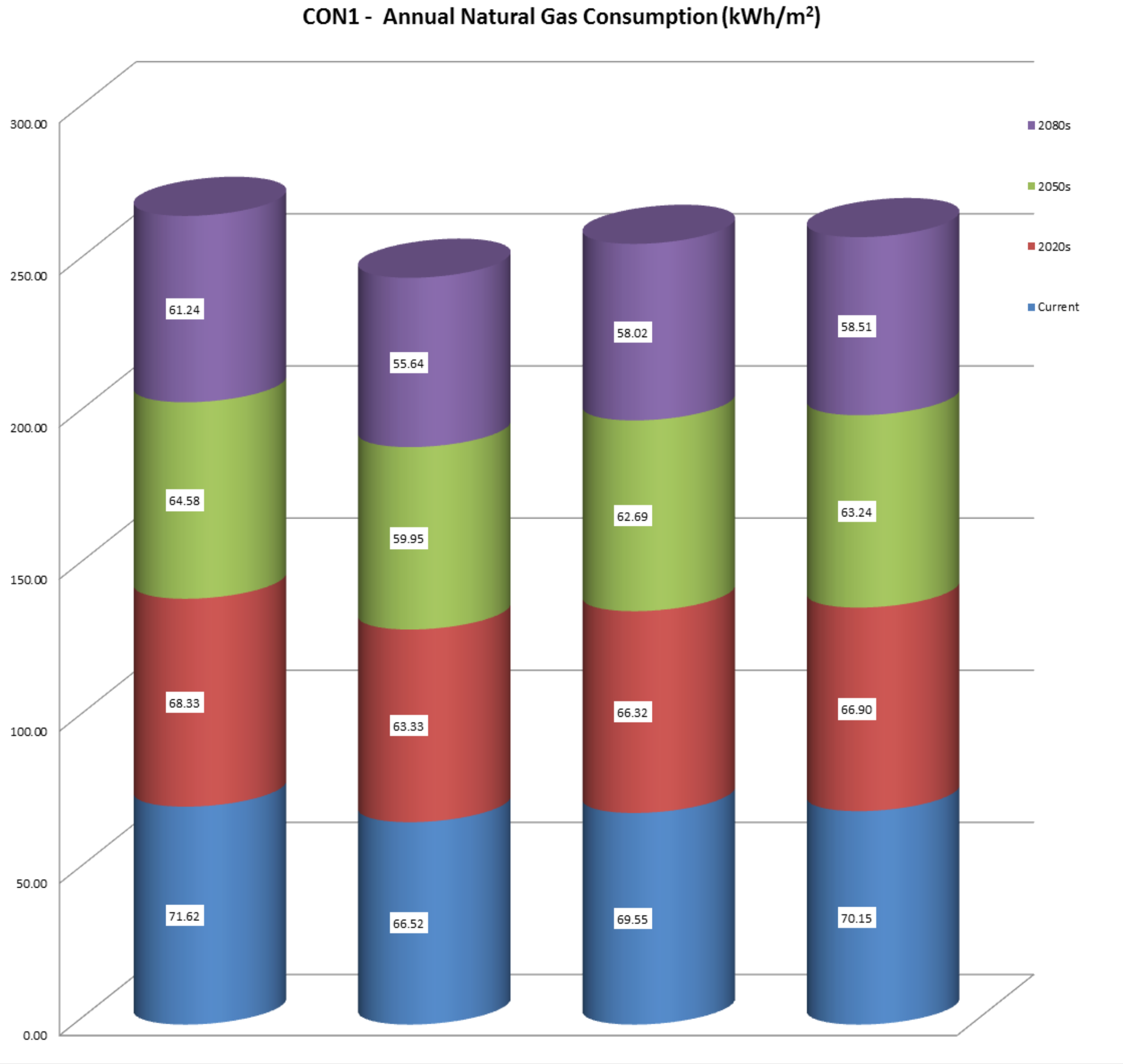
The annual gas consumption results indicated in figures 9.4(a) – 9.4(c) show an observable decrease in gas consumption for all the three conservatory designs in scenario 2; when the attached conservatory to the main building is unheated and uncooled throughout the heating and non-heating seasons respectively. The declining trend is observed in the respective climate change progression timelines of current, 2020s, 2050s and 2080s for all conservatory designs. The mean percentage decrease of annual natural gas consumption for conservatory 1 to 3 was 7.69, 9.88 and 14.56 respectively and these amounts to 5.08, 6.57 and 9.69 kWh/m^2 respectively. This declining trend points to a general decrease in annual gas consumption with progressive increase in conservatory floor area/surface area and indicate a significant contribution to a dwelling's annual natural gas consumption when a conservatory is attached to it. The reasons for the declining trend could again be ascribed to the reasons outlined earlier on in relation to the declining trend associated with the annual energy consumption.

Again, the gains attributed to the annual natural gas consumption in scenario 2 are also negated in consideration of scenario 3 when the conservatories are heated during the heating season. The mean percentage of in annual gas consumption lost due to the heating of the three conservatories was observed to be 4.53, 7.99 and 13.73 for the current and future weather data set.

Furthermore, in considering scenario 4, when the conservatories are heated and cooled in the respective seasons, a further lost in mean percentage annual gas consumption was observed to be 5.44, 9.46 and 16.16, for the current and future weather data sets

CON1 - Annual Natural Gas Consumption (kWh/m^2)

	S1	S2	S3	S4		%Dec Con1 Unheated & Uncooled	%Dec Con1 Heated but Uncooled	% Lost due to Con1 Heated but Uncooled	% Lost due to Con1 Heated & Cooled
Current	71.62	66.52	69.55	70.15		7.12	2.89	4.55	5.46
2020s	68.33	63.33	66.32	66.90		7.32	2.94	4.73	5.64
2050s	64.58	59.95	62.69	63.24		7.17	2.93	4.57	5.49
2080s	61.24	55.64	58.02	58.51		9.15	5.27	4.28	5.17
					Mean %Dec	7.69	3.51	4.53	5.44
					Std. Dev	0.98	1.17	0.19	0.20

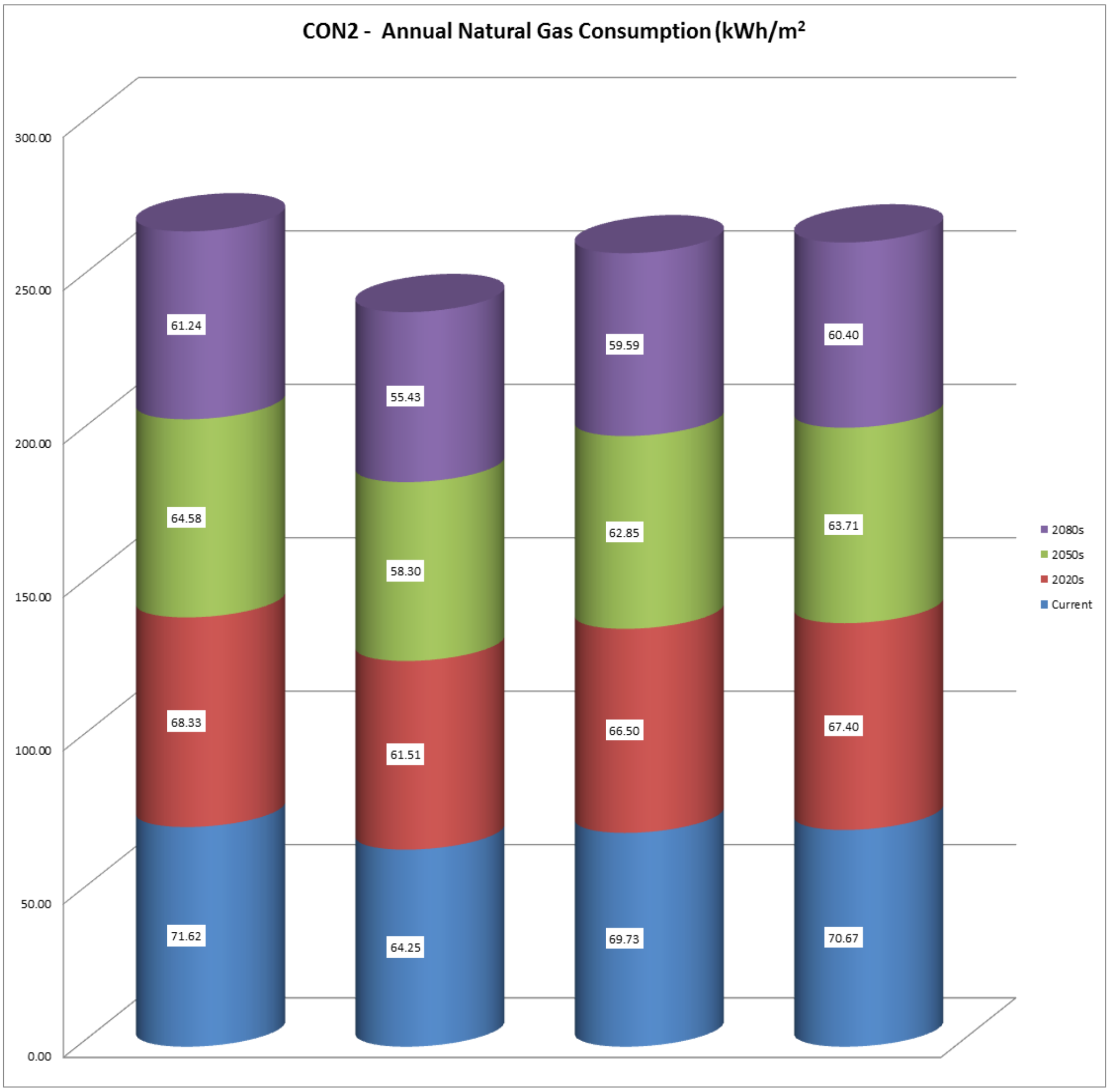


S1 - Senario 1 - Main building heating in the absence of conservatory
S2 - Senario 2- Main building heating with conservatory attached but conservatory is not heated and cooled
S3 - Senario 3- Main building heating with conservatory attached and conservatory is heated but not cooled
S4 - Senario 4- Main building heating with conservatory attached and conservatory is heated and cooled

Figure 9.4(a) Conservatory 1 – Annual Natural Gas Consumption (kWh/m^2)

CON2 - Annual Natural Gas Consumption (kWh/m^2)

	S1	S2	S3	S4		%Dec Con2 Unheated & Uncooled	%Dec Con2 Heated but Uncooled	% Lost due to Con2 Heated but Uncooled	% Lost due to Con2 Heated & Cooled
Current	71.62	64.25	69.73	70.67		10.29	2.64	8.52	9.99
2020s	68.33	61.51	66.50	67.40		9.99	2.67	8.12	9.59
2050s	64.58	58.30	62.85	63.71		9.73	2.68	7.81	9.29
2080s	61.24	55.43	59.59	60.40		9.50	2.71	7.50	8.97
					Mean %Dec	9.88	2.68	7.99	9.46
					Std. Dev	0.34	0.03	0.44	0.43

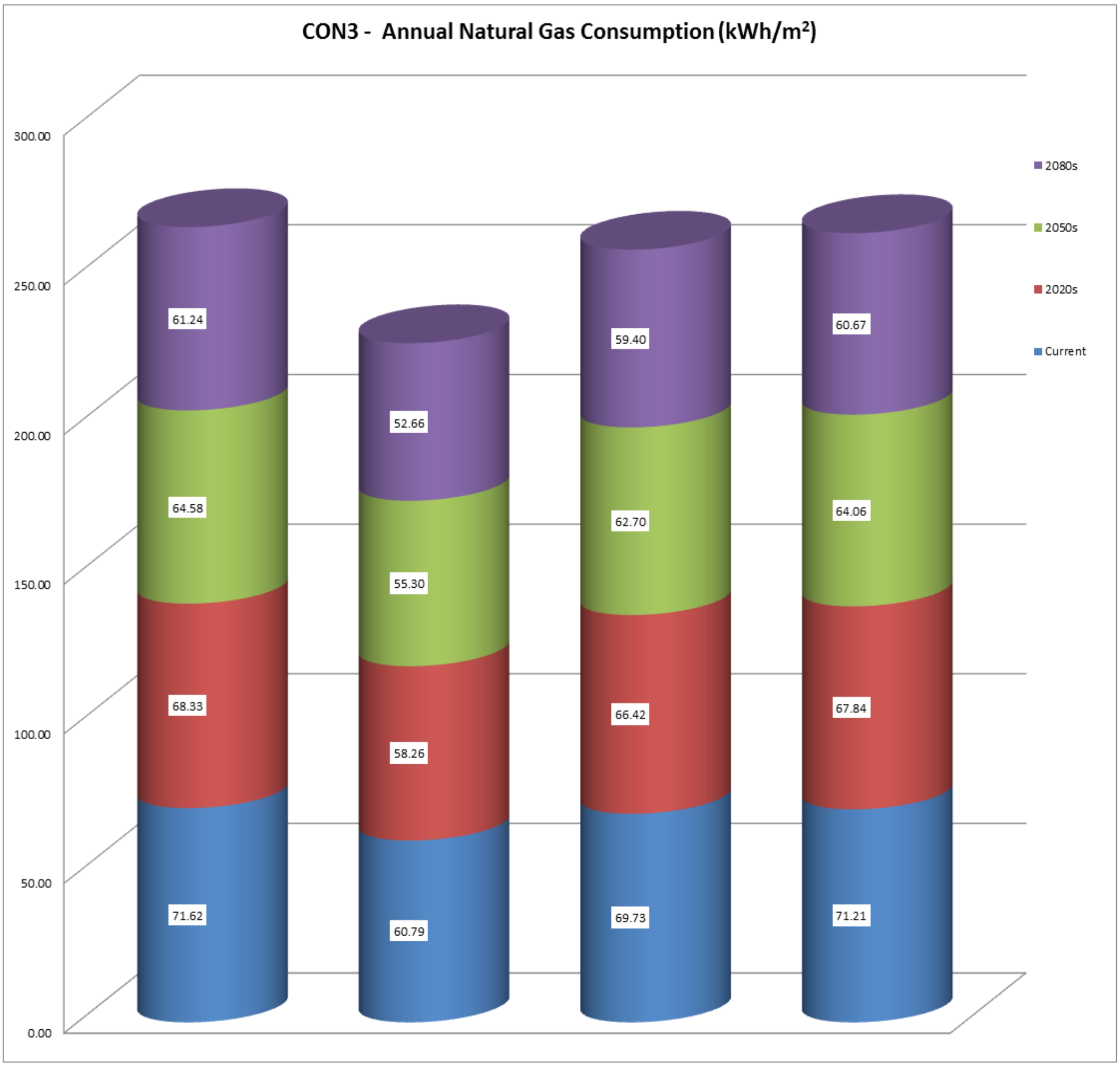


S1 - Senario 1 - Main building heating in the absence of conservatory
S2 - Senario 2- Main building heating with conservatory attached but conservatory is not heated and cooled
S3 - Senario 3- Main building heating with conservatory attached and conservatory is heated but not cooled
S4 - Senario 4- Main building heating with conservatory attached and conservatory is heated and cooled

Figure 9.4(b) Conservatory 2 – Annual Natural Gas Consumption (kWh/m^2)

CON3 - Annual Natural Gas Consumption (kWh/m^2)

	S1	S2	S3	S4		%Dec Con3 Unheated & Uncooled	%Dec Con3 Heated but Uncooled	% Lost due to Con3 Heated but Uncooled	% Lost due to Con3 Heated & Cooled
Current	71.62	60.79	69.73	71.21		15.13	2.64	14.72	17.15
2020s	68.33	58.26	66.42	67.84		14.73	2.79	14.01	16.44
2050s	64.58	55.30	62.70	64.06		14.37	2.91	13.39	15.84
2080s	61.24	52.66	59.40	60.67		14.02	3.02	12.80	15.22
					Mean %Dec	14.56	2.84	13.73	16.16
					Std. Dev	0.48	0.16	0.82	0.82



S1 - Senario 1 - Main building heating in the absence of conservatory
S2 - Senario 2- Main building heating with conservatory attached but conservatory is not heated and cooled
S3 - Senario 3- Main building heating with conservatory attached and conservatory is heated but not cooled
S4 - Senario 4- Main building heating with conservatory attached and conservatory is heated and cooled

Figure 9.4 (c) Conservatory 3 – Annual Natural Gas Consumption (kWh/m^2)

9.3.2 Thermal comfort overheating results and analysis

9.3.2.1 CIBSE TM52 thermal comfort overheating analysis

Figures 9.5 to 9.7 show the CIBSE TM52 thermal comfort overheating analysis results for the non-heating season of conservatory 3 designs based on the earmarked simulated ventilation and shading scenarios for the 2050s weather data set. This is an extract of the CIBSE TM52 thermal comfort overheating analysis results for the three conservatory designs as shown in appendix 9.1 to 9.4. The figures stipulate the external air temperature, $T_{external}$, the internal operative temperature, $T_{operative}$, the upper limit of the range comfort temperatures, $T_{maximum}$ and the absolute upper limit for the operative temperature, T_{upper}. The figures indicate the temperature variance for the late spring, summer and early autumn months of May through September as specified in the CIBSE TM52 adaptive thermal comfort criteria.

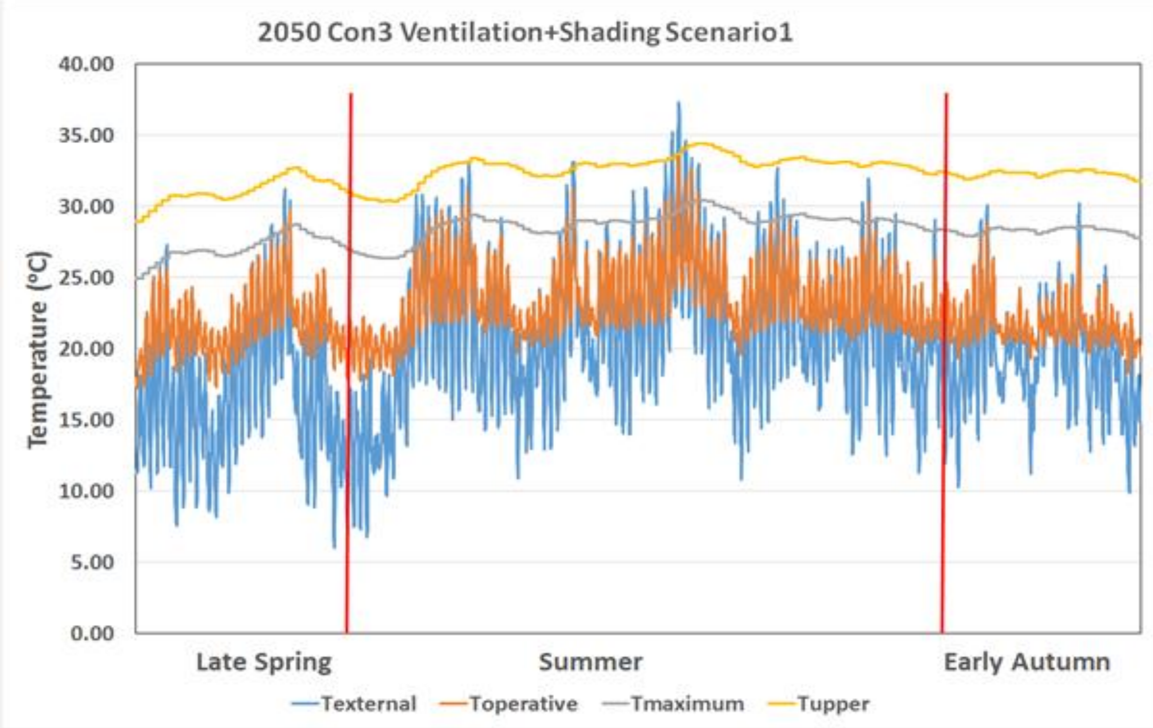


Figure 9.5 2050s weather conservatory3 non heating season scenario 1 analysis

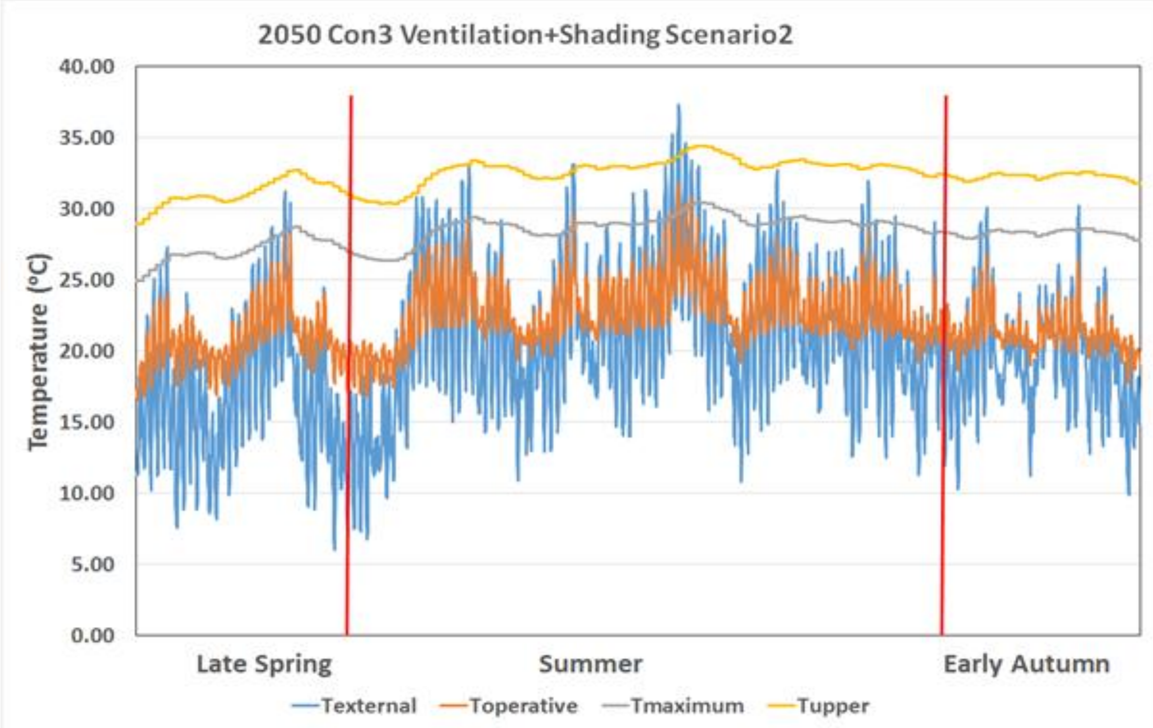


Figure 9.6 2050s weather conservatory 3 non heating season scenario 2 analysis

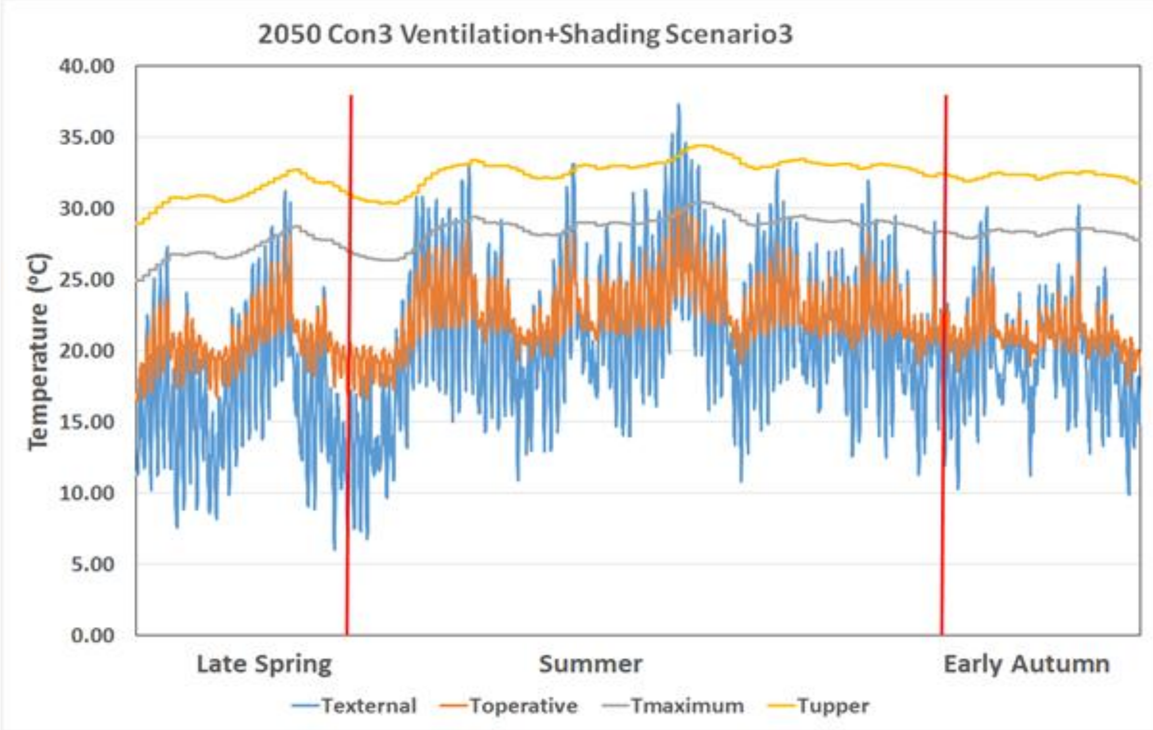


Figure 9.7 2050s weather conservatory 3 non heating season scenario 3 analysis

Comparison of figures 9.5 to 9.7 indicate that the operative temperature variability generally peaks at summer. In figure 9.5, there is evidence of the internal operative temperatures exceeding the threshold comfort temperature at certain times in late spring and early autumn for scenario 1, where there is no shading. This variability gradually decreases in figures 9.6 and 9.7 reflecting the relevance of night ventilation and shading in scenarios 2 and 3 in mitigating overheating in conservatories.

Appendix 9.1 to 9.4 show the CIBSE TM52 thermal comfort overheating analysis results for the non-heating season of the three conservatory designs based on the designated simulated ventilation and shading scenarios for the current and future weather data set. The results show that the use of awnings/overhangs to block excessive solar radiation during the non-heating period coupled with night time ventilation as specified in scenario 2 could offer a significant reduction of operative temperatures to enhanced thermal comfort. A further reduction in the trend is realised in scenario 3, when additional shading is provided to the east and west façades of the conservatories.

Figures 9.8 to 9.11 indicate the analysis of the three conservatory designs based on CIBSE TM52 overheating criteria of hours of exceedance, daily weighted exceedance and the absolute upper limit temperature. These analyses compliment the analyses on appendix 9.1 to 9.4.

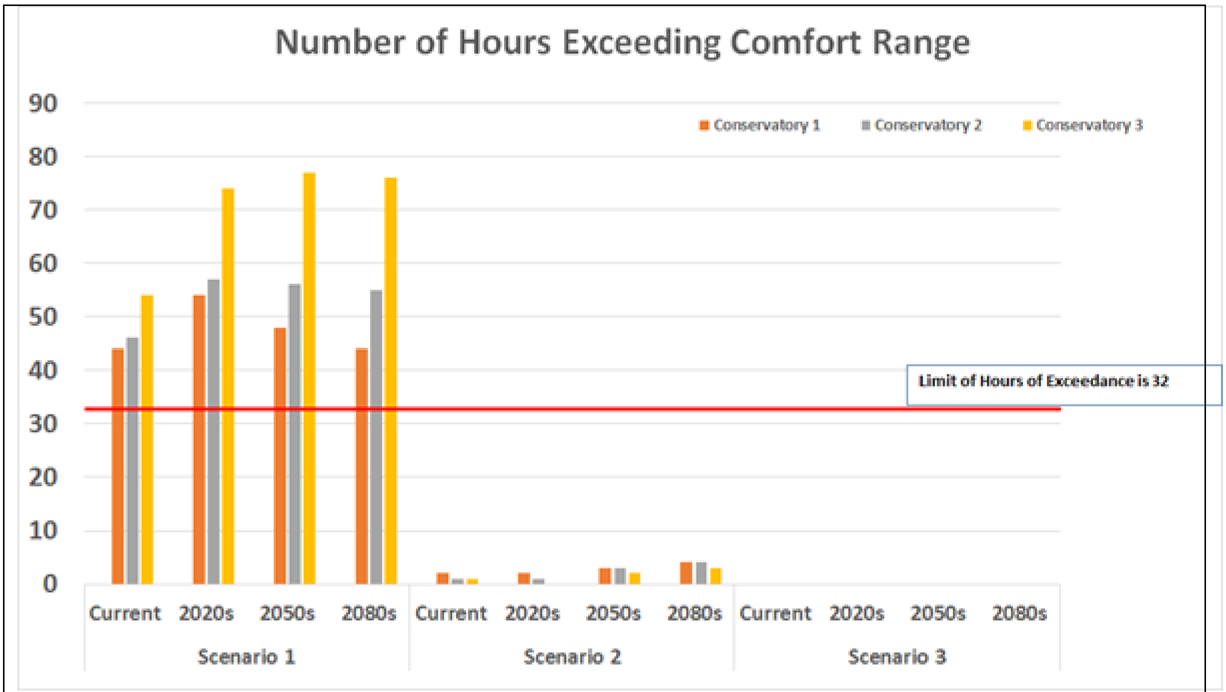


Figure 9.8 Adaptive thermal comfort criteria – Number of hours exceeding comfort range

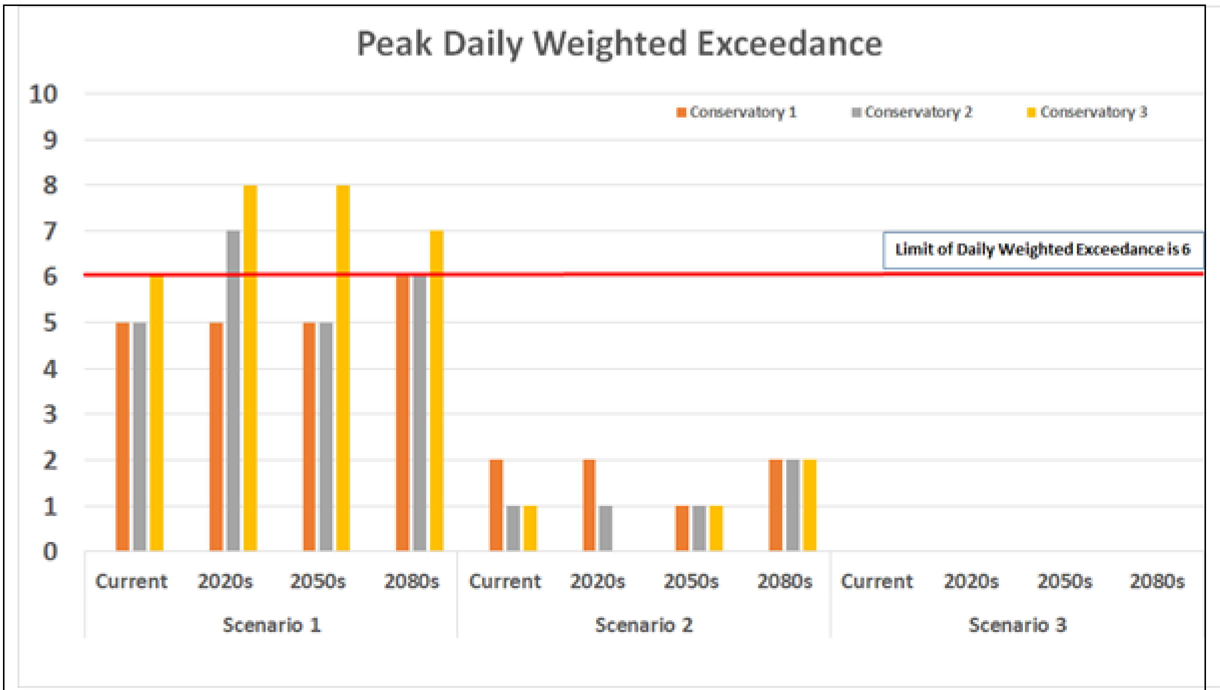


Figure 9.9 Adaptive thermal comfort criteria – Peak daily weighted exceedance

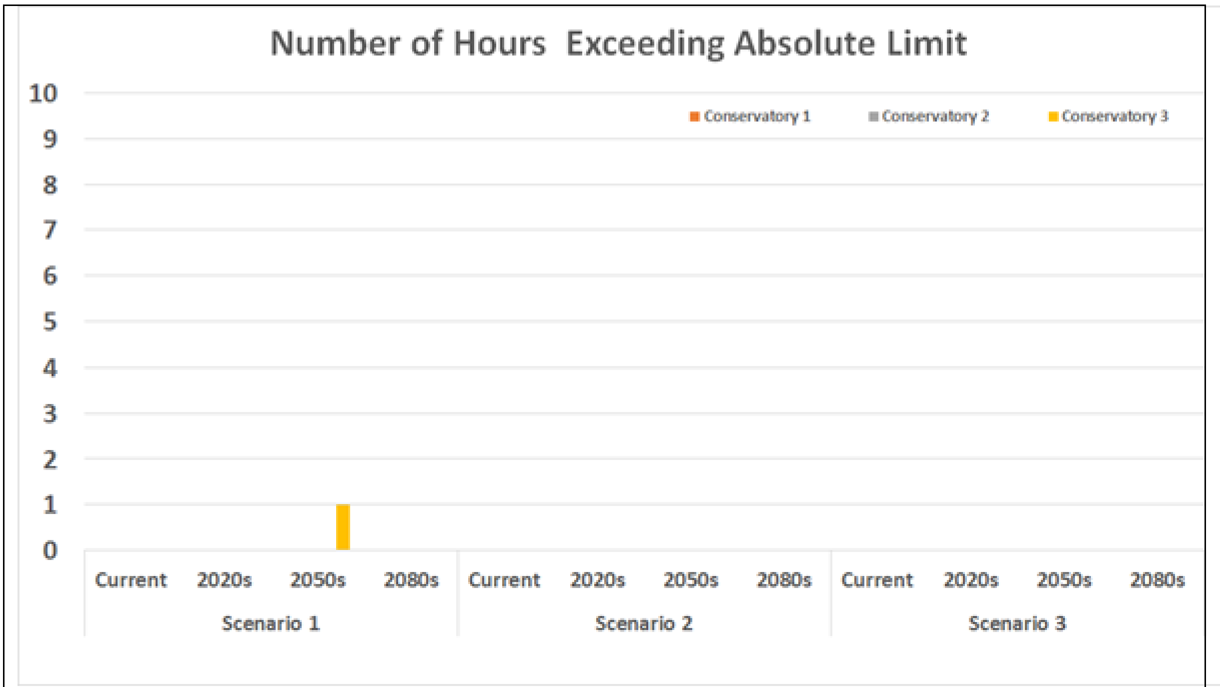


Figure 9.10 Adaptive thermal comfort criteria – Number of hours exceeding absolute limit

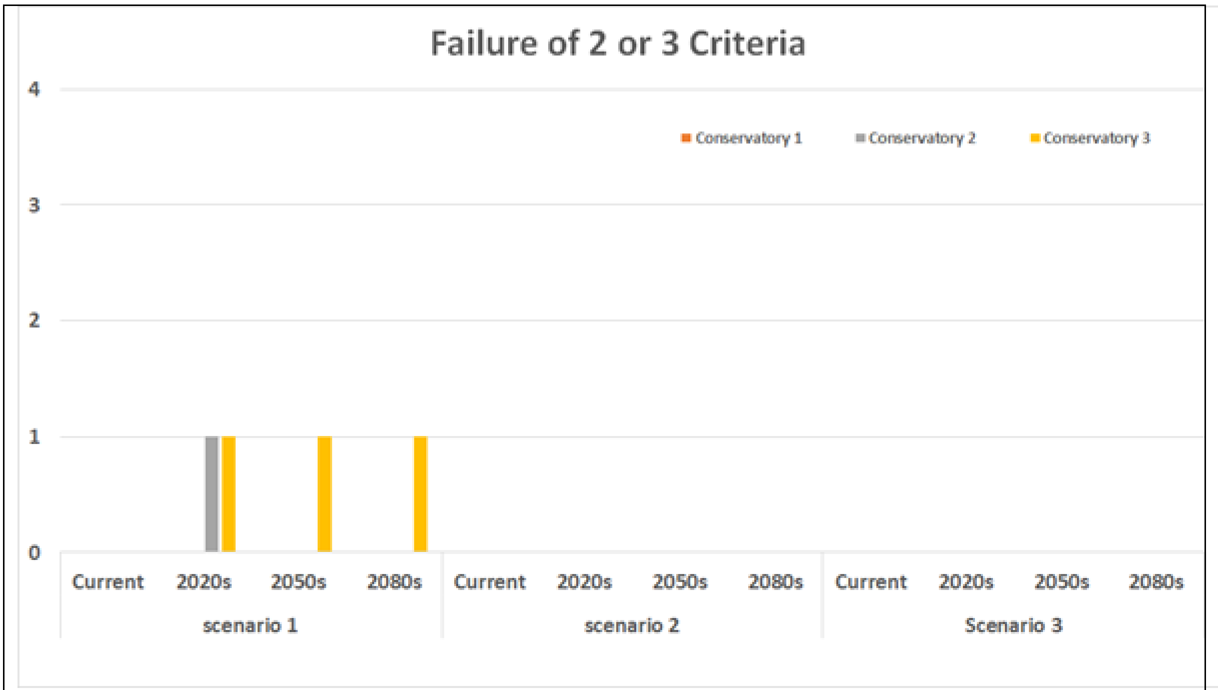


Figure 9.11 Adaptive thermal comfort criteria – Failure of 2 or 3 criteria

In figure 9.8, all the three conservatories, fail under scenario 1 for the current and future weather data sets as hours of operative temperature exceeds the 32 limit of hours of exceedance. The limit of hours of exceedance is the 3 percent of occupied hours. Under scenario 2, where shading is applied to the roof and south facing side of the conservatory during day time coupled with night ventilation, significant reduction of overheating is observed with all the conservatories number of hours of the operative temperatures below the limit of hours of exceedance. The scenario 3 where shading is applied to both the east and west section of the conservatories together with the conditions set out in scenario 2 offers the most effective means of mitigating overheating in conservatories with no observable overheating during the occupied hours.

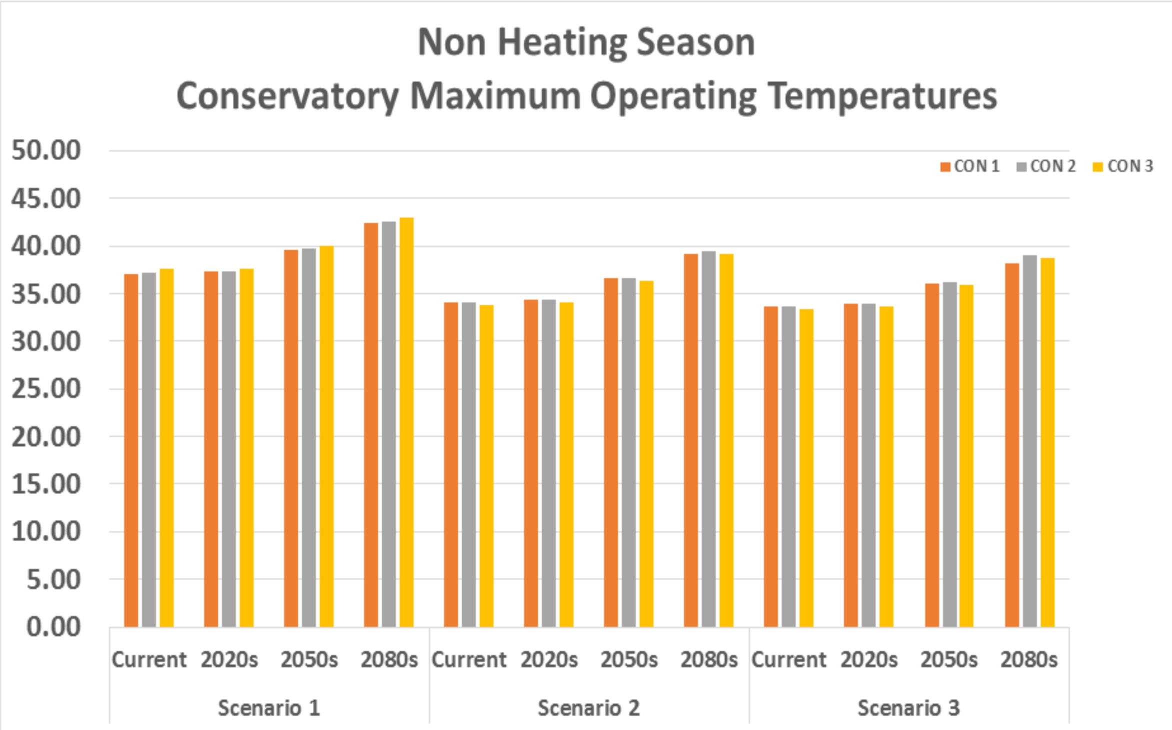
Figure 9.9, shows the peak daily weighted exceedance which is an indication of the severity of overheating underpinned by the limit of daily weighted exceedance of not more than 6. The greatest severity of overheating is observed under scenario 1 with conservatory 3 failing in all future weather patterns. The severity of overheating gradually decreases under scenarios 2 and 3 respectively.
In figure 9.10, it is only conservatory 3 that once exceeds the absolute upper limit temperature of overheating. Figure 9.11 provides information on the conservatories failing two or three adaptive thermal comfort criteria. Conservatory 3 is observed to fail two or three comfort criteria under scenario 1, but the frequency and severity of overheating are mitigated with the application of the shading and night ventilation scenarios. For the non-shaded conservatory with day ventilation scenario 1, the high variability of operative temperatures for the late spring, summer and early autumn suggest that strategic passive provision of shading and ventilation must be in place during this period. The results thus show that the use of awnings/overhangs to block excessive solar radiation during the non-heating period coupled with night time ventilation as specified in scenario 2 could offer a significant reduction of operating temperatures to enhanced thermal comfort. A further reduction in the trend is realised in scenario 3, when additional shading is provided to the east and west facades of the conservatories.

9.3.2.2 Non heating season maximum, minimum, average and range operating temperature analysis.

Figures 9.12 to 9.15 show analysis of the operative temperatures of the three conservatory designs for specified ventilation and shading scenarios during the non-heating season for the current and future weather data set. Figure 9.12

indicates that the application of scenario 2 and 3 leads to a 8.39% and 9.64% reduction of maximum operative temperatures respectively. These amounts to an average of about 3 °C decrease in maximum operative temperature when considering scenario 2 and a further decrease of 1 °C in maximum operative temperatures when considering of scenario 3. Similar trend is observed in the variability of the minimum operative temperatures and that of the average operative temperatures. The minimum operative temperature decrease for scenarios 2 and 3 are 5.29 and 6.77 percent respectively. The average operative temperature decrease percentage is 4.90 and 6.02 respectively for conservatories 2 and 3 respectively. This buttress the fact that optimum conservatory design with an aspect ratio of at least 1.67 will eventually lead to the reduction of operative temperatures and mitigate overheating risk.

	Non Heating Season Conservatory Maximum Operating Temperatures											
	Scenario 1				Scenario 2				Scenario 3			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
CON 1	37.07	37.29	39.58	42.44	34.11	34.38	36.60	39.24	33.63	33.91	36.12	38.17
CON 2	37.21	37.40	39.71	42.61	34.09	34.36	36.63	39.44	33.68	33.97	36.21	38.99
CON 3	37.67	37.68	40.04	42.98	33.76	34.03	36.34	39.19	33.32	33.63	35.90	38.69
CON 1	% Decrease in Maximum Operating Tempearature				7.98	7.80	7.53	7.54	9.28	9.06	8.74	10.06
CON 2					8.38	8.13	7.76	7.44	9.49	9.17	8.81	8.50
CON 3					10.38	9.69	9.24	8.82	11.55	10.75	10.34	9.98
	Average % Dec in Max Operating Temp				8.39				9.64			

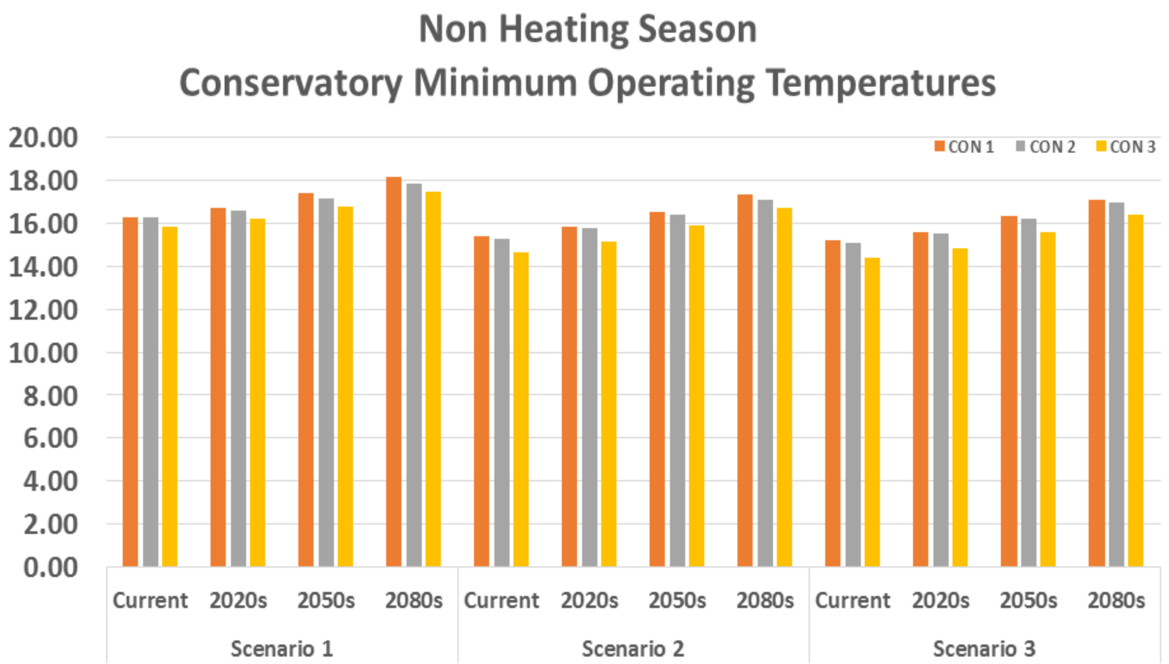


Senario 1- No shading, Cross day ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.
Senario 2- Roof and south facing conservatory side shading, Cross day/night ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.
Senario 3- Roof, south, east and west facing conservatory sides shading, Cross day/night ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.

Figure 9.12 Non heating season conservatory maximum operative temperatures

Non Heating Season Conservatory Minimum Operating Temperatures

	Scenario 1				Scenario 2				Scenario 3			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
CON 1	16.29	16.73	17.39	18.12	15.41	15.85	16.52	17.33	15.20	15.58	16.30	17.09
CON 2	16.25	16.59	17.17	17.86	15.27	15.78	16.37	17.10	15.05	15.53	16.20	16.93
CON 3	15.84	16.19	16.77	17.45	14.61	15.15	15.92	16.69	14.36	14.82	15.57	16.39
CON 1	% Decrease in Minimum Operating Tempearature				5.40	5.26	5.00	4.36	6.69	6.87	6.27	5.68
CON 2					6.03	4.88	4.66	4.26	7.38	6.39	5.65	5.21
CON 3					7.77	6.42	5.07	4.36	9.34	8.46	7.16	6.07
	Average % Dec in Min Operating Temp				5.29				6.77			

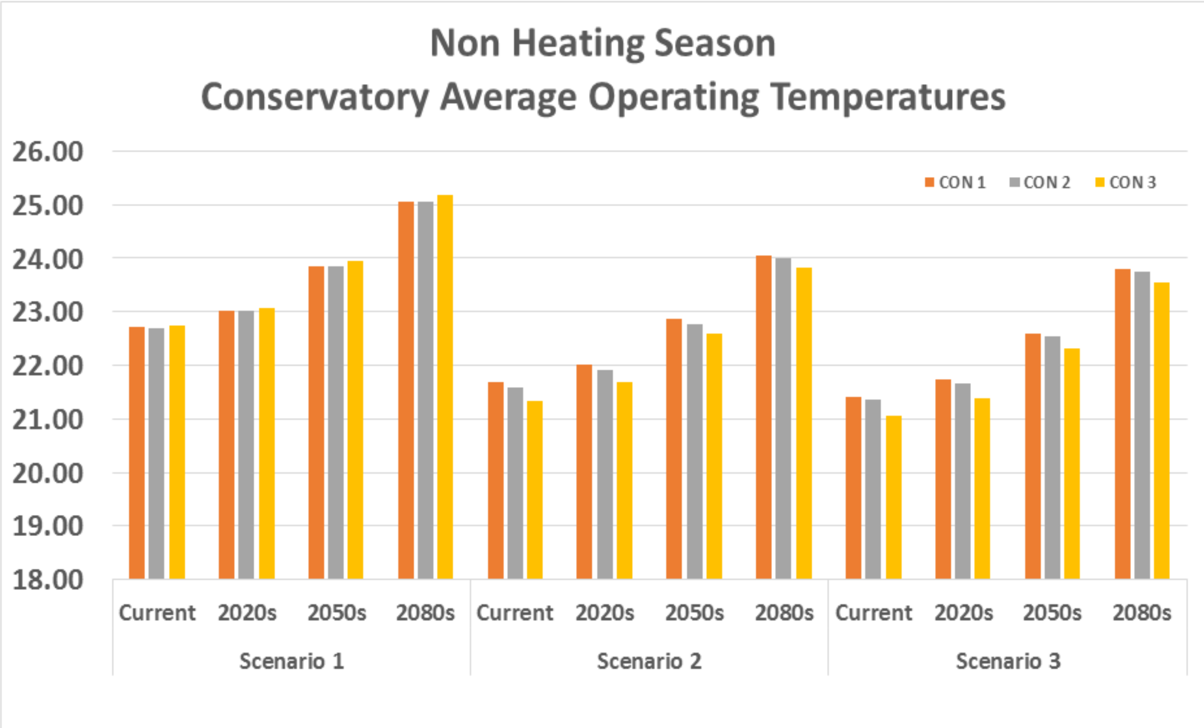


Senario 1- No shading, Cross day ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.
Senario 2- Roof and south facing conservatory side shading, Cross day/night ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.
Senario 3- Roof, south, east and west facing conservatory sides shading, Cross day/night ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.

Figure 9.13 Non heating season conservatory minimum operative temperatures

Non Heating Season Conservatory Average Operating Temperatures

	Scenario 1				Scenario 2				Scenario 3			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
CON 1	22.73	23.03	23.86	25.05	21.68	22.01	22.87	24.06	21.41	21.73	22.60	23.79
CON 2	22.70	23.01	23.85	25.06	21.59	21.92	22.78	23.99	21.35	21.67	22.54	23.75
CON 3	22.74	23.08	23.94	25.18	21.34	21.69	22.59	23.82	21.05	21.39	22.31	23.55
CON 1	% Decrease in Average Operating Tempearature				4.62	4.43	4.15	3.95	5.81	5.64	5.28	5.03
CON 2					4.89	4.74	4.49	4.27	5.95	5.82	5.49	5.23
CON 3					6.16	6.02	5.64	5.40	7.43	7.32	6.81	6.47
	Average % Dec in Av. Operating Temp				4.90				6.02			



Senario 1- No shading, Cross day ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.

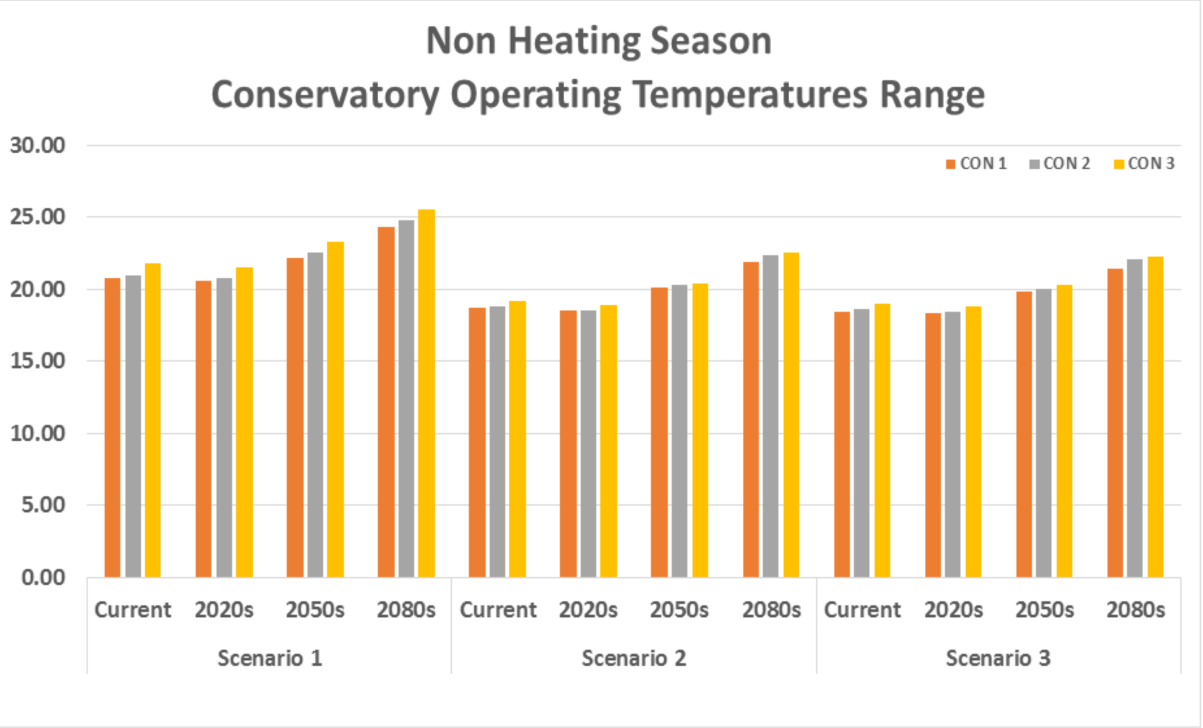
Senario 2- Roof and south facing conservatory side shading, Cross day/night ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.

Senario 3- Roof, south, east and west facing conservatory sides shading, Cross day/night ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.

Figure 9.14 Non heating season conservatory average operative temperatures

Non Heating Season Conservatory Operating Temperatures Range

	Scenario 1				Scenario 2				Scenario 3			
	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s	Current	2020s	2050s	2080s
CON 1	20.79	20.56	22.19	24.32	18.70	18.53	20.09	21.91	18.44	18.33	19.82	21.38
CON 2	20.96	20.81	22.54	24.76	18.82	18.54	20.26	22.34	18.63	18.44	20.01	22.07
CON 3	21.81	21.49	23.27	25.53	19.16	18.88	20.42	22.51	18.96	18.81	20.34	22.30
CON 1	% Decrease in Range Operating Tempearature				10.05	9.87	9.46	9.91	11.30	10.85	10.68	12.09
CON 2					10.21	10.91	10.12	9.77	11.12	11.39	11.22	10.86
CON 3					12.15	12.15	12.25	11.83	13.07	12.47	12.59	12.65
	Average % Dec in Range Operating Temp					10.72				11.69		



Senario 1- No shading, Cross day ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.
Senario 2- Roof and south facing conservatory side shading, Cross day/night ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.
Senario 3- Roof, south, east and west facing conservatory sides shading, Cross day/night ventilation in all direction, Openable window proportion 100%; at least 5% of total floor area.

Figure 9.15 Non heating season conservatory range operative temperatures

9.4 Summary and conclusions

The study evaluated the impact of conservatory as a passive solar design on three key dwelling energy performance indicators of annual energy consumption, building emission rate and annual natural gas consumption of UK detached dwellings. An investigation of internal temperatures was also done using CIBSE adaptive thermal comfort methods to access the overheating of conservatories. Thermal analysis simulation based on the synergetic passive design strategies that seek to optimize solar energy gains through the varying future climatic conditions based on CIBSE weather data set, variable occupant behaviour, building orientation, adequate provision of thermal mass, advance glazing, appropriate ventilation and sufficient level of shading which influence the potential thermal performance of conservatory was performed on three conservatories with varying sizes.

The simulation results showed that the integration of passive solar strategies in conservatory design could significantly decrease energy consumption, building emission rate and natural gas consumption. The amount of percentage decrease was inversely proportional to the increase of conservatory size when the increment is done along the southern orientation of the building facade. This increase in conservatory southern façade dimension facilitated the increase in solar radiation gains during the heating season and also offered a thermal buffer effect. The balanced energy benefits by pre-heating of the main building by means of conservatory does not necessarily replaced the mechanical heating systems, but the process offers a noticeable decrease in the thermal performance parameters when the conservatory is not heated during the heating season. Heating conservatories negates the energy and thermal performance gains with increase in energy consumption, building emission rate and natural gas consumption. Heating conservatories is therefore not in consonance with the energy balance of the use of conservatory as a passive solar design. The investigations also indicated that the provision of optimum ventilation strategy depending on the period of the year coupled with the efficient design of awnings/overhangs and the provision of external adjustable shading on the east and west facades of the conservatory could significantly enhance the thermal comfort of conservatories. This consideration points to the evidence of overheating of the entire non-shaded conservatory with day ventilation scenario now and in the future without the application of the integrated passive design strategies. This variability suggest that failure to incorporated passive solar strategies in conservatory design would necessitate the introduction of cooling systems in conservatories and thus increase the dwelling energy demand and higher carbon dioxide emissions.

The utilization of passive solar design has virtually no negative impact to the environment as it does not use any form of operational energy to provide thermal comfort and also does not incur operational cost. Rather a holistic passive solar design which takes cognisance of passive solar principles offers a significant reduction for energy demand and building emission rate. However, passive solar design solutions are underpinned by variable occupant behaviour. Thus, the incorporation of smart house technological solutions such as automatic external shading and demand control ventilation strategies could enhance the design intent of the application of the passive solar principles.

This case study has shown the potential of conservatories to serve as an effective passive solar design which can significantly offer a positive contribution to the energy performance and enhancement of thermal comfort of a dwelling, when passive solar design principles are applied and the conservatory is neither heated nor air-conditioned. The results show that the judicious integration of the passive solar design strategies in conservatories with increasing conservatory size in elongated south facing orientation with an aspect ratio of at least 1.67 could on an average decrease annual energy consumption (by 5 kWh/m^2), building emission rate (by 2.0 $KgCO_2/m^2$) and annual gas consumption (by 7 kWh/m^2). Thus this work indicates that passive solar design of conservatories through thermal analysis simulations offers a viable solution to reduce dwelling energy consumption, enhance thermal comfort and help mitigate the impact of climate change and thereby contribute to environmental sustainability achievements.

CHAPTER 10: Conclusions and Recommendations

10.1 Chapter summary and conclusions

Judicious decisions for long term strategic infrastructure investments entail the making of cost benefit analysis and sustainable environmental consideration with regards to building energy performance and thermal comfort. The work undertaken in this research employed integrated passive design strategies of varying future climatic conditions, variable occupant behaviour, building orientation, adequate provision of thermal mass, advanced glazing, appropriate ventilation and sufficient level of external shading which influence the potential thermal performance of dwellings and a methodology that combines thermal analysis modelling and simulation coupled with the application of CIBSE overheating criteria to investigate the thermal comfort and energy balance of dwellings and habitable conservatories. Moreover, Bland-Atman’s method of comparison is used as a validation tool in building simulation. This serves as a knowledge contribution to the civil and construction engineering practice in the area of building simulation validation.

This thesis comprised of six studies, each of which investigated the simulation of variability of future climatic conditions, energy usage characteristics of building occupants, building energy efficiency measures, thermal performance of buildings systems and passive design strategies to improve building energy efficiency and further mitigate adverse climatic conditions to secure the right balance of energy consumption and thermal comfort in dwellings.

10.1.1 Case Study 1: Method of comparison analysis

In the first of the six studies (chapter 4) the aim was to explore the use of Bland-Altman's method of comparison as a building simulation validation technique. The case study conducted indicated a strong linear relationship in analysing the statistical agreement between monitored dwelling temperatures and thermal analysis simulated operative temperatures of detached dwellings. The results further confirmed the accuracy of using the EDSL TAS as a credible simulation tool for building energy performance analysis.

10.1.2 Case Study 2: Impact of varying weather data sets

The second case study (chapter 5) investigated the variability between the CIBSE TM48 and CIBSE TM49 Design Summer Year weather files for London Heathrow, Gatwick and London Weather Centre for the current, 2020s, 2050s and 2080s weather data sets. This study employed Monte Carlo simulation for uncertainty and sensitivity quantification and identified the dry bulb and radiant temperatures as the most influential weather parameters which affect thermal comfort on dwellings. The study's results further indicated marginal differences in maximum and minimum operative temperatures for comparable Heathrow DSY Medium High and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios. Moreover, the time series analysis of internal operative temperatures using CIBSE TM52 as overheating criteria for the UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow DSY 1989 Medium 50% probabilistic scenarios weather data sets also showed a very strong similarity between the respective timelines for the two weather data sets.

The deterministic analysis results of the UKCP09 Heathrow DSY Medium 50% probabilistic scenarios for 1976, 1989 and 2003 indicated a progressive increase in maximum internal operative temperatures for the 1976 and 2003 years for all timelines scenarios. Gatwick had the lowest maximum operative temperatures whilst London Weather Centre was observed to have the highest operative temperatures. This confirmed the incorporation of the urban heat island effect of the London Weather Centre weather data sets of CIBSE TM49 as compared to the Heathrow and Gatwick weather files.

The Monte Carlo uncertainty analysis results of the median lines showed that the 50^{th} percentiles of the UKCP09 for the 2020s and 2050s are slightly higher than that of the UKCIP02 weather projections, whilst the opposite is realised with regards to the 2080s weather data set. However, the overall pattern of variability of the two weather data sets indicated no marked observable effect of change in internal operative temperatures in the two sets of the uncertainty analysis results. The case study further indicated the relevance of climate sensitive design in engineering practice to improve thermal comfort in dwellings.

10.1.3 Case Study 3: Impact of climate change on building performance

The third case study (chapter 6) investigated the variability of future climatic conditions on newly built detached dwellings in the United Kingdom. The results indicated a consistent declining trend of annual building energy consumption, annual building natural gas consumption, building emission rate and heating demand over the different timelines used in the simulation. These declines are in consonance with the range of annual average temperature change predicted by the GCM based on the IPCC scenarios which generally shows an increase in temperature over stipulated timelines.

The case study further confirmed that a predicted increase in future temperatures might result in reduction in energy use for space heating and emissions but conversely lead to the increase in cooling demand, thus offsetting the gains in heating demand.

10.1.4 Case Study 4: Impact of four standard construction specifications on thermal comfort on three major cities in the United Kingdom

The fourth case study (chapter 7) investigated the impact of four standard construction specifications which show a progressive improved thermal mass coupled with passive cooling strategies to optimize the thermal comfort in detached dwellings in London, Birmingham and Glasgow using the CIBSE TM52 criteria for assessing adaptive overheating in free-running dwellings. The CIBSE TM52 criteria proved to be an effective and credible assessment tool as the results obtained in this work are in consonance with what is presented in literature.

The findings indicated a strong positive correlation between improved building fabric, strategic ventilation scenarios with external shading and indoor adaptive overheating thermal performance. This integrated approach resulted in substantial reduction of indoor operative temperatures leading to an enhanced thermal comfort environment in London and Birmingham locations. The results indicated that the day ventilation scenario for Glasgow was more effective in mitigating internal operative temperatures than the night ventilation and night ventilation with shading scenarios which is contrary to the observable trends in London and Birmingham.

The results also indicated a progressive decrease in swing of the operative temperatures during the non-heating periods with increase in thermal mass. The PassivHaus standard construction specification with the incorporation of passive cooling strategies of improved night ventilation with shading offered the best case scenario analysis of the optimization of indoor operative temperatures in London and Birmingham with relative decrease in the fluctuations of operative temperature during the observed period.

This case study indicated that thermal comfort in dwellings can be enhanced by analysis of future climatic patterns, improved building fabric and provision of passive design consideration of improved ventilation and shading. It also confirmed that the utilization of appropriate mitigation strategies to enhance thermal comfort could contribute to the reduction of the environmental implications to the built environment and facilitate the drive towards the attainment of future sustainability requirements.

10.1.5 Case Study 5: Impact of four standard construction specifications on thermal comfort on three weather locations in London

The fifth case study (chapter 8) employed Monte Carlo Monte Carlo uncertainty and sensitivity analysis in quantifying and predicting the most influential building envelope and systems parameters which affect dwellings' thermal comfort for Gatwick, Heathrow and London Weather Centre.

The medians for the day ventilation scenarios were generally higher than those of the night ventilation and night ventilation with shading scenarios. The results indicated that applying the mitigation scenarios of night ventilation and shading have a significant impact on reducing internal operative temperatures, and thus enhancing thermal comfort in dwellings. The PassivHaus equivalent presented the most stable internal operative temperature conditions as its plot showed less uncertainty.

The sensitivity analysis results indicated that glazing is the most dominant parameter that influences thermal comfort for both the SRC and PCC. In addition to glazing, total transmittance was also observed to have a positive effect in increasing the internal operative temperatures. However, the occupancy latent gain has a significant opposite effect on internal operative temperature. The study indicated that more consideration should be given to glazing and internal heat gains when seeking to improve the thermal comfort of dwellings.

10.1.6 Case Study 6: Conservatory as a passive design solution.

The sixth case study (chapter 9) evaluated the impact of conservatory as a passive solar design on three key dwelling energy performance indicators of annual energy consumption, building emission rate and annual natural gas consumption of UK detached dwellings.

The simulation results showed that the integration of passive solar strategies in conservatory design could significantly decrease energy consumption, building emission rate and natural gas consumption. The amount of percentage decrease was inversely proportional to the increase of conservatory size when the increment is done along the southern orientation of the building facade. The study also indicated that the provision of optimum ventilation strategy depending on the period of the year coupled with the efficient design of awnings/overhangs and the provision of external adjustable shading on the east and west facades of the conservatory could significantly enhance the thermal comfort and energy performance of conservatories when they are neither heated nor air-conditioned.

10.2 Limitations and exclusions of the studies in this work

The assumptions of the thermal analysis simulation software to determine thermal and energy performance of dwellings have been acknowledged in this work. The outline assumptions in the methodology of weather data sets which are based on historic data patterns to be applicable to actual weather conditions of the case studies' building locations, the use of the standardized dwelling internal conditions activity and occupant behaviour as the prevailing conditions and the use of static U-values, all have the potential to influence the final results of the work.

This thesis does not focus on bridging the gap between design intent and real energy consumption and thermal performance. The modelling and simulation as used in this work is to evaluate alternatives to building elements and design through passive design strategies to address issues involving climate change effect in order to improve energy and thermal performance of residential buildings. The results of the case studies are situations specific based on the various scenarios detailed in the methods and the results may differ from different weather data sets for a given location and with varying occupant behaviours different from the conditions earmarked in the CIBSE Guide A which is used in this work. Moreover, the case studies do apply to the CIBSE weather datasets underpinned by the UKCP09 climatic change projections probabilistic scenarios of 10% and 90%.

10.3 Recommendations for future work

The following outlines a number of gaps identified in existing knowledge which would augur for future research beyond the scope of the issues discussed in this thesis.

10.3.1 Method comparison analysis as a validation technique

As outlined in section 4.4 of the thesis, the Bland-Altman's method of comparison analysis for validation technique is underpinned by the British Standards Institute definition of a repeatability coefficient which stipulates that 95% of the differences to be less than two standard deviations. The degree of acceptance and applicability for what the level of agreement should be in building simulation practice needs further investigation. Moreover, the method comparison analytical technique may not be valid in the consideration of non-linear and perhaps more complicated uncertain parameters, and hence further investigations would be required to address these issues.

10.3.2 EDSL Thermal Analysis Simulation Software

The EDSL TAS software generally accomplished the set objectives designated in this thesis. The functional capabilities of the EDSL TAS program would be enhanced if uncertainty and sensitivity analysis coupled with optimization techniques could be incorporated as key standard functionalities of its modelling and thermal simulation analysis. TAS graphical representation of the whole building analysis is only weather based but does not truly reflect the indoor operative temperatures as defined in CIBSE TM52 overheating criteria. In addition, TAS lacks fully-featured optimisation and cost-benefit analysis; such as Pareto Front, as seen in DesignBuilder simulation software. Further investigations in these areas could augur well for the software acceptability in the prediction of key thermal performance parameters and the assessment of energy conservation measures.

10.3.3 Improved algorithms of the Test Reference Years and Design Summer Years weather data files.

The thesis has indicated the importance of weather data in obtaining credible building simulation results. Changing climatic patterns with its extreme weather conditions in the United Kingdom coupled with urban heat island effect in London underpin the relevance of plausible weather files in building simulation practice. Projected future weather dataset different from future reality would lead to different adaptation strategies and cost implications. There is still a gap between simulation results when compared to actual measurable data. Investigations to continuously improve current methodologies use to produce weather data sets or to offer alternative algorithms may rectify this shortfall.

10.3.4 In-depth understanding of variable occupant behaviours

The thesis focus on using modelling and simulation to evaluate alternatives to building elements and design through passive design strategies instead of bridging the gap between design intent and real energy consumption and thermal performance. Further investigations in the area of integrated passive control measures, systems control and post occupancy behaviours should be pursued. It is envisage that studies in this area could bridge the gap between building simulation performance and actual performance.

REFERENCES

Abrahamse, W., Steg, L., Vlek, C., and Rothengatter, T., (2007). The effect of tailored information, goal setting, and tailored feedback on household energy use, energy-related behaviors, and behavioural antecedents. *Journal of Environmental Psychology*, 27, p.265-276

Aksoy, U.T., and Inalli, M., (2006), “Impacts of some building passive design parameters on heating demand for a cold region”, *Building and Environment.* 41(12). 1742-1754

Ali, A.A.M., and Ahmed, T.M.F. (2012), “Evaluating the impact of shading devices on the indoor thermal comfort of residential buildings in Egypt”, *Fifth National Conference of IBPSA-USA Madison,* Wisconsin

Amoako-Attah, J., and B-Jahromi, A., (2015), “Method comparison analysis of dwellings’ temperatures in the UK” *Proceedings of the Institution of Civil Engineers journal Engineering Sustainability.* 168 February 2015 Issue ES1 Pages 16-26

Amoako-Attah, J., and B-Jahromi, A., (2014), “Impact of standard construction specification on thermal comfort in UK dwellings”, *Advances in Environmental Research (AER): An International Journal of interdisciplinary research in environmental science, technology, and management Techno-Press*. 3(3). 253-281

Amoako-Attah, J., and B-Jahromi, A., (2013), “Impact of future climate change on UK building performance”, *Advances in Environmental Research (AER): An International Journal of interdisciplinary research in environmental science, technology, and management Techno-Press*. 2(3). 203-227.

American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. Standard 55 – 1992 – Thermal Environmental Conditions for Human Occupancy. Atlanta. ANSI.

Aude,P., Tabary, L., and Depecker, L. (2000). Sensitivity analysis and validation of building thermal models using adjoint-code method, Energy and Buildings 31 267-283.

Anderson, B., and Michal, C., (1978), “Passive solar design”, *Annual Review of Energy.* 3 (1). 57-100.

Anderson, W., and White, V., (2009). Exploring consumer preferences for home energy display functionality. *Report to the Energy Saving Trust*.
Centre for sustainable Energy.1-50

Anh-Tuan, N., and Reiter, S. (2014), “Passive designs and strategies for low-cost housing using simulation-based optimization and different comfort criteria”, *Journal of Building Performance Simulation,* In Press

ANSI/ASHRAE Standard 140-2001, Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs. ASHRAE Inc. 1791 Tullie Circle NE Atlanta, GA 30329. www.ashrae.org.

Armstrong, J.S., and Collopy, F. (1992), Error Measures For Generalizing About Forecasting Methods: Empirical Comparisons, International Journal of Forecasting, 8, 69-80

ASHRAE (2010). “Thermal Environmental Conditions for Human Occupancy.” ANSI/ASHRAE 55. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA.

ASHRAE (2004). “Thermal Environmental Conditions for Human Occupancy.” ANSI/ASHRAE 55. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA.

ASHRAE (1997). ASHRAE Handbook. Fundamentals. Atlanta. American Society of Heating, Refrigeration and Air-Conditioning Engineers.

ASHRAE (1992). “Thermal Environmental Conditions for Human Occupancy.” ANSI/ASHRAE 55. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, USA.

Ayers, I., Raseman, S., and Shih, A., (2009). *Evidence from Two Large Field Experiments That Peer Comparison Feedback Can Reduce Residential Energy Usage,* NBER Working Paper 15386

Azar, E and Menassa, C (2010) *A Conceptual Framework To Energy Estimation in Buildings Using Agent Based Modelling*. Proceedings of the 2010 Winter Simulation Conference, Baltimore, Maryland, p.3145-3155

Bahaj, A.S., James, P.A.B., and Jentsch, M.F., (2008), “Potential of emerging glazing technologies for highly glazed buildings in hot arid climates”, *Energy and Building.* 40. 720-731.

Baker, N., (1984), “The use of passive solar gains for the pre-heating of ventilation air in houses”, Commission of the European Communities, First E.C. Conference on Solar Heating, ECSC, EEC, EAEC, Brussels and Luxembourg. 465-469

Bakos, G.C., and Tsagas, N.F., (2000), “Technology, thermal analysis and economic evaluation of a sunspace located in northern Greece”, *Energy and Building.* 31. 261-266.

Balara, C.A., (1996), “The role of thermal mass on the cooling load of buildings. An overview of computational methods”, *Energy and Building,* 24. 1-10.

Banacos, P. C., (2011). Box and Whiskers Plots for Local Climate Datasets: Interpretation and Creation using Excel 2007/2010. Eastern Region Technical Attachment. 2011-01.

Banos, R., Manzano-Agugliaro, F., Montoya, F.G., Gil, C., Alcayde, A., and Gomez, J., (2011), "Optimization methods applied to renewable and sustainable energy: A review", *Renewable and Sustainable Energy Reviews.* 15. 1753 – 1766.

Barclays, M., Sharples, S., Kang, J., and Watkins, R. (2012). The natural ventilation performance of buildings under alternative future weather projections. Building Services Engineering Research and Technology: Sage Publication, Ltd. 33:35-50.

Bartak, M., Drkal, F., Hensen, J.L.M., Matuska, J., Schwarzer, J. and Sourek, B. (2001). *Simulation to support sustainable HVAC design for two historical buildings in Prague*. Proceedings of the 18th Conference on Passive and Low Energy Architecture PLEA 2001. Florianopolis: Federal University of Santa Catarina, p.903-908

Bataineh, K.M., and Fayez, N., (2011), "Analysis of thermal performance of building attached sunspace", *Energy and Buildings.* 43. 1863-1868

Bessoudo, M., Tzemelikos, A., Athientis, A.K., and Zmeureanu, R. (2010), "Indoor thermal environment conditions near glazed facades with shading devices – Part I:

Experiments and building thermal model", *Building and Environment,* (45), 2506-2516.

Bland, J.M., and Altman, D.G., (2003) Applying the right statistics: analyses of measurement studies. *Ultrasound Obstet Gynaecol.* 22. 85-93

Bland, J.M., and Altman, D.G., (2007) Agreement between methods of measurement with multiple observations per individual. *J Biopharm Stat.* 17: 571-582

Bland, J.M., and Altman, D.G., (1986) Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet.* 1:307-310

Boduch, M. and Fincher, W., (2009). Standards of Human Comfort: Relative and Absolute. UTSoA – Seminar in Sustainable Architecture. Meadows Seminar Fall.

Borrego, M., Douglas, E. and Amelink, C. (2009). Quantitative, qualitative and mixed methods in engineering education. *Journal of Engineering Education*, 98(1), 53-66

Boyle, G., (2012), "Renewable energy power for a sustainable future", 3rd edition, Oxford University Press.

Brager, G.S., and de Dear, R. (2001). Climate, Comfort and Natural Ventilation: A new adaptive comfort standard for ASHRAE Standard 55. Proceedings: Moving

Thermal Comfort Standard into the 21st Century, Oxford Brookes University, Windsor, UK, April 2001.

Brazdzionyte, J., and Macas, A., (2007) Bland-Altman analysis as an alternative approach for statistical evaluation of agreement between two methods for measuring hemodynamics during acute myocardial infarction. *Medicina (Kaunas),* **43**(3). 208-214

BRE (2014), Standard Assessment Procedure (SAP 2012) updated June 2014. Building research establishment. Available at: http://www.bre.co.uk/sap2012/page.jsp?id=2759

BRE (1988), "Exploiting sunshine in house design", Eclipse Research Consultants, Building Research Establishment for the Department of Energy's Energy Technology Support Unit.

Breesch, H., and Janssens, A. (2010). A Performance evaluation of passive cooling in office buildings based on uncertainty and sensitivity analysis. Solar Energy. 84. 1453-1467.

Brounen, D., Kok, N., and Quigley, J.M. (2011). Residential Energy Use and Conservation: Economics and Demographics. *Working Paper*. Berkeley: Berkeley Program on Housing and Urban Policy.

BSI (2007), BS EN 15251: 2007: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lightning and acoustics. London: British Standard Institution

BSI (2005), BS EN ISO 7730: 2005; Ergonomics of the thermal environment, Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. London: British Standard Institution

BSI (1991), BS 5925: 1991: Code of practice for Ventilation principles and designing for natural ventilation. London: British Standard Institution

BSI (1975), Precision of test methods 1: Guide for the determination and reproducibility for a standard method. BS 597, Part 1. London: British Standard Institution

Burhenne, S., Tsvetkova, O., Jacob, D., Henze, G.P., and Wagner, A. (2013). Uncertainty quantification for combined building performance and cost-benefit analysis. Building and Enviornment. 62. 143-154.

Burns, L., and Kabak, M., (2014), “Lighting by passive and active solar use design”, Burnham-Moores Center, University of San Diego, MSRE. Available at: http://www.josre.org/wp-content/uploads/2012/10/Lighting-Systems-by-Lauren-Burns-and-Matt-Kabak.pdf. Accessed 18 July, 2014.

Button, D., (1982), “Energy options for housing design: glazing options”, *Journal of the Royal Institute of British Architects*, 89 (10).

Capon, R., (2012), “Using UKCP09 to assess adaptation measures”, CIBSE, ARUP. Available at http://ukclimateprojections.metoffice.gov.uk/media.jsp?mediaid=88433&filetype=pdf. Accessed 19 January 2014.

Carlucci, S., Pagliano, L., and Sangalli, A. (2014). “Statistical analysis of ranking capability of long-term thermal discomfort indices and their adoption in optimization processes to support building design”, *Building and Environment.* Available at http://www.sciencedirect.com/science/article/pii/S0360132313003739. Accessed 20 January 2014.

CEC (2010), “Energy Performance of Building Directive, Directive 2010/31/EU”, *Official Journal of the European Communities.* 13-35.

Chen, Q. (2009), “Ventilation performance prediction for buildings: A method overview and recent applications”, *Building and Environment,* (44), 848-858.

Chan, A.L.S., (2011). Developing future hourly weather files for studying the impact of climate change on buildings energy performance in Hong Kong. Energy and Buildings. 43: 2860-2868.

CIBSE (2014) Design for future climate case studies. CIBSE TM55:2014. London: Chartered Institution of Building Services Engineers.

CIBSE (2013) Evaluating operational energy performance of buildings at the design stage CIBSE TM54:2013. London: Chartered Institution of Building Services Engineers.

CIBSE (2013), “The limits of thermal comfort: avoiding overheating in European buildings CIBSE TM52”, Chartered Institution of Building Services Engineers.

CIBSE (2009), The use of climate change scenarios for building simulation: the CIBSE Future Weather Years. CIBSE TM48. London: Chartered Institution of Building Services Engineers.

CIBSE (2006), CIBSE Guide A – Environmental Design. London: Chartered Institution of Building Services Engineers.

CIBSE (2005), “Climate change and the indoor environment: impacts and adaptation CIBSE TM36”, Chartered Institution of Building Services Engineers.

CIBSE (2004). Energy efficiency in buildings CIBSE Guide F. London: Chartered Institution of Building Services Engineers.

CIBSE (2004), Cibse Briefing 10. Thermal Comfort in a 21st century climate. Addressing the impact of Climate Change on the built environment. London: Chartered Institution of Building Services Engineers.

Clarke, J.A., Johnstone, C.M., Kelly, N.J., Strachan, P.A., and Tuohy, P., (2008), "The role of built environment energy efficiency in a sustainable UK energy economy", *Energy Policy.* 36(12). 4605-4609

CLG (2007), "Building a Greener Future: Policy Statement, Communities and Local Government", *Communities and Local Government,* UK

Clevenger, C.M., and Haymaker, J., (2006), "The Impact of Building Occupant on Energy Modelling Simulation". Available at: http://www.stanford.edu/group/peec/cgi-bin/docs/people/profiles/The Impact of the Building Occupant On Energy Modelling Simulations.pdf. Accessed 1 July 2014.

Climate Change Act (2008). Available at http://www.legislation.gov.uk/ukpga/2008/27/contents. Accessed 20 April 2013.

Cochran, W.G. 1963. Sampling Techniques, 2nd Ed., New York: John Wiley and Sons, Inc.

Collins, L., Natarajan, S., and Levermore, G. (2010). Climate change and future energy consumption in UK housing stock. Building Services Engineering Research and Technology. Sage Publication, Ltd. 31:75-90.

Crawley, D.B (2003). Impact of Climate change on buildings, Proceedings of the CIBSE/ASHRAE International Conference 2003, Edinburgh, Scotland, London: CIBSE

Crawley, D.B (2008). Estimating the impacts of climate and urbanization on building performance, Journal of Building Performance Simulation, 1:2, 91-115.

Creswell, J.W., (2003). *Research Design: Qualitative, quantitative and mixed method approaches (*2nd Ed). Sage Publications, Inc. Thousand Oaks, CA.

Darby, S. 2006. The effectiveness of feedback on energy consumption. A review for DEFRA of the literature on metering, billing and direct displays. Environmental Change Institute, University of Oxford. Available at: http://www.eci.ox.ac.uk/research/energy/electric-metering.php [Accessed 1 November 2011]

Darby, S. (2008). *Why, What, when, How, Where and Who? Developing UK Policy on Metering, Billing and Energy Display Devices*. Proceedings, ACEEE Summer study on energy Efficiency in Buildings, Asilomar, CA. 7 p.137

DCLG (3013), Proposed Changes to Part L of the Building Regulations 2013, Department of Communities and Local Government. Available at http://www.gov.uk/government/uploads/system/uploads/attachment_data/file/226965/Part_L_2013_IA.pdf Accessed 20 December, 2013

DCLG, AECOM (2012), Department of Communities and Local Government, AECOM, Investigation into overheating in homes. Literature review. Available at http://www.gov.uk/government/uploads/system/uploads/attachment_data/file/7604/2185850.pdf Accessed 17 October 2013.

de Dear, R.J., and Brager, G.S. (1998), "Developing an adaptive model of thermal comfort and preference." *Proceedings of the 1998 ASHRAE Winter Meeting.* Pt 1A ed. San Francisco, CA, USA: ASHRAE; 1998:145-146

de Dear R.J., Brager, G.S., and Cooper, D.J. (1997), Developing an Adaptive Model of Thermal Comfort and Preference - Final Report, ASHRAE RP-884. Sydney :MRL

de Wilde, P. and Coley, D. (2012), "The Implications of a Changing Climate for Buildings", *Building and Environment*, (56), 1-7. ISSN 0360-1323

de Wilde, P., and Tian, W., (2012). Management of thermal performance risks in buildings subject to climate change. Building and Environment. 55. 167-177.

de Wilde, P., and Tian, W., (2009). Identification of key factors for uncertainty in the prediction of the thermal performance of an office building under climate change. Building Simulation. 2. 157-175

DECC (2011a). Department of Energy and Climate Change. Available at: http://www.decc.gov.uk/assets/decc/11/stats/climate-change/3224-great-britains-housing-energy-fact-file-2011.pdf [Accessed 8 November 2011]

DECC (2011). *Energy consumption in the United Kingdom: 2011, Domestic energy consumption in the UK since 1970*. Department of Energy and Climate Change. A National Statistics Publication 28 July 2011. Available at: http://www.decc.gov.uk/en/content/cms/statistics/publications/ecuk/ecuk.aspx [Accessed 9 November 2011]

Demanuele. C., Tweddell, T., and Davis, M., (2010). *Bridging the gap between predicted and actual energy performance in schools*. World Renewable Energy Congress WREC XI, Abu Dhabi, UAE, p.25-30

Desideri, U., Arcioni, L., Leonardi, D., Cesaretti, L., Perugini, P., Agabitini, E., and Evangelisti, N., (2013), “Design of a multipurpose ‘zero energy consumption’ building according to European Directive 2010/31/EU: Architectural and technical plants solutions”, *Energy.* 58. 157-167

Dominguez-Munoz, F., Cejudo-Lopez, J.M., and Carrillo-Andres, A. (2010). Uncertainty in peak cooling load calculations. Energy and Buildings. 42. 1010-1018

Du, H., Edge, J., and Underwood, C. (2011). Modelling the impacts of new UK future weather data on a school building. 12th Conference of International Building Performance Simulation Association, Sydney. Proceedings of Building Simulation.

Du, H., Underwood, C.P., and Edge, J.S. (2012). “Generating test reference years from the UKCP09 projections and their application in building energy simulations”, *Building Services Engineering Research and Technology*, 33(4). 387-406

EDSL TAS (2014). Available at http://www.edsl.net/main/Software/Designer/NVandPD.aspx Accessed 10 May 2014.

Eisenhower, B., Neill, Z.O., Foroberov, V.A., and Mezic, I. (2011). Uncertainty and sensitivity decomposition of building energy models. Journal of Building simulation. 1-14.

Eames, M., Kershaw, T., and Coley, D. (2011). “On the creation of future probabilistic design weather years from UKCP09”, *Building Services Engineering Research and Technology*, 32(2). 127-142

Eames, M., Kershaw, T., and Coley, D. (2012). “A comparison of future weather created from morphed observed weather and created by a weather generator”, *Building and Environment*, 56. 252-264

EN Standards, Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics (Pilsen, Czech Republic: EN Standards, 2007).

English, H., and Walker, A., (2000), “Passive Solar Design: The Foundation for Low-energy Federal Buildings”, U.S. Department of Energy. Available at: http://www1.eere.energy.gov/femp/pdf/26015.pdf. Accessed July 8, 2014.

EREC (2000), “Passive solar design for the home”. Energy Efficiency and Renewable Energy Clearinghouse, Available at: http://www.nrel.gov/docs/fy01sti/29236.pdf. Accessed July 14, 2014.

Erickson, V., Lin, Y., Kamthe, A., Brahme, R., Surana, A., Cerpa, A.E., Sohn, M.D., and Narayanan, S. (2009). *Energy Efficient Building Environment Control Strategies Using Real-time Occupancy Measurements*. Available at: http://andes.ucmerced.edu/papers/Erickson09a.pdf [Accessed 9 November 2011]

Fanger, P.O., (1970), “Thermal comfort: Analysis and applications in environmental engineering”, *Danish Technical Press*

FENSA (2014), The Fenestration Self-Assessment Scheme. Available at: http://www.fensa.co.uk. Accessed July 15, 2014.

Florides, G.A., Kalogirou, S.A., Tassou, S.A., and Wrobel, L.C., (2000), “Modeling of the modern houses of Cyprus and energy consumption analysis”, *Energy.* 25(10). 915-937

Frank, T., (2005). Climate change impacts on building heating and cooling energy demand in Switzerland, Energy and Buildings. 37: 1175-1185.

Frankfort-Nachmias, C., and Nachmias, D. (1992). *Research methods in the social sciences* (4th ed) New York. Saint Martin’s Press

Gan, G., (2001), “Analysis of mean radiant temperature and thermal comfort”, *Building Services Engineering Research and Technology.* (22), 95-101.

Gaterell, M.R., and McEvoy, M.E. (2005). The impact of climate uncertainties on the performance of energy efficiency measures applied to dwellings. Energy and Buildings, 37, 982-995

Georgiou, G., Efttekhari, M., and Eames, P., (2014), Calibration and validation of residential buildings: 8 case studies of detached houses. Proceedings of Building Simulation and Optimization, 2nd IBPSA-England conference on Building Simulation and Optimization, UCL, UK.

GeSI (2008), Smart2020: Enabling the low carbon economy in the information age. United State report Addendum, p.26-28. Available at: http://www.smart2020.org/. [Accessed 5 November 2011].

GHH (2014). Available at: http://greenharmonyhome.com/image/The_energy_for_life_guide1.pdf. Accessed July 15, 2014.

Gupta, R., Gregg, M., Du, H., and Williams, K. (2013). “Evaluative application of UKCP09-based downscaled future years to simulate overheating risk in typical English homes”, Structural Survey ,Emerald Group Publishing Limited, 32(4). 231-252

Guyon, G and Palomo, E. (1999). Validation of two French software programs. Part1. Analytical verifications, Transactions of the ASHRAE, SE-99-6-2

Haase, M., da Silva, F.M., and Amato, A. (2009), “Simulation of ventilated facades in hot and humid climates”, *Energy and Buildings,* (41), 361-373.

Hacker, J., Capon, R., and Mylona, A. (2009). Use of climate change scenarios for building simulation: the CIBSE future weather years. The Chartered Institution of Building Services Engineers, London, UK. CIBSE TM48:2009

Hacker, J.N., De Saullers, T.P., Minson, A.J., and Holmes, M.J. (2008) Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. Energy and Buildings. 40: 375-384.

Hacker, J. N., Holmes, M., Belcher, S., and Davies, G. (2005). Climate change and indoor environment: impacts and adaptation. The Charted Institution of Building Services Engineers, London.

Hanneman, S.K., (2008) Design, analysis and interpretation of method-comparison studies. *AACN Adv Crit Care.* 19(2). 223-234

Helton, J.C., Johnson, J.D., Sallaberry, C., and Storlie, C.B. (2006). Survey of sampling-baased methods for uncertainty and sensitivity analysis. Reliability Engineering and System Safety. 91. 1175-1209.

HLGGI (2010), "Energy efficiency in Traditional Buildings", Heritage and Local Government, Government of Ireland. Available at http://www.ahg.gov.ie/en/Publications/HeritagePublications/BuiltHeritagePolicyPublications/Energy%20Efficiency%20in%20Traditional%20Buildings%20(2010).pdf. Accessed July 15, 2014.

Hoes, P., Hensen, J.L., Loomans, M.G.L.C, de Vries, B., and Bourgeois, D., (2009). *User Behavior in Whole Building Simulation. Energy and Buildings*, Elsevier, 41 p.295-302

Hogg, N., and Botten, C., (2012) A tale of two buildings. Are EPCs a true indicator of energy efficiency? Jones Lang LaSalle.

Hopfe, C.J., and Hensen, J.L.M., (2011). Uncertainty analysis in building performance simulation for design support. Energy and Buildings. 43. 2798-2805.

Hulme, M., Jenkins, G.L., Lu, X., Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M., Hassel, D., Boorman, P., McDonald, R., and Hills,S., (2002). Climate change scenarios for the United Kingdom: The UKCIP02 Scientific Report. Norwich: Tyndall Centre for Climate Change Research, University of East Anglia.

Hygh, J.S., DeCarolis, J.F., Hill, D.B., and Ranji Ranjithan, S., (2012). Multivariate regression as an energy assessment tool in early building design. Building and Environment. 57. 165-175.

Intergovernmental Panel on Climate Change (2001). Climate Change 2001: Impacts, Adaptation and Vulnerability, Cambridge: Cambridge University Press.

International Organization for Standardization (ISO), ISO 7730:2005. Ergonomics of the Thermal Environment – Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV And PPD Indices and Local Thermal Comfort Criteria, (Geneva: International Organization for Standardization, 2005).

IPCC (2013). Intergovernmental Panel on Climate Change. Climate Change 2013. The Physical Science Basis. Working Group 1 Contribution to the Fifth Assessment Report of the IPCC. Available at http://www.climatechange2013.org/images/uploads/WG1_AR5_SPM_brochure.pdf Accessed January 19, 2014.

IPCC (2007). Intergovernmental Panel on Climate Change. Climate change 2007: the physical science basis. Available from: http://www.ipcc.ch/publications. Accessed 20 April 2013.

James, P.A.B., and Bahaj, A.S., (2005), "Holographic optical elements: various principles for solar control of conservatories and sunrooms", *Solar Energy.* 78. 441 – 454.

Jensen, O.M., (2003). *Visualisation Turns Down Energy Demand. Danish Building and Urban Research*. ECEEE Summer Study. Time to turn down energy demand. P.451-454. Available at: domo.cust.pdc.nl/9307000/d/q49.pdf. [Accessed 9 November 2011]

Jentsch, M.F., Levermore, G.J., Parkinson, J.B., and Eames, M.E., (2014). Limitations of the CIBSE design summer year approach for delivering representative near-extreme summer weather condition. Building Services Engineering Research and Technology 35 (2) 155-169

Jentsch, M., Jahn, M., Reiner, R., and Kirschenmann, U. (2011). *Collecting Factors for Motivating Energy-Saving Behavior*. Service computation 2011: The Third International Conferences on Advanced Service Computing. Rome, Italy

Jenkins, G.J., Murphy, J.M., Sexton, D.M.H., Lowe, J.A., Jones, P., and Kilsby, C.G., (2009). UK Climate Projections: Briefing report. Met Office Hadley Centre, Exeter, UK.

Judkoff, R., Wortman, D., O'Doherty, B., and Burch, J., (2008) A methodology for validating building energy analysis simulations. Technical Report NREL/TP-550-42059

Kamal, M.A., (2012), "An Overview of Passive Cooling Techniques in Buildings: Design Concepts and Architectural Interventions", *Acta Technica Napocensis: Civil Engineering and Architecture.* 55(1), 84-97

Kim, J.J., (2014), "Energy self-sufficiency of office buildings in four Asian cities", *Advances in Energy Research (AER): An International Journal of interdisciplinary research in environmental science, technology, and management Techno-Press*. 2(1). 11-20

Kim, T., Song, D., Kato, S., and Murakami, S., (2007), "Two-step optimal design method using genetic algorithms and CFD-coupled simulation for indoor thermal environments", *Applied Thermal Engineering,* 27(1), 3-11

Kochaniuk, P., (2012), "Passive solar design". Available at http://www.greenextension.eu/pdf/Passive%20solar%20design.doc. Accessed 14 July, 2014

Kolokotroni, M., (2001), "Night ventilation cooling of office buildings: parametric analysis of conceptual energy impacts" *ASHRAE Transactions,* 107(1), 479-89

Kruzner, K., Cox, K., Machmer, B., and Klotz, L., (2013), "Trends in observable passive solar design strategies for existing homes in the U.S.", *Energy Policy.* 55. 82-94.

Kulstad, E.B., Courtney, D.M., Shanley, P., Metzger, A., Matsuura, T., Rees, J., and McKnite, S., (2013), Agreement between temperature measurements during cooling and warming through the esophagus. Critical Care, 17 (2) p.314

Laouadi, A., (2004). Development of a radiant heating and cooling model for building energy simulation software. *Building and Environment*. 39 (4) p. 421-431

Lau, C.C.S., Lam, J.C., and Yang, L., (2007), "Climate classification and passive solar design implications in China", *Energy Conversion and Management.* 48 (7). 2006-2015.

Lee, E.S., and Tavil, A., (2007), "Energy and visual comfort performance of electrochromic windows with overhangs", *Building and Environment.* 42. 2439-2449

Levermore, G.J., and Parkinson, J.B., (2006). "Analyses and algorithms for the new Test Reference Years and Design Summer Years for the UK", *Building Services Engineering Research and Technology*, 27 (4) 311-325

Lomas, K.J., and Giridharam (2012). Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: A case-study of hospital wards. Building and Environment. 55. 57-72.

Lomas, K.J., and Ji, Y. (2009). Resilience of naturally ventilated buildings to climate change: Advanced natural ventilation and hospital wards. Energy and Buildings. 41:629-653.

Lu, K., Quach, B., Tong, T.K., and Lau, P.W.C., (2003). Validation of leg-to-leg bio-impedance analysis for assessing body composition in obese Chinese children. *Journal of Exercise Science and Fitness.* **1**(2). 97-103

Macdonald, I.A. (2003). *Applying uncertainty considerations to Building Energy conservation Equation.* Eighth International IBPSA conference, Eindhoven, Netherlands, International Building Performance Simulation Association p.760

Mantha, S., Roizen, M.F., Fleisher, L.A., Thisted, R., and Foss, J., (2000), Comparing methods of clinical measurement: reporting standards for Bland and Altman analysis. Anesthesia and analgesia, 90(3). 593-602

Mattern, F., Staake, T., and Weiss, M. (2010). *ICT for green*, In Proceedings of the 1st International Conference on Energy-Efficient Computing and Networking – e-Energy 2010. Passau, Germany: ACM Press.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P., and Oikonomou, E., (2012). Building Characteristics as determinants of propensity to high indoor summer temperatures in London dwellings. Building and Environment. 55. 117-130.

Mc Graw Hill, van Stralen, K.J., Dekker, F.W., Zoccali, C., and Jager, K.J., (2012) Measuring agreement, more complicated than it seems. *Nephron Clinical Practice.* 120:c162-c167

Met Office Climate Averages 1981 – 2010. Available at www.metoffice.gov.uk/climate/uk/averages/19812010/england.html (Accessed June 9, 2013.)

Mihalakakou, G., and Ferrante, A., (2000), “Energy conservation and potential of a sunspace: sensitivity analysis”, *Energy Conversion and Management.* 41. 1247-1264.

Monahan, J., and Powell, J.C., (2011), “A comparison of the energy and carbon implications of new systems of energy provision in new build house in the UK”, *Energy Policy.* 39. 290-298

Moran, F., Blight, T., Natarajan, S., and Shea, A., (2014), “The use of passive house planning package to reduce energy use and $C0_2$ emissions in historic dwellings”, *Energy and Buildings.* 75. 216-227

Moran, F., Natarajan, S. and , Nikolopoulou,M., (2012). Developing a database of energy use for historic dwellings in Bath, UK . Energy and Buildings. 55. 218-226.

Morrissey, J., Moore, T., and Horne, R.E., (2011), “Affordable passive solar design in a temperate climate: An experiment in residential building orientation”, *Renewable Energy.* 36. 568 – 577

Mottard, J.M., and Fissore, A., (2007), “Thermal simulation of an attached sunspace and its experimental validation”, *Solar Energy.* 81. 305-315.

Murphy, J.M., Sexton, D.M.H., Jenkins, G.J., Booth, B., Brown, C.C., Clark, R.T., Collins, M., Harris, G.R., Kendon, E.J., Betts, R.A., Brown, S.J., Humphrey, K.A., McCarthy, M.P., McDonald, R.E., Stephens, A., Wallace, C., Warren, R., Wilby, R., and Wood, R.A., (2009), UK Climate projections science report: Climate Change projections, Met Office, Hadley Centre, Exeter.

Mylona, A., (2012), The use of UKCP09 to produce weather files for building simulation. Building Services Engineering Research and Technology, CIBSE, Sage, 2012, 33 (1), 51-62

Mylona, A., Mavrogianni, A., Davis, M., and Wilkinson, P., (2015). “Defining overheating – Evidence review”, Zero Carbon Homes. Available at: http://www.zerocarbonhub.org/sites/default/files/resources/reports/ZCH-OverheatingEvidenceReview-Definitions.pdf Accessed July 5, 2015.

Nakicenovic, N. and Swart, R. (Eds), (2000). Emissions Scenarios. Cambridge University Press, UK

Nicol, J.F., Hacker.J., Spires, B., and Davis, H., (2009). Suggestion for new approach to overheating diagnostics. Building Research and Information. 37 (4). 348-357.

Nicol, J.F., and Humphreys, M.A. (2002), "Adaptive thermal comfort and sustainable thermal standards for buildings", *Energy and Buildings,* (34), 563-572

Nitz, P., and Hartwig, H., (2005), "Solar control with thermotropic layers", *Solar Energy.* 79. 573-583

ODPM (2010), England and Wales Building Regulations 2000 Approved Document Part F: Means of Ventilation, 2010 edition, Office of the Deputy Prime Minster. Available at: http://www.planningportal.gov.uk/loads/br/BR_PDF_ADF_2010.pdf. Accessed 3 July 2014.

Olds, B.M., Moskal, B.M., and Miller, R.L. (2005). Assessment in engineering education: Evolution, approaches and future collaborations. *Journal of Engineering Education*, 94 (1), p.13-25

Oliveira Panao, M.J.N., Camelo, S.M.L., and Gonalves, H.J.P., (2012), "Solar Load Ratio and ISO 13790 methodologies: indirect gains from sunspace", *Energy and Building.* 1-26.

ONS - Office for National Statistics (2009). Annual Abstract of Statistics, No 145 – 2009 Edition. Basingstoke: Palgrave Macmillan

ONS - Office for National Statistics (2011) Environmental News Release. *Domestic energy consumption increased by 18 percent between 1970 and 2009*. Government Buildings, Cardiff Road, Newport

Onwuegbuzie, A.J. (2003). Expanding the framework of internal and external validity in quantitative research. *Research in the Schools*, 10, p.71-90

Onwuegbuzie, A.J., and Collins, K.M.T. (2007). A typology of Mixed Methods Sampling Designs in Social Science Research. *The Qualitative Report*, 12 (2) p.281-316

Owens, P., (1984), "Low emissivity coatings on glass windows", *UK-ISES Conference Proceedings (C38), Coatings for energy efficiency and solar applications*. 11-21

Pallant, J., (2013). A step by step guide to data analysis using IBM SPSS. 5th edition. 61-66.

Palme, M., Isalgue, A., and Coch. H. (2013). Avoiding the Possible Impact of Climate Change on the Built Environment: The Importance of the Building's Energy Robustness. Buildings, 3, 191-204. ISSN 2075-5309

Palmer, J. and Cooper, I. (2011). Great Britain's housing energy fact file 2011. Available at: www.decc.gov.uk. [Accessed 2 November 2011].

Palmer, J.M., Curtis, S.G., and Pane, W., (2005), "Thermal Mass in Buildings – Practical Issues with Concrete Construction", *CTU Congress,* Dundee.

Palmero-Marrero, A.I., and Oliveira, A.C., (2010), "Effect of louver shading devices on building energy requirements", *Applied Energy.* 87. 2040-2049

Palomo Del Barrio, E., and Guyon, G. (2002). Using parameters space analysis techniques for diagnostic purpose in the framework of empirical model validation, report of Task 22 IEA, 2002.

Passerini, F., Albatici, R., and Frattari, A., (2013), "Quasi-steady state calculation method for energy contribution of sunspaces: a proposal for the European standard improvement" *Building Simulation Applications BSA 2013, 1st IBPSA Italy conference, Bozen- Bolzano, 30th January – 1st February 2013,* 141-150.

Patidar, S., Jenkins, D., Banfill, P., Gibson, G., (2014). Simple statistical model for complex probabilistic climate projection: Overheating risk and extreme events. Renewable Energy. 61. 23-28.

Peeters, L.F.R., de Dear, R., Hensen, J.L.M., and D'Haeseleer, W. (2009), Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. Applied Energy, 86 (5). 772-780.

Planning Portal (2014), "Guide to the planning permission and permitted development regimes for conservatories", Available at: http//www.planningportal.gov.uk/permission/commonprojects/conservatories/miniguide. Accessed 14 July, 2014

Pulselli, R.M., Simoncini, E., and Marchettini, N., (2009), "Energy and energy based cost benefit evaluate of building envelopes relative to geographical location and climate", *Building and Environment.* 44(5). 920-928

Pungila, C., Teodor-Florin, F., and Aritoni, O., (2009), "Benchmarking Database Systems for the Requirements of Sensor Readings", *IETE Technical Review*. **26** (5). 342-349.

Radhi, H., Eltrapolsi, A., and Sharples, S., (2009), "Will energy regulations in the Gulf States make buildings more comfortable? – a scoping study of residential buildings", *Applied Energy.* 86(12). 2531-2539.

Ralegaonkar, R.V., and Gupta, R., (2010), "Review of intelligent building construction: A passive solar architecture approach", *Renewable and Sustainable Energy Reviews.* 14. 2238-2242.

Robson, L.S., Shannon, H.S., Goldenhar, L.M. and Hale, A.R. (2001). Guild to Evaluate the Effectiveness of Strategies for Preventing Work Injuries: How to Show Whether a Safety Intervention Really Works. Centers for Disease Control and Prevention National Institute for Occupational Safety and Health. DHHS (NIOSH), 2001-119

Rodriguez, G.C., Carrillo-Andres, A., Dominguez-Munoz, F., Cejudo-Lopez, J.M., and Zhang, Y., (2013). Uncertainties and sensitivity analysis in building energy simulation using macroparameters. Energy and Buildings. 67. 79-87.

Sadineni, S.B., Madala, S., and Boehm, R.F., (2011), “Passive building energy savings: A review of building envelope components”, *Renewable and Sustainable Energy Reviews.* 15. 3617 – 3631.

Saltelli, A. (1999). Sensitivity analysis: could better methods be used? Journal of Geophysical Research. 104. 3789-3793.

Saltelli, A., Tarantola, F., Campolongo, M., and Ratto, M., (2004). Sensitivity Analysis in Practice: A Guide to Assessing Scientific Models. John Wiley and Sons Ltd.

Saunders, M., Lewis, P., and Thornhill, A., (2006). *Research methods for business students*. Pearson Education 4th ed.

Shamash, M., Mylona, A., and Metcalf, G. (2012). What guidance will building modellers require for integrating future climates into building performance simulation? First Building Simulation and Optimization Conference, Loughborough, UK. IBPSA – England, 253-260.

Shamash, M., Mylona, A., and Metcalf, G. (2012). Understanding future climate data from UKCP09 for weather data selection: a methodology. CIBSE ASHRAE Technical Symposium, Imperial College, London UK.

Smith, J., (1988). The problem of criteria for judging interpretive inquiry. Educational Evaluation and Policy Analysis. 6, p.379-391

Smith, S.T., and Hanby, V.I. (2012). "Methodologies for the generation of design summer years for building energy simulation using UKCP09 probabilistic climate projections", Building Services Engineering Research and Technology, 33(1). 9-17

Spanos, I., Simons, M., and Holmes, K.L., (2005), "Cost savings by application of passive solar heating", *Structural Survey.* 23(2). 111-130.

Spitz,C., Mora, L., Wurtz, E., and Jay, A., (2012). Practical application of uncertainty and sensitivity analysis in building energy simulation using macro parameters. Energy and Building. 67. 79-87.

Stravrakakis, G.M., Koukou, M.K., Vrachopoulos, M.G., and Markatos, N.C. (2008), "Natural cross-ventilation in buildings: Building-scale experiments, numerical simulation and thermal comfort evaluation", *Energy and Buildings,* (40), 1666-1681

Stevanovic, S., (2013), "Optimization of passive solar design strategies: A review", *Renewable and Sustainable Energy Reviews.* 25. 177 – 196

Storlie, C.B., Swiler, L.P., Helton, J.C., Sallaberry, C.J., (2009). Implementation and evaluation of non-parametric regression procedures for sensitivity analysis computationally demanding modules. Reliability Engineering and System Safety. 94 (11) 1735-1763.

Szokolay, S., (1984). "Passive and low energy design for thermal and visual comfort", *Passive and Low Energy Ecotechniques, 3rd Int. PLEA Conference. Mexico City.* 6-11. pp. 11-28

Taleb, H.M., (2014), "Using passive cooling strategies to improve thermal performance and reduce energy consumption of residential buildings in U.A.E buildings", *Frontiers of Architectural Research.* 3. 153-165.

Taleghani, M., Sailor, D., Tenpierik, M., and Dobbelsteen, A. (2014), "Thermal assessment of heat mitigation strategies: the case of Portland State University, Oregon, USA", *Building and Environment,* In Press

Tham, Y., Muneer, T., Levermore, G.J., and Chow, D. (2011), "An examination of UKCIP09 and UKCP09 solar radiation data sets for the UK climate related to their use in building design”, *Building Services Engineering Research and Technology*, 32(3). 207-228

Thermal Comfort. Available from: http://www.hse.gov.uk/temperature/thermal/factors.htm#radiant. Accessed May 29, 2013.

Thompson, R.L., Mead, C.M., and Edwards, R., (2007). Effective storm-relative helicity and bulk shear in supercell thunderstorm environment. Weather Forecasting. 22. 102-115.

Tian, W., (2013). A review of sensitivity analysis methods in building energy analysis. Renewable and Sustainable Energy Reviews, 20, 411-419.

Tian, W., and de Wilde (2011). Uncertainty and sensitivity analysis of building performance using probabilistic climate projections: A UK case study. Automation in Construction. 20. 1096 – 1109.

Tian, W., and Choudhary, R., (2012). A probabilistic energy model for non-domestic building sectors applied to analysis of school buildings in greater London. Energy and Building. 54. 1-11.

Triantaphyllou, E., (1997). A Sensitivity analysis approach for some deterministic multi-criteria decision making methods. *Decision Sciences*, 28 (1), p.151-194

Turner, C. and M. Frankel. 2008. *Energy Performance of LEED for New Construction Buildings*. Technical Report, New Buildings Institute, Vancouver, WA. Available at: http://www.usgbc.org/ShowFile.aspx?DocumentID=3930 [Accessed 1 November 2011].

Tzemelikos, A., Bessoudo, M., Athientis, A.K., and Zmeureanu, R. (2010), “Indoor thermal environment conditions near glazed facades with shading devices – Part II: Thermal comfort simulation and impact of glazing and shading properties”, *Building and Environment,* (45), 2517-2525.

UK Climate Projections (2010) UK Climate Projections 2009 Weather Generator User Interface (version 1). Available at: http://ukclimateprojections-ui.defra.gov.uk/ui/admin/login.php. Accessed: 19 April, 2013.

UNEP, (2007). Building and Climate Change: Status, challenges and opportunities, United Nations Environmental Programme.

United States Department of Energy (USDOE). 2002. International Performance Measurement and Verification Protocols: Concepts and Options for Determining Energy and Water Savings. Volume I. DOE/GO-102000-1132. Washington, D.C. United States Department of Energy.). Available at http://www.ipmvp.org. Accessed 10 October 2014

van Esch, M.M.E., Looman, R.H.J., de Bruin-Hordijk, G.J., (2012), “The effect of urban and building design parameters on solar access to the urban canyon and the potential for direct passive solar heating strategies”, *Energy and Buildings.* 47. 189-200

Van Treeck, C., Krafczyk, M., Kuhner, S. and Rank, E., (2001). *Direct Building Energy Simulation Based on Large Eddy Techniques and Lattice Boltzmann Methods*. International IBPSA Conference. Rio de Janeiro, Brazil, 51-58

Vaughan, A. (2011) How energy use by UK households has risen 18% in 40 years. The Guardian, Datablog. Facts are sacred.

Virk, G., Mylona, A., Mavrogianni, A., and Davies, M., (2015). “Using the new CIBSE design summer years to assess overheating in London: Effect of the urban heat island on design”, *Building Services Engineering Research and Technology*, 36(2). 115-128

Voeltzel, A., Carrie, F.R., and Guarracino, G., (2001), “Thermal and ventilation modelling of large highly-glazed spaces”, *Energy and Building.* 33. 121-132.

Watkins, R., Levermore, G.J., and Parkinson, J.B. (2011). “Constructing a future weather file for use in building simulation using UKCP09 projections”, *Building Services Engineering Research and Technology*, 32(3). 293-299

Williams, D., Elghali, L., France, C. and Wheeler, R.C. (2011) Projecting building energy demand using probabilistic weather conditions accounting for climate change. *CIBSE Technical Symposium*, DeMontfort University, Leicester, UK.

Witte, M.J., Henninger, R.H., Glazer, J., and Crawley, D.B., (2001) Testing and validation of a new building energy simulation program. *Seventh International IBPSA Conference,* Rio de Janeiro, Brazil*.*

Wood, G., and Newborough, M., (2003). Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. *Energy and Buildings*, 35, p. 821-841

Yamene, T., (1967). Statistics: An Introductory Analysis, 2nd Ed., New York: Harper and Row

Yang, B., Schiavon, S., Sekhar, C., Cheong, D., Tham, K.W., and Nazaroff, W.W., (2015). Building and Environment. 85. 196-204.

Yohanis, Y. G., Mondol, J.D., Wright, A., and Norton, B. (2008). Real-life energy use in the UK: How occupancy and dwelling characteristics affect domestic electricity use. *Energy and Buildings*, 40 (6), p.1053-1059

Yohanis, Y.G., and Norton, B., (2002), “Useful solar heat gains in multi-zone non-domestic buildings as a function of orientation and thermal time constant”, *Renewable Energy.* 27(1). 87-95.

Yudelson, L. 2010. *Greening Existing Buildings*. New York: Green Source/McGraw-Hill.

Zain-Ahmed, A., Sopian, K., Othman, M.Y.H., Sayigh, A.A.M., and Surendran, P.N., (2002), “Daylighting as a passive solar design strategy in tropical buildings: a case study of Malaysia”, *Energy Conversion and Management.* 43. 1725-1736

Zanghirella, F., Perino, M., and Serra, V. (2011), “A numerical model to evaluate the thermal behaviour of active transparent facades” *Energy and Building,* (43), 1123-1138.

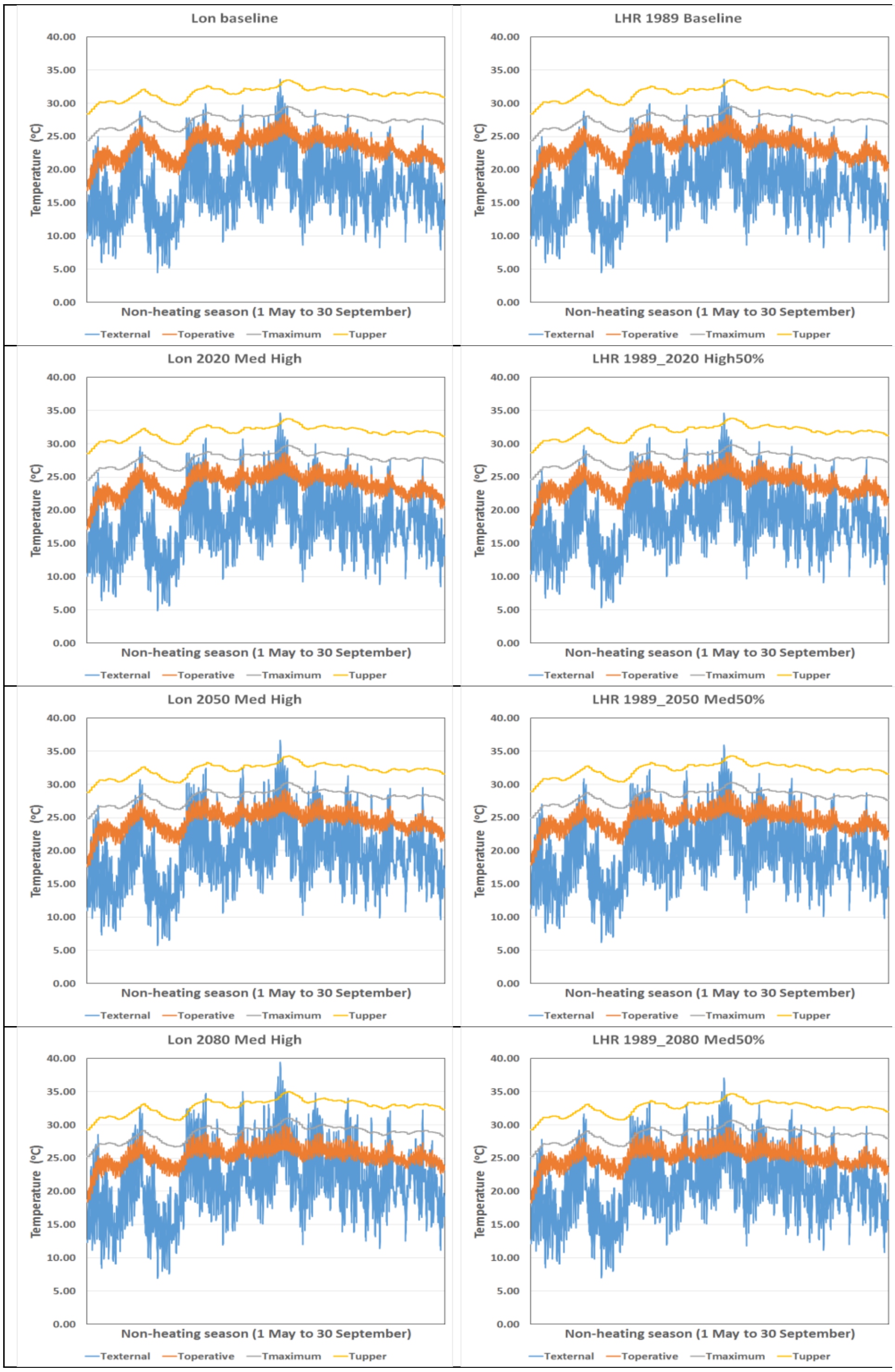
ZCH (2009), Defining a Fabric Energy Efficiency Standard for Zero Carbon Homes. Appendix A. Work Group 1 Form and Fabric. Zero Carbon Hub (ZCH), National House-Building Council (NHBC) Foundation. London and Milton Keynes, UK

ZCH (2010), Carbon Compliance – Topic 3 – Future Climate Change. Zero Carbon Hub (ZCH), National House-Building Council (NHBC) Foundation. London and Milton Keynes, UK. Available at: http://www.zerocarbonhub.org/resourcefiles/TOPIC3_ORANGE_5August.pdf. Accessed November 6, 2013.

ZCH (2012). Overheating in Homes: An introduction for planners, designers and property owners. Zero Carbon Hub (ZCH), National House-Building Council (NHBC) Foundation. London and Milton Keynes, UK.

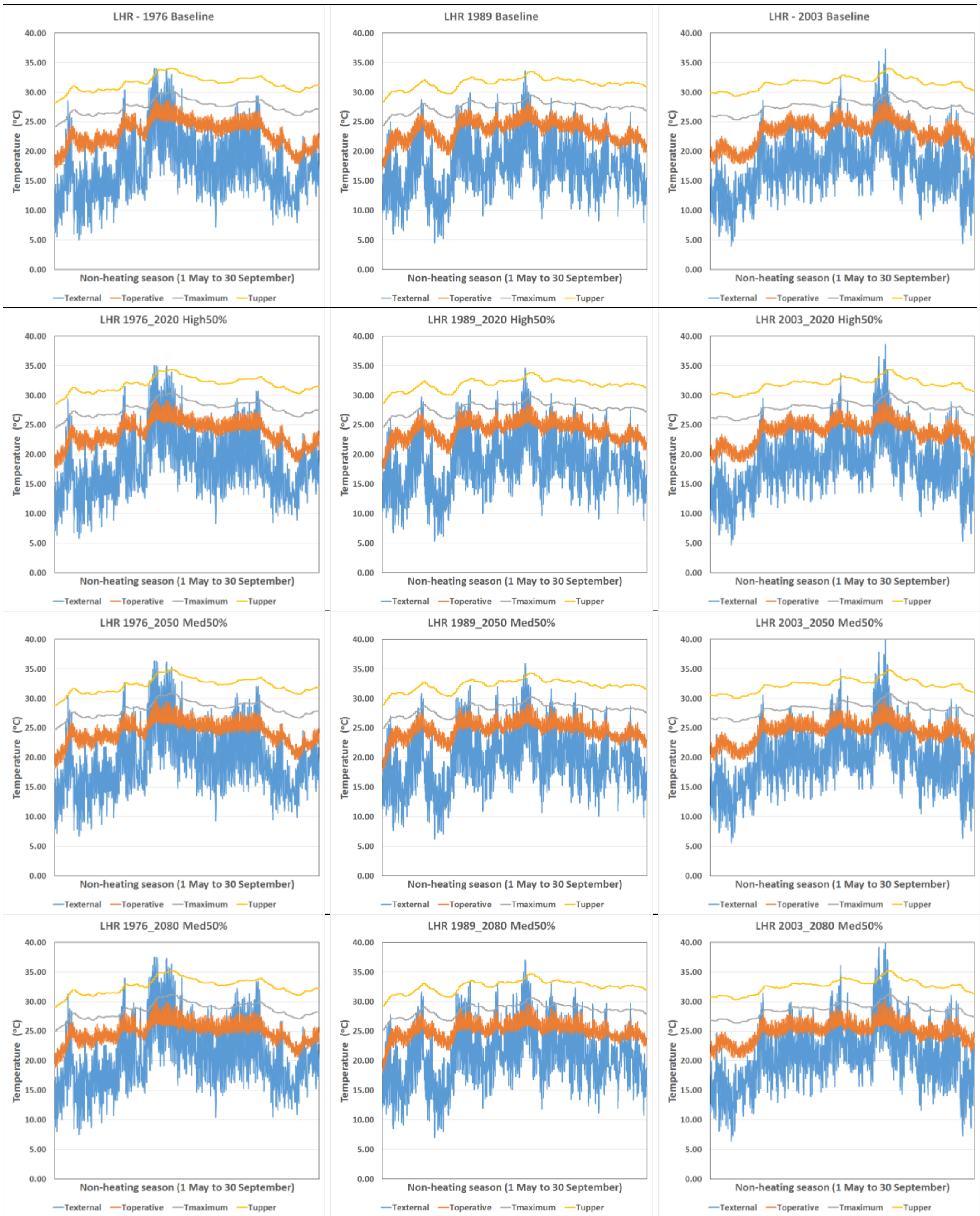
APPENDICES

Appendix 5.1



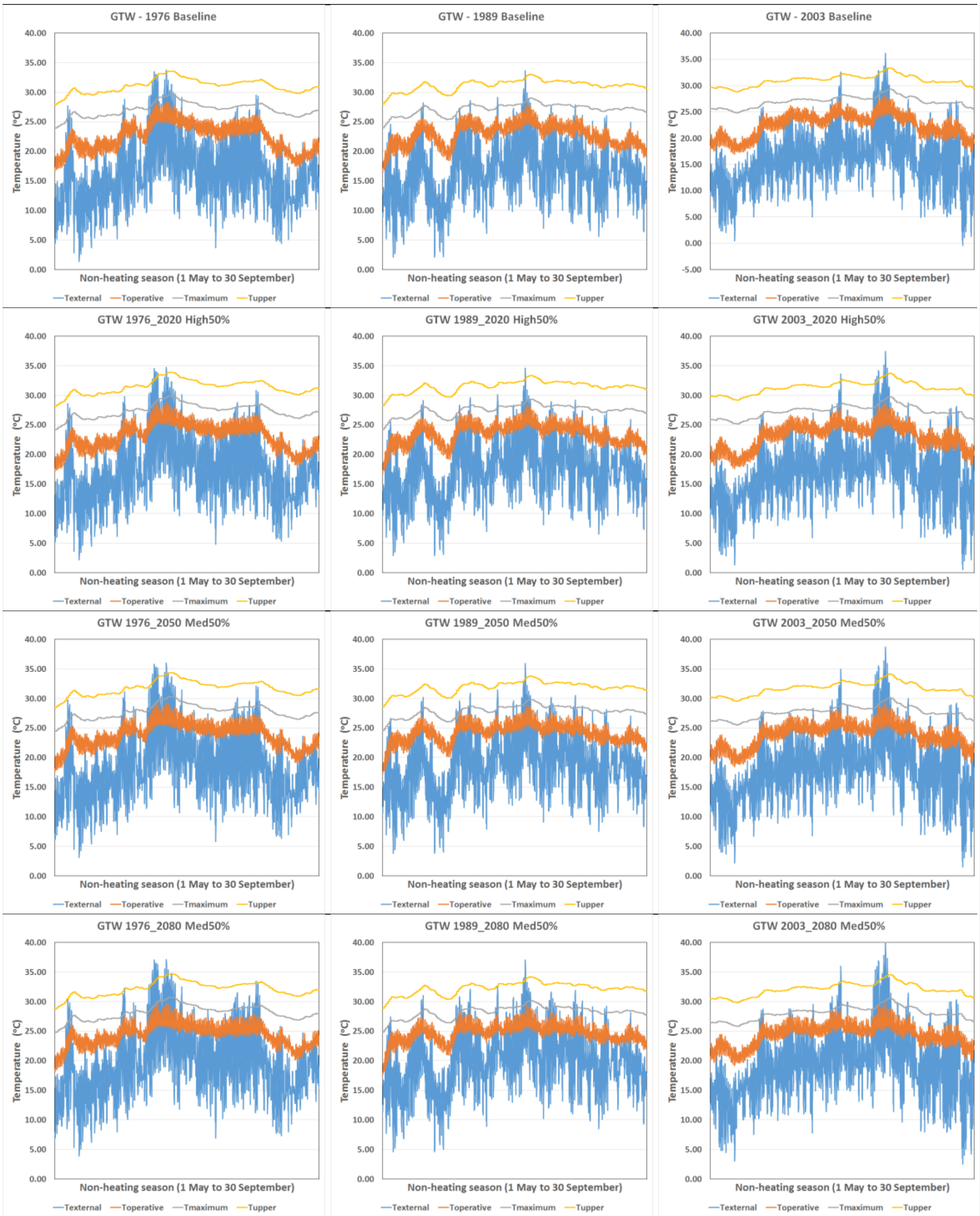
Appendix 5.1 A comparison of internal operative temperatures for UKCIP02 Heathrow DSY Medium High and UKCP09 Heathrow 1989 medium 50% probabilistic scenarios based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 5.2



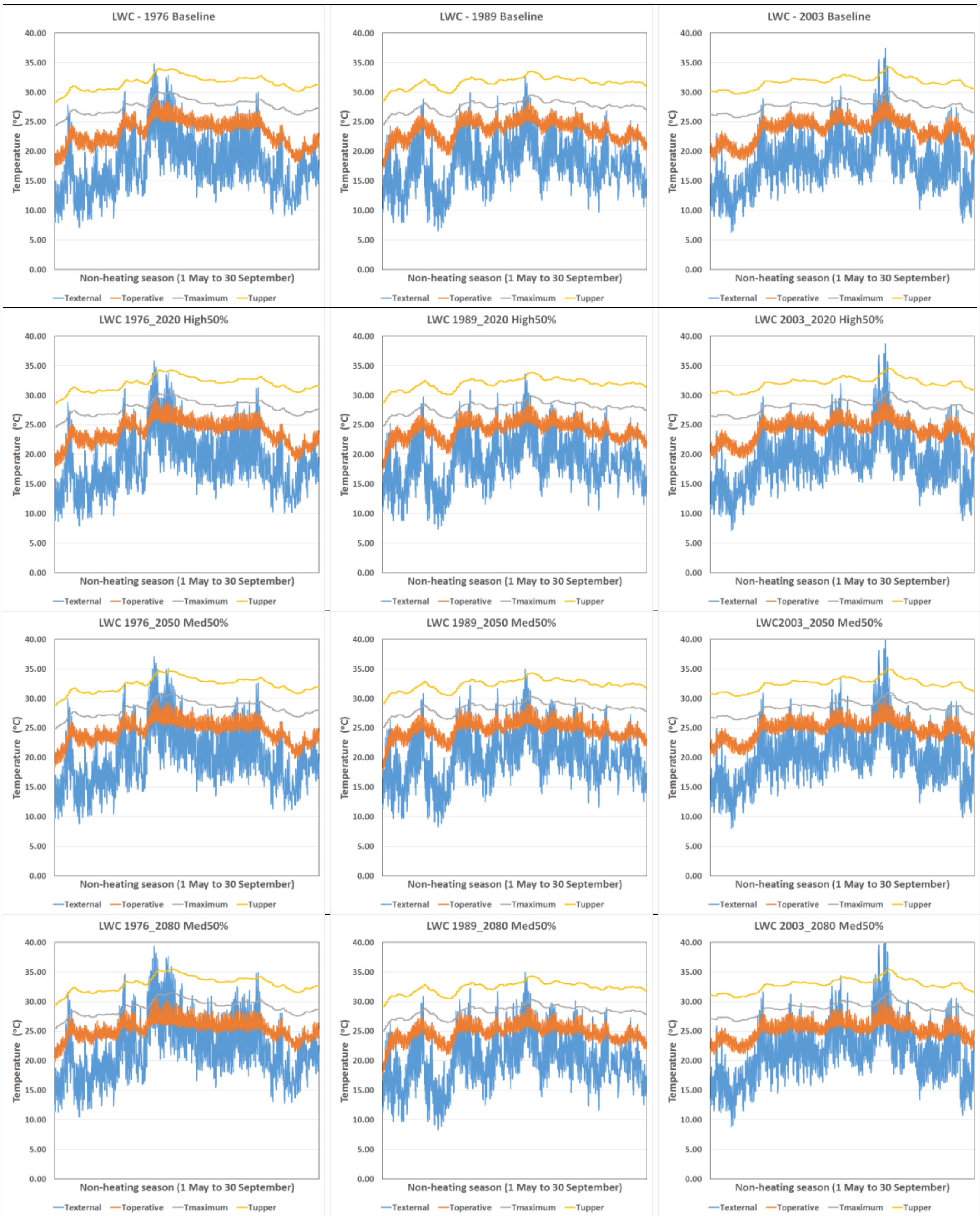
Appendix 5.2 A comparison of internal operative temperatures for Heathrow using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 5.3



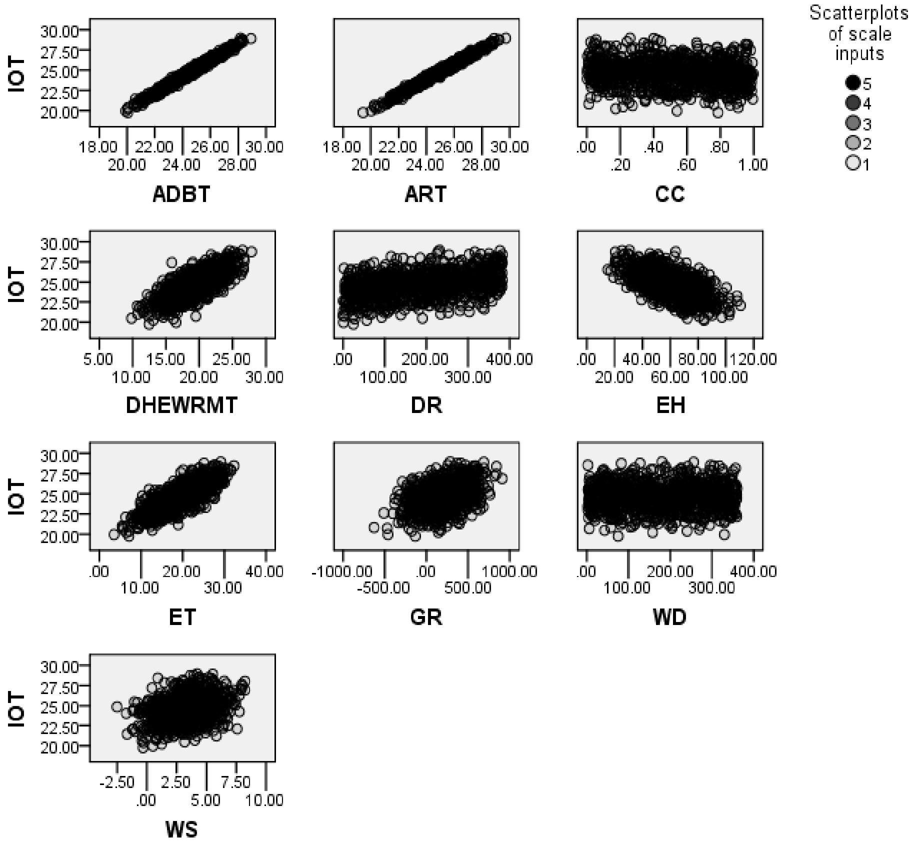
Appendix 5.3 A comparison of internal operative temperatures for Gatwick using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 5.4



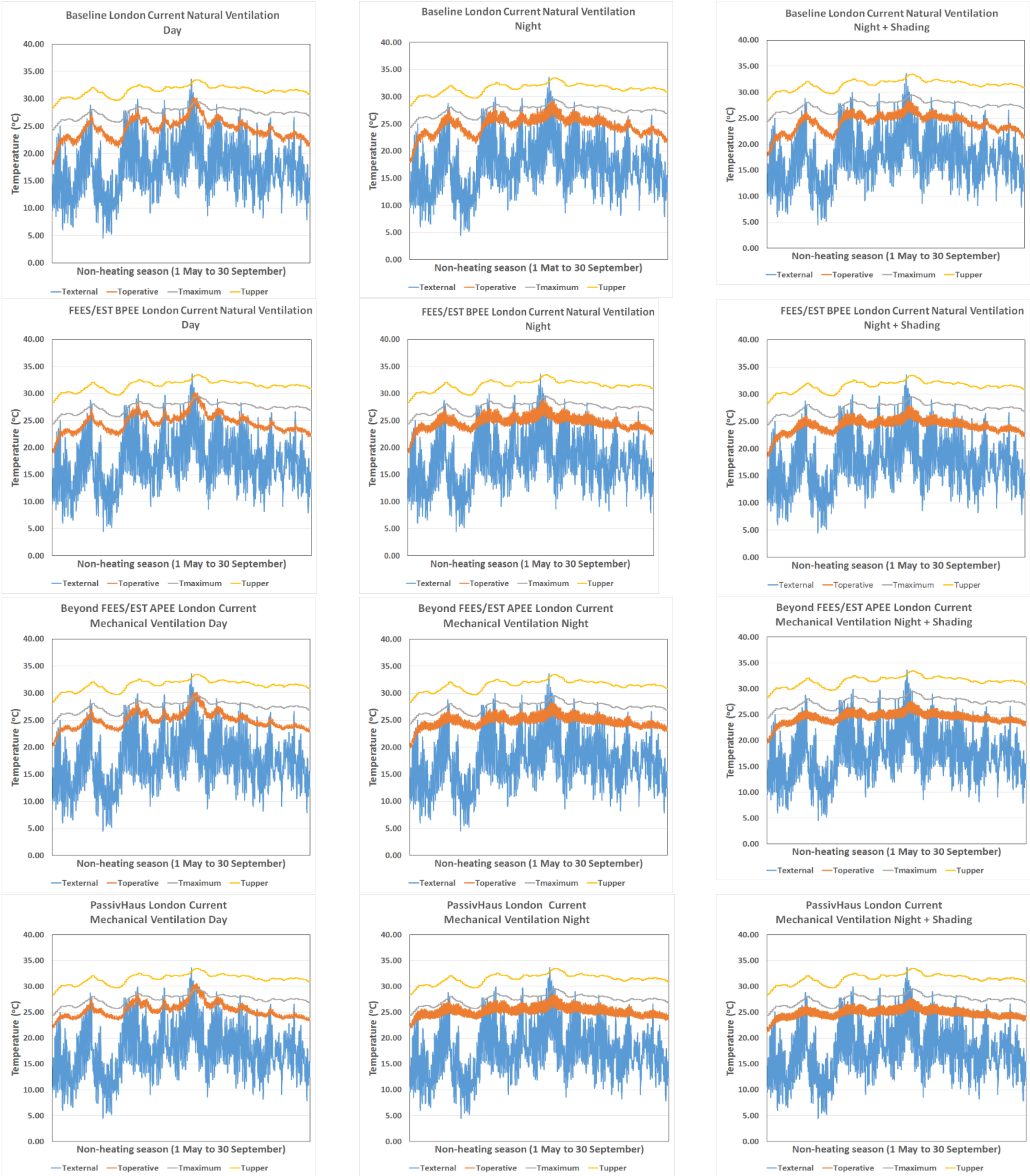
Appendix 5.4 A comparison of internal operative temperatures for London Weather Centre using UKCP09 1976, 1989 and 2003 medium 50% probabilistic weather data set scenarios with overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 5.5



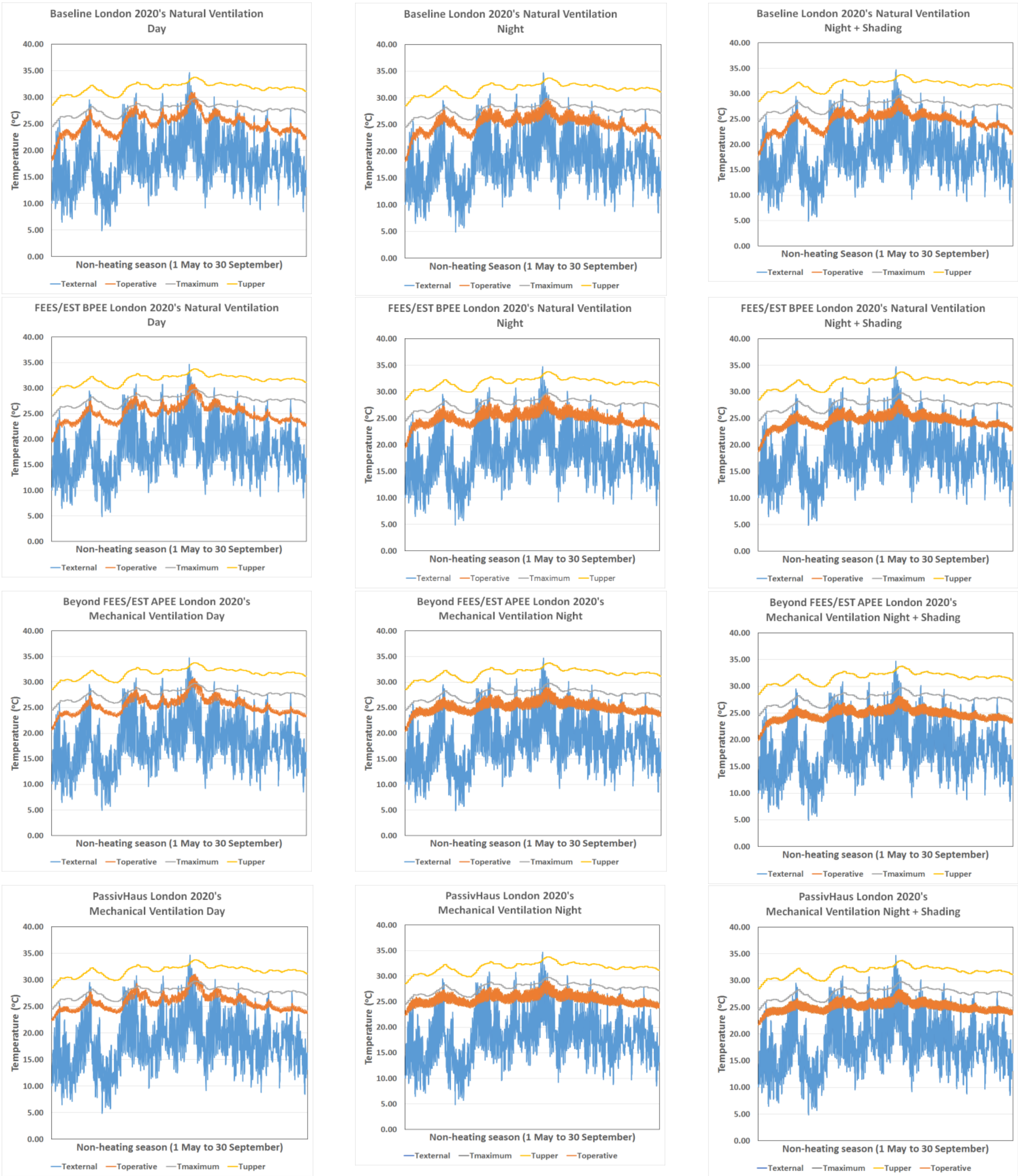
Appendix 5.5 Scatter plots of the input weather variables

Appendix 7.1



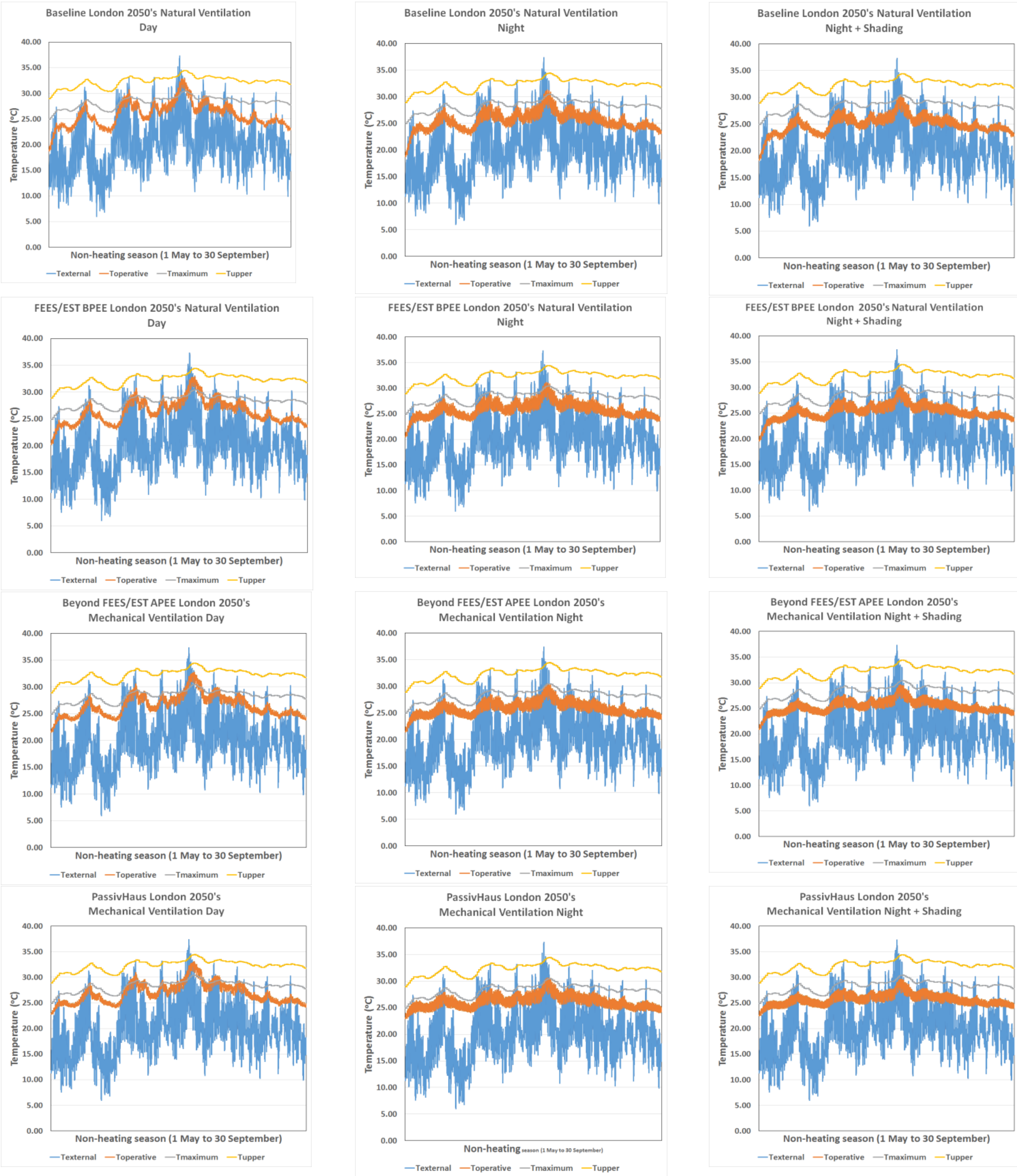
Appendix 7.1 A comparison of whole building internal operative temperatures for London using CIBSE current weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.2



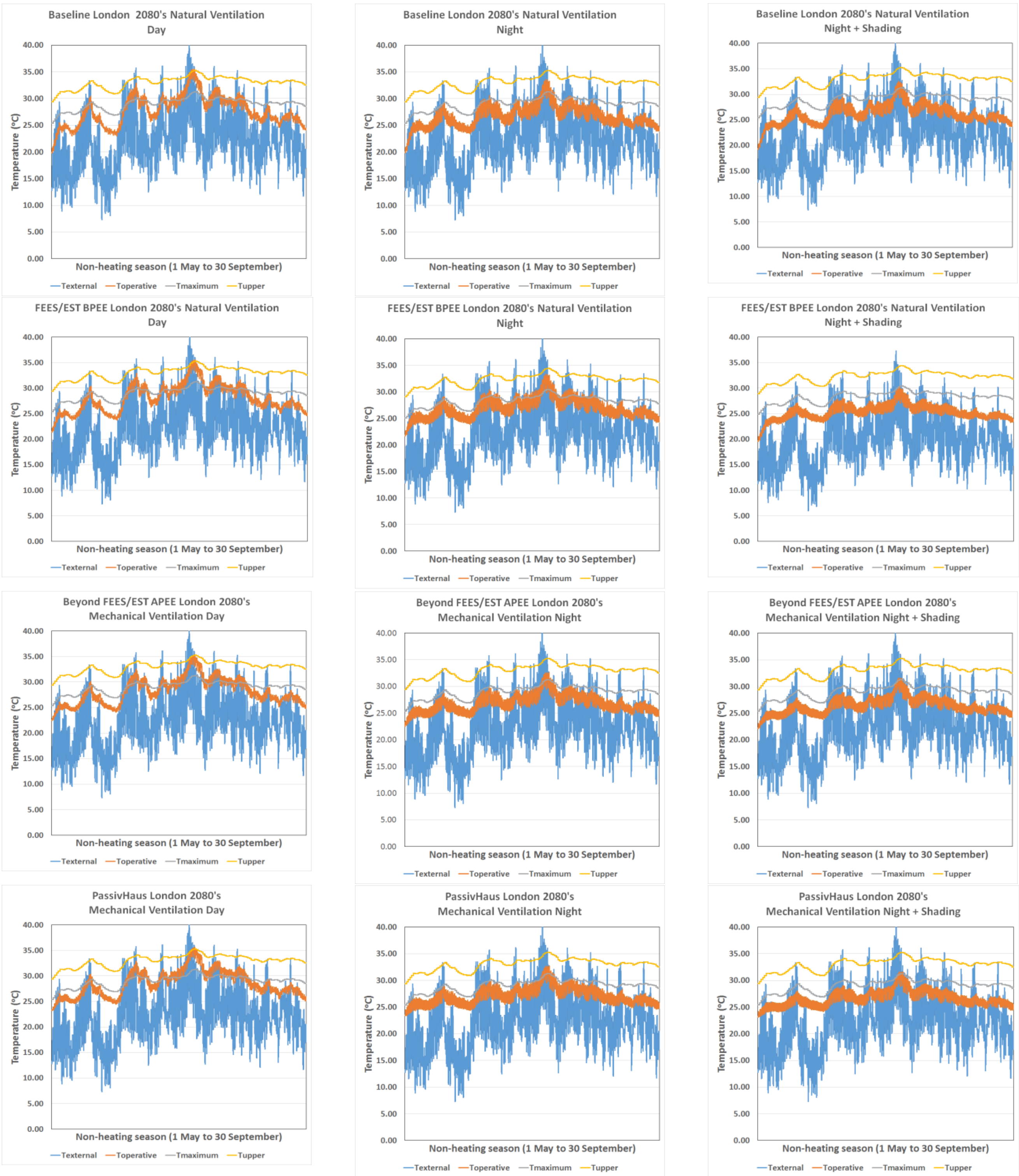
Appendix 7.2 A comparison of whole building internal operative temperatures for London using CIBSE 2020's weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.3



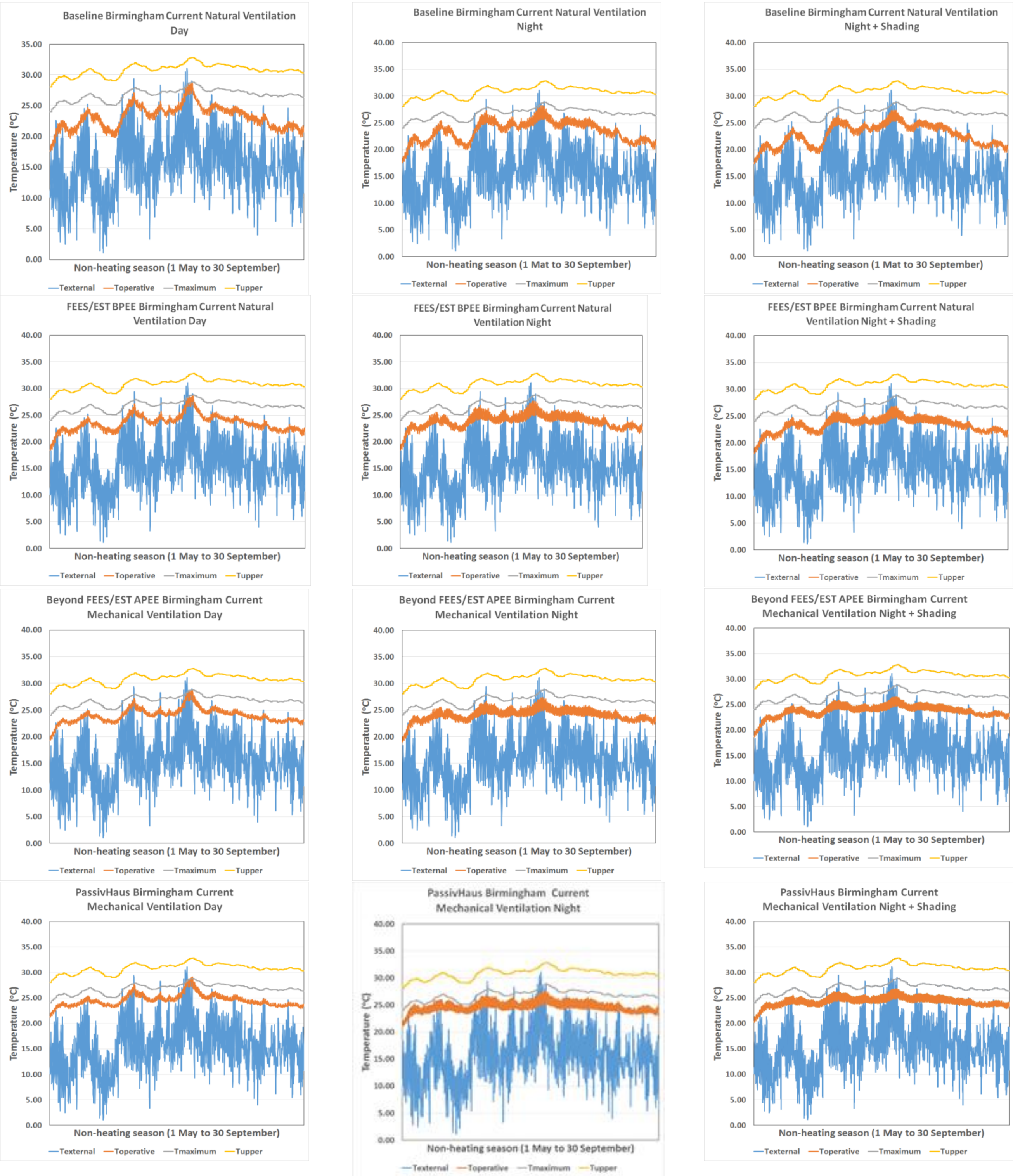
Appendix 7.3 A comparison of whole building internal operative temperatures for London using CIBSE 2050's weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.4



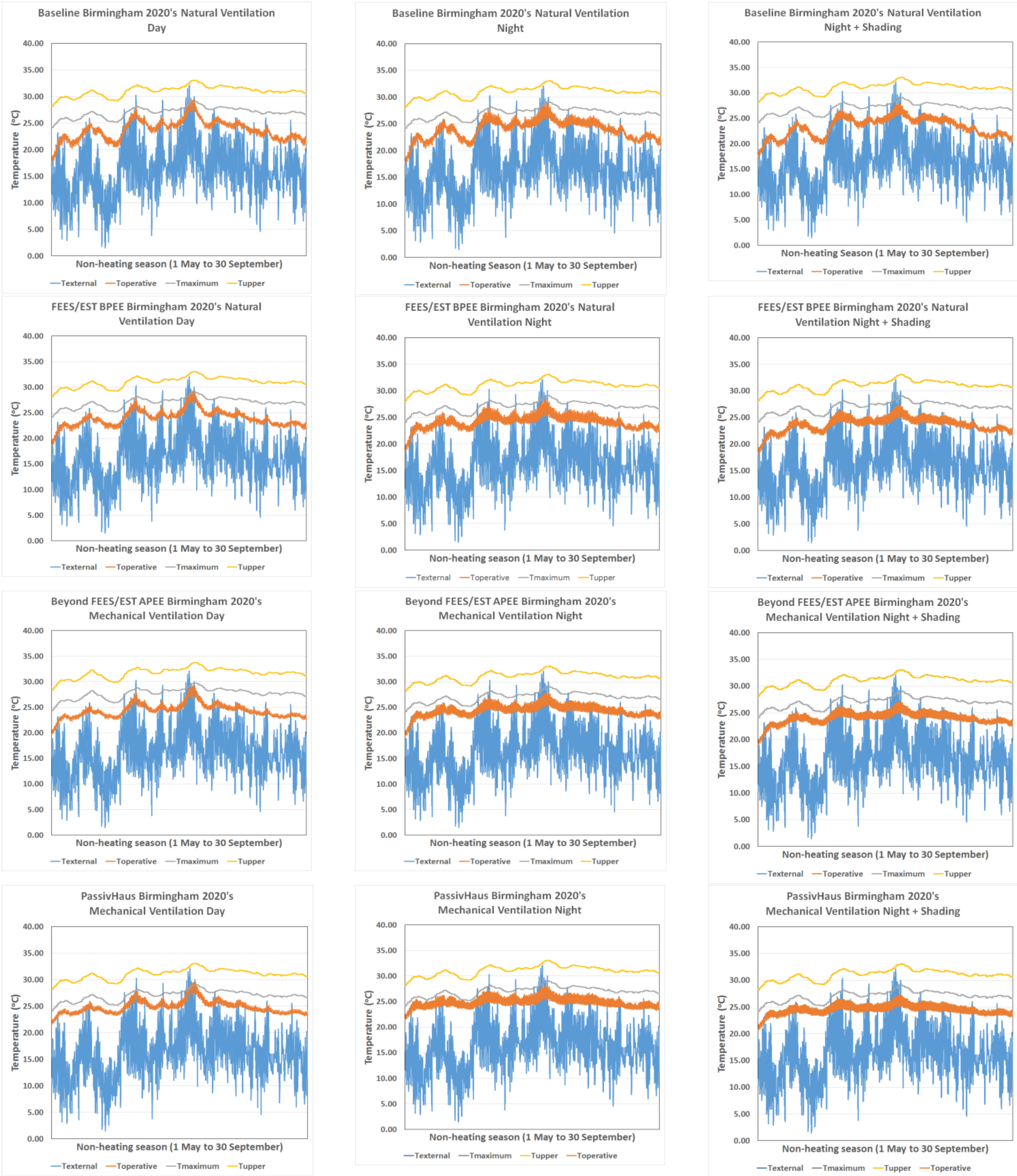
Appendix 7.4 A comparison of whole building internal operative temperatures for London using CIBSE 2080's weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.5



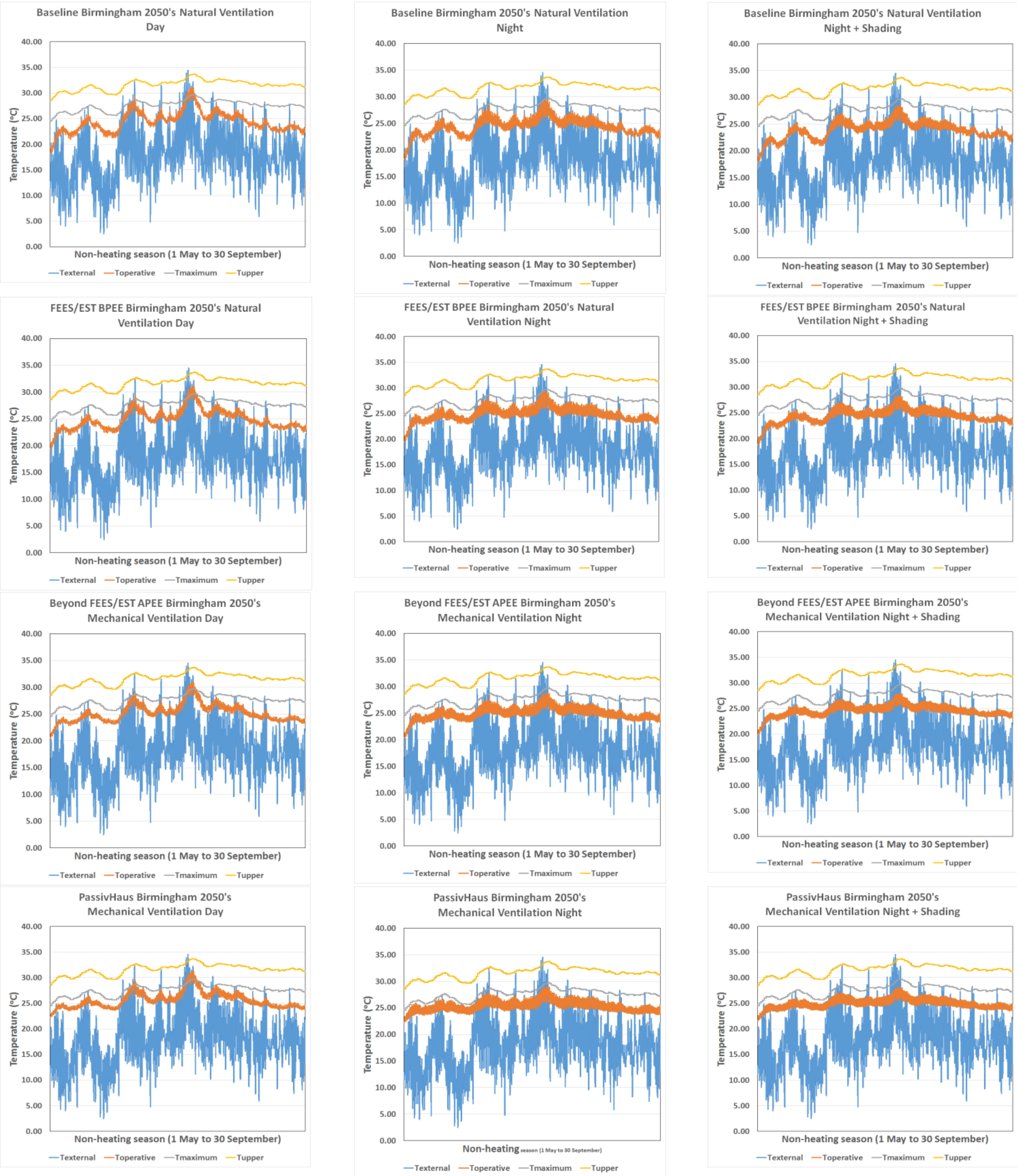
Appendix 7.5 A comparison of whole building internal operative temperatures for Birmingham using CIBSE current weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.6



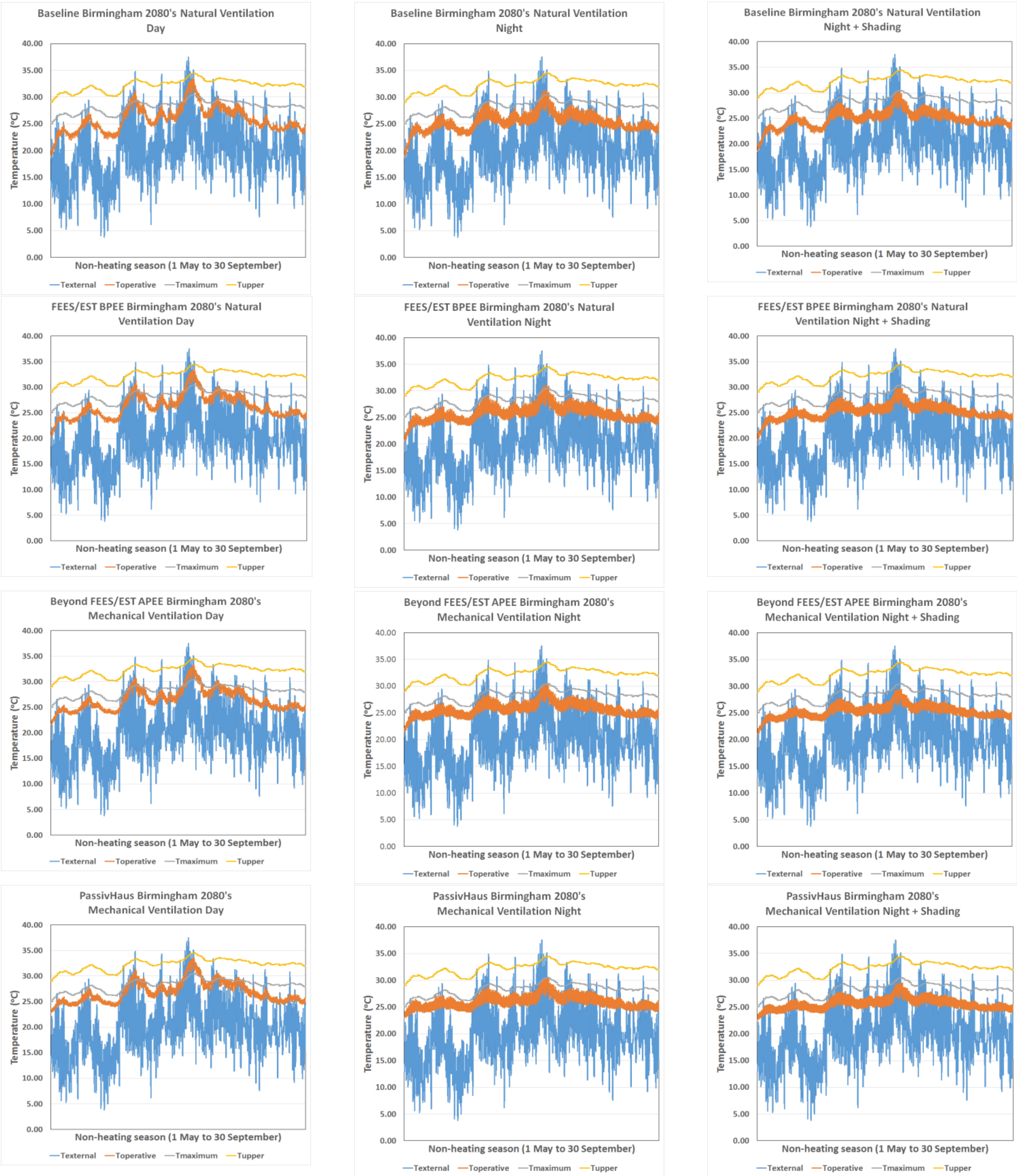
Appendix 7.6 A comparison of whole building internal operative temperatures for Birmingham using CIBSE 2020's weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.7



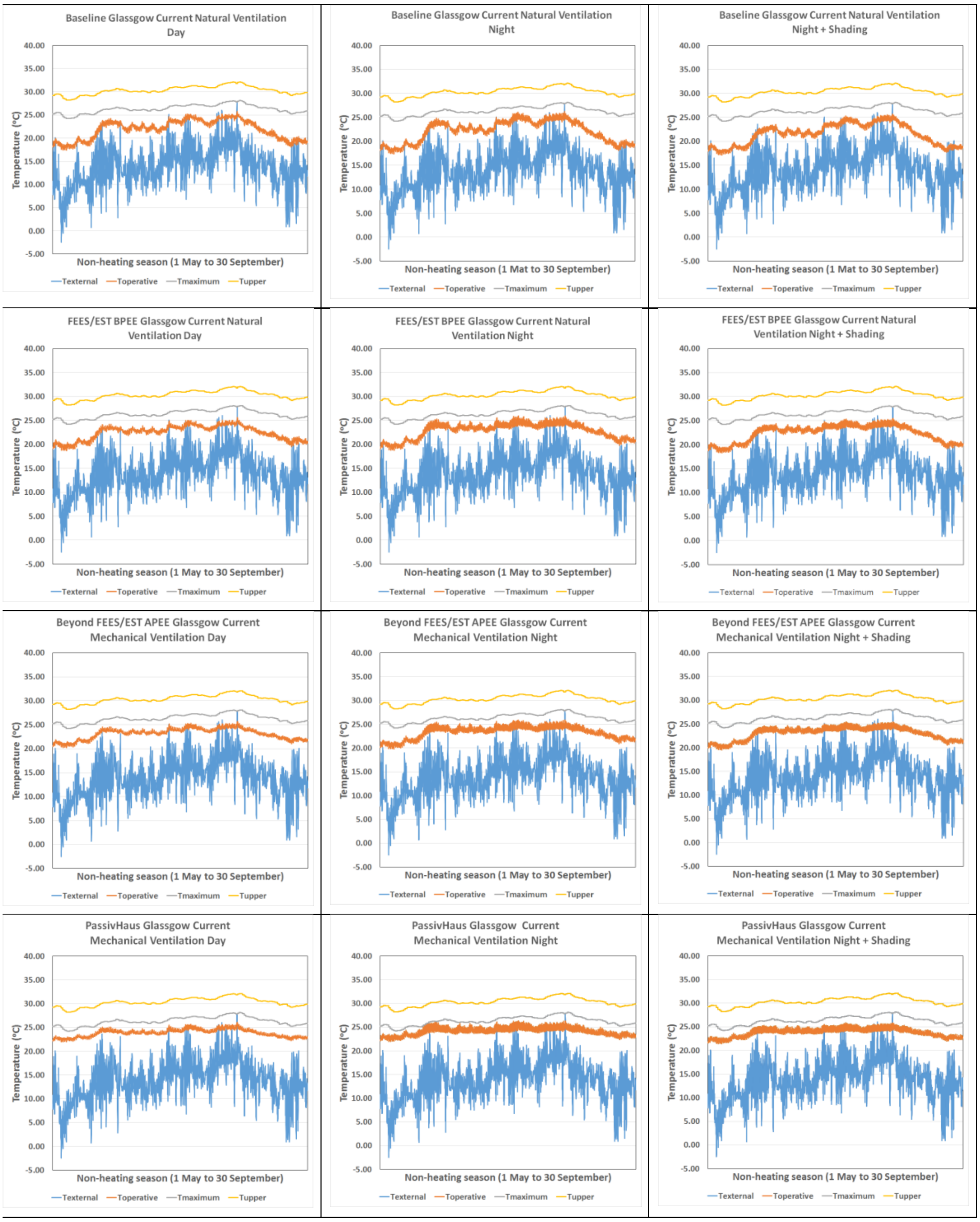
Appendix 7.7 A comparison of whole building internal operative temperatures for Birmingham using CIBSE 2050's weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.8



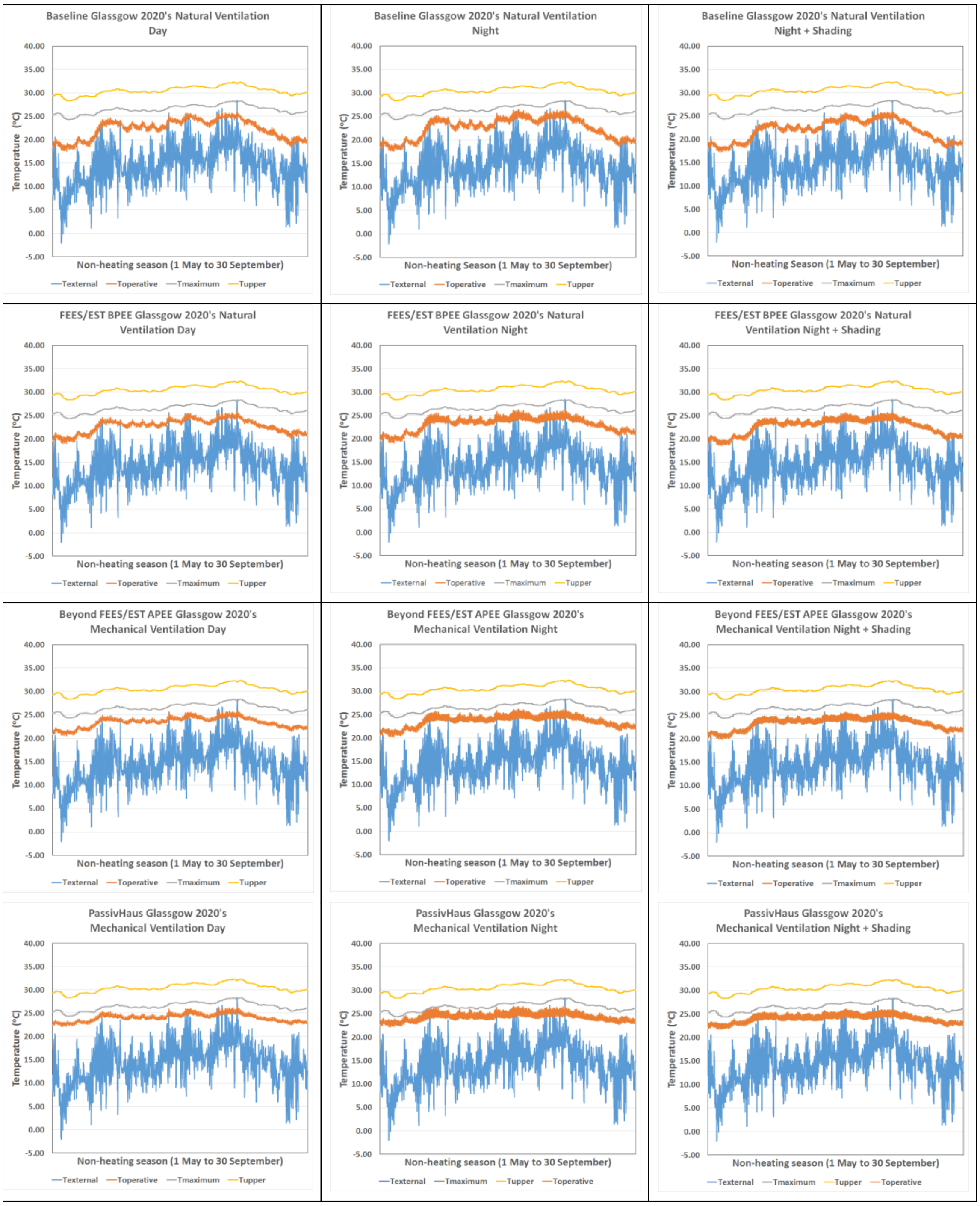
Appendix 7.8 A comparison of whole building internal operative temperatures for Birmingham using CIBSE 2080's weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.9



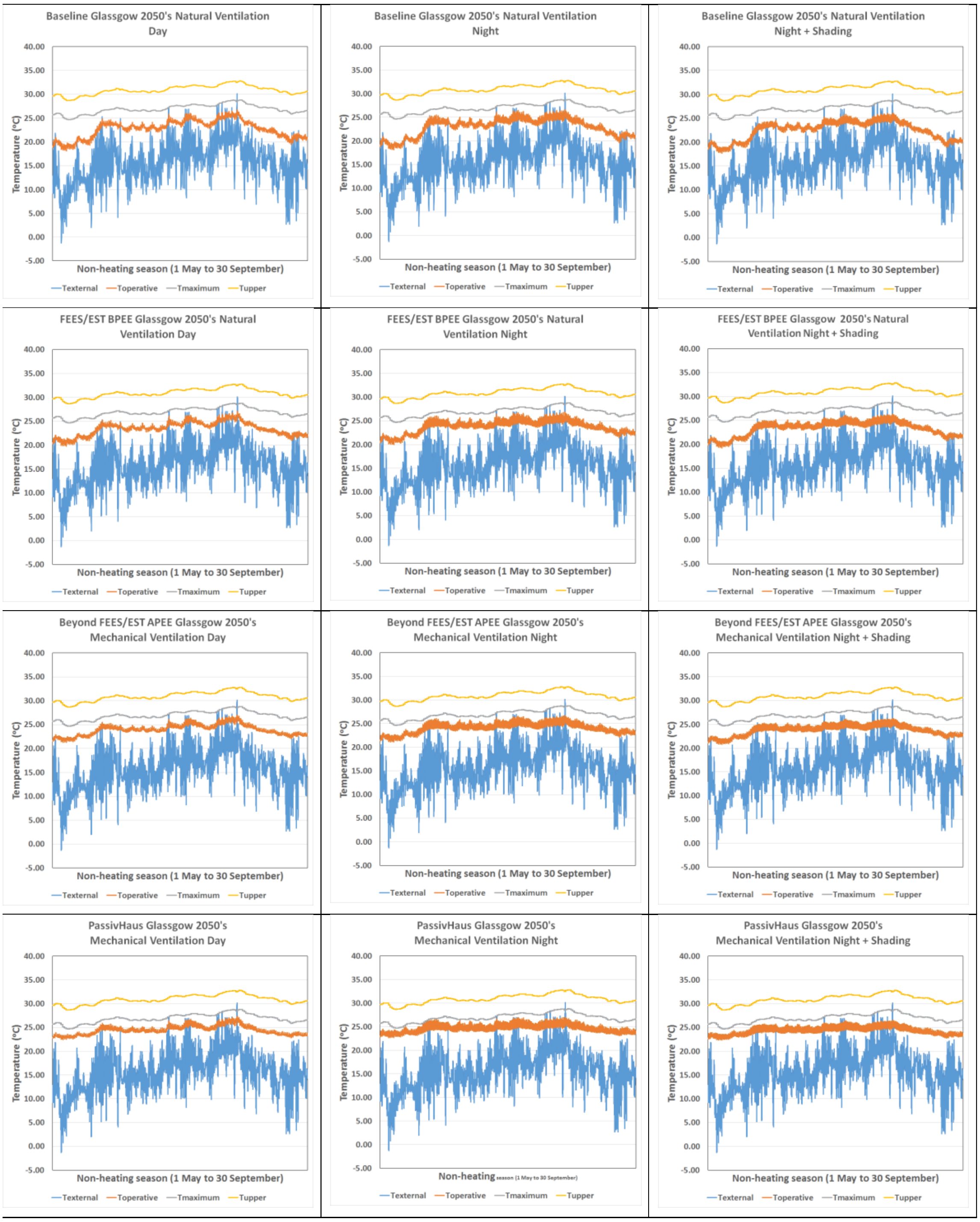
Appendix 7.9 A comparison of whole building internal operative temperatures for Glasgow using CIBSE current weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.10



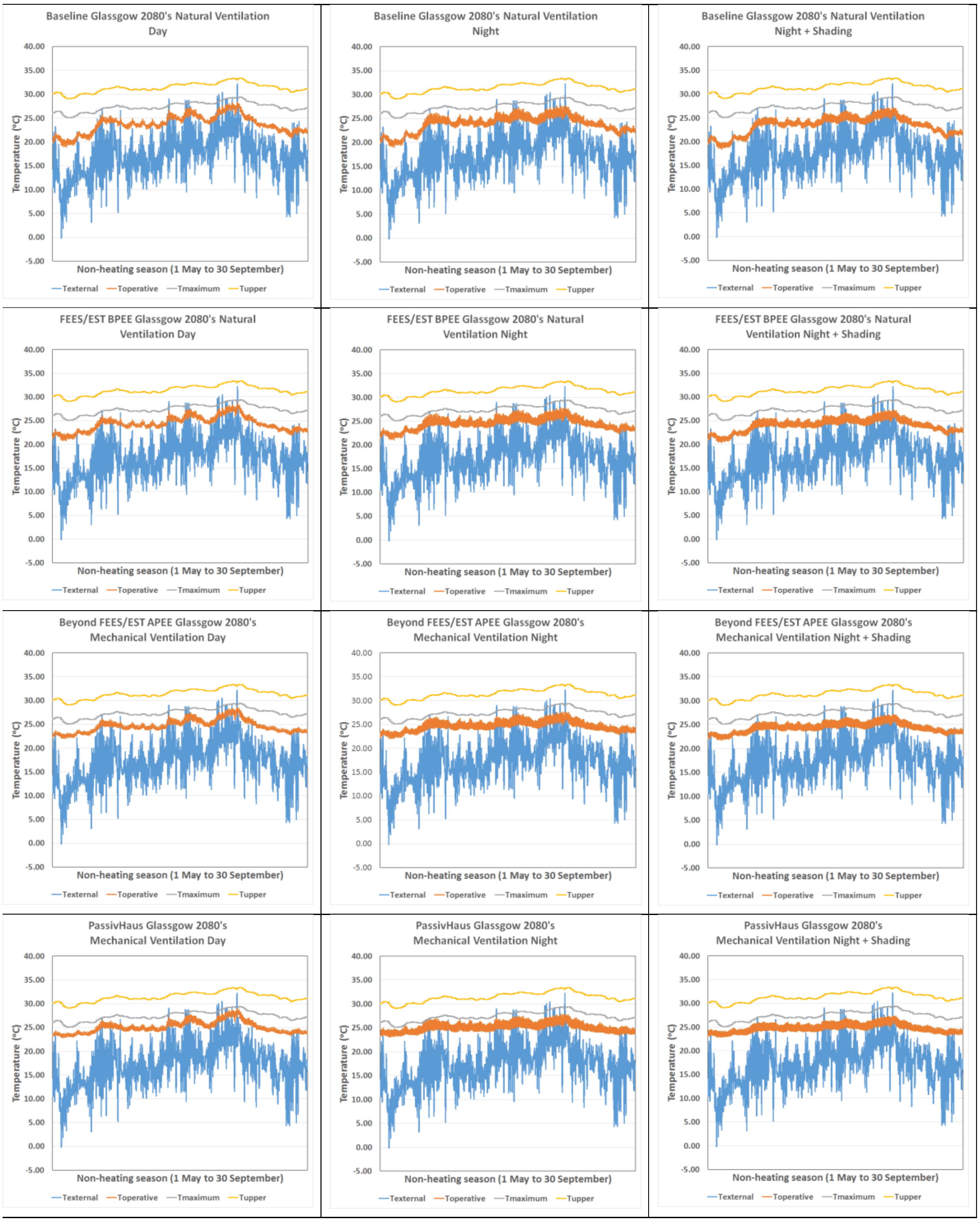
Appendix 7.10 A comparison of whole building internal operative temperatures for Glasgow using CIBSE 2020's weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.11



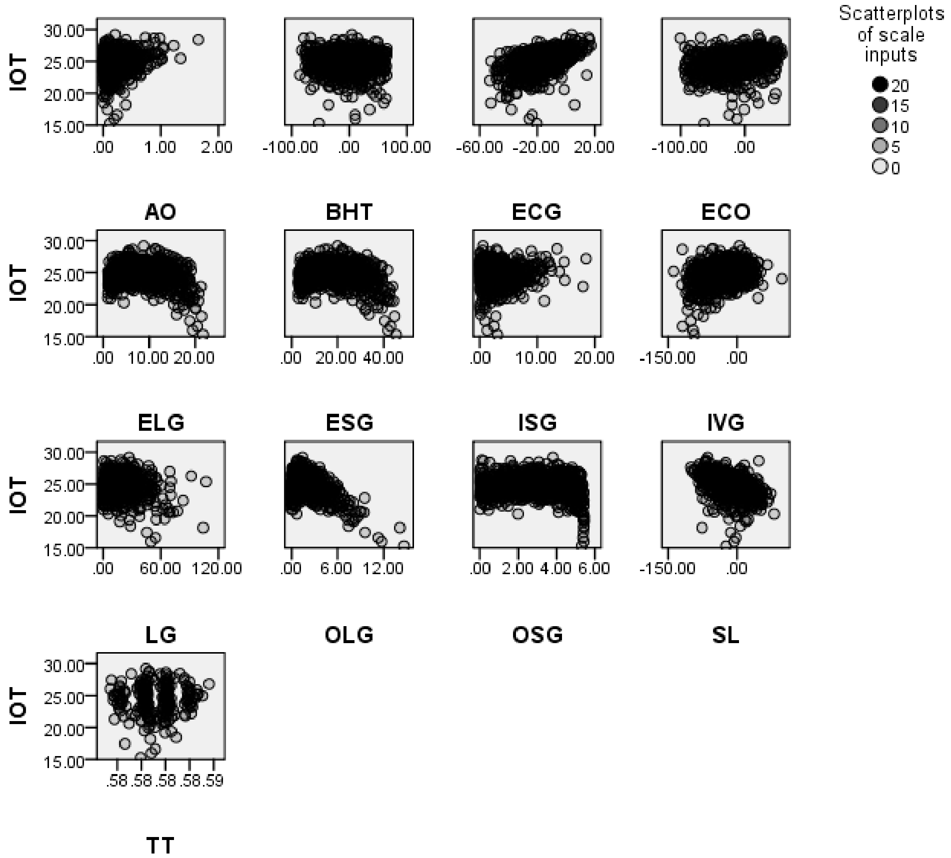
Appendix 7.11 A comparison of whole building internal operative temperatures for Glasgow using CIBSE 2050's weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 7.12



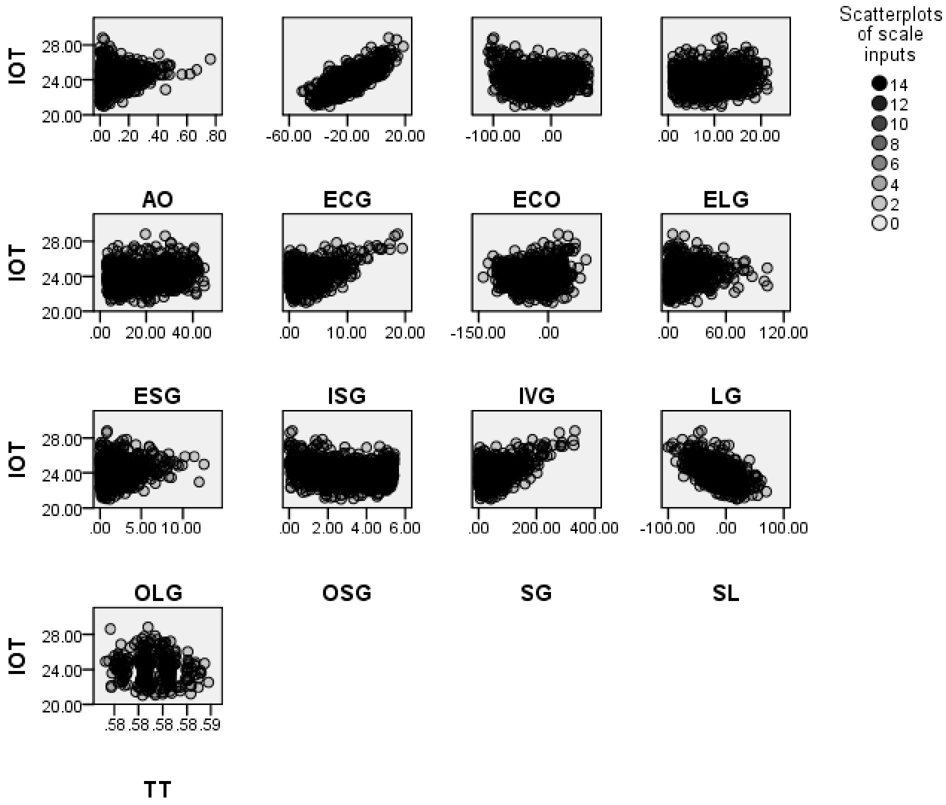
Appendix 7.12 A comparison of whole building internal operative temperatures for Glasgow using CIBSE 2080's weather data set based on UKCIP02 climatic projections, varying ventilation scenarios and overheating analysis based on CIBSE TM52 adaptive thermal comfort criteria.

Appendix 8.1



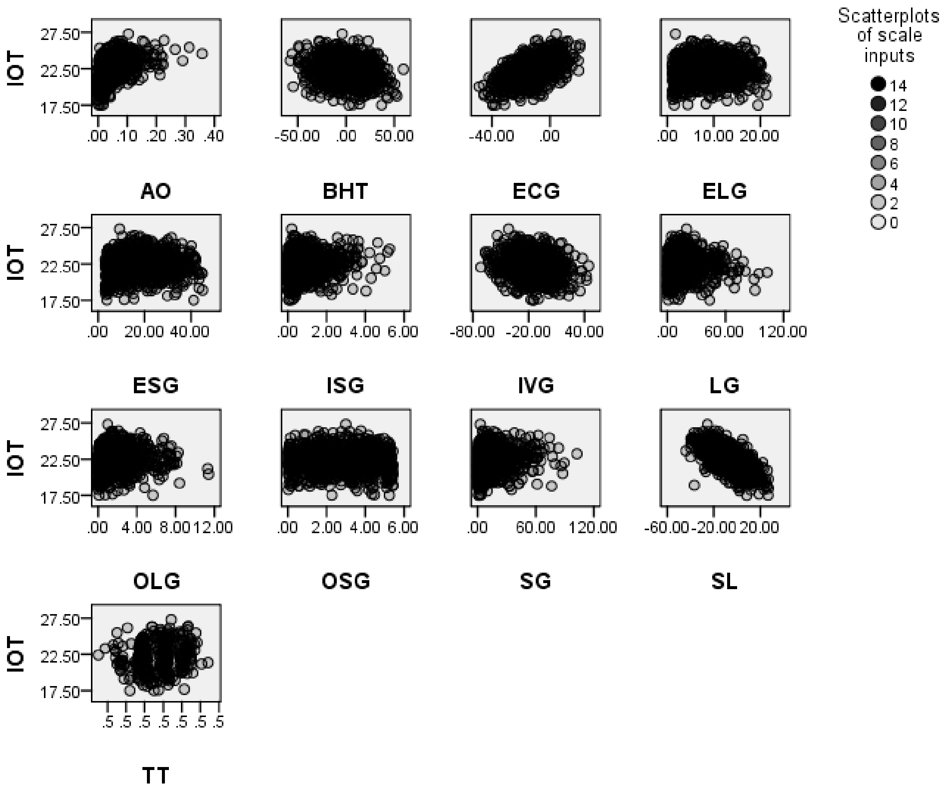
Appendix 8.1 Scatter plot for baseline scenario UKCP09 GTW 2003-2050 Med 50% Day

Appendix 8.2



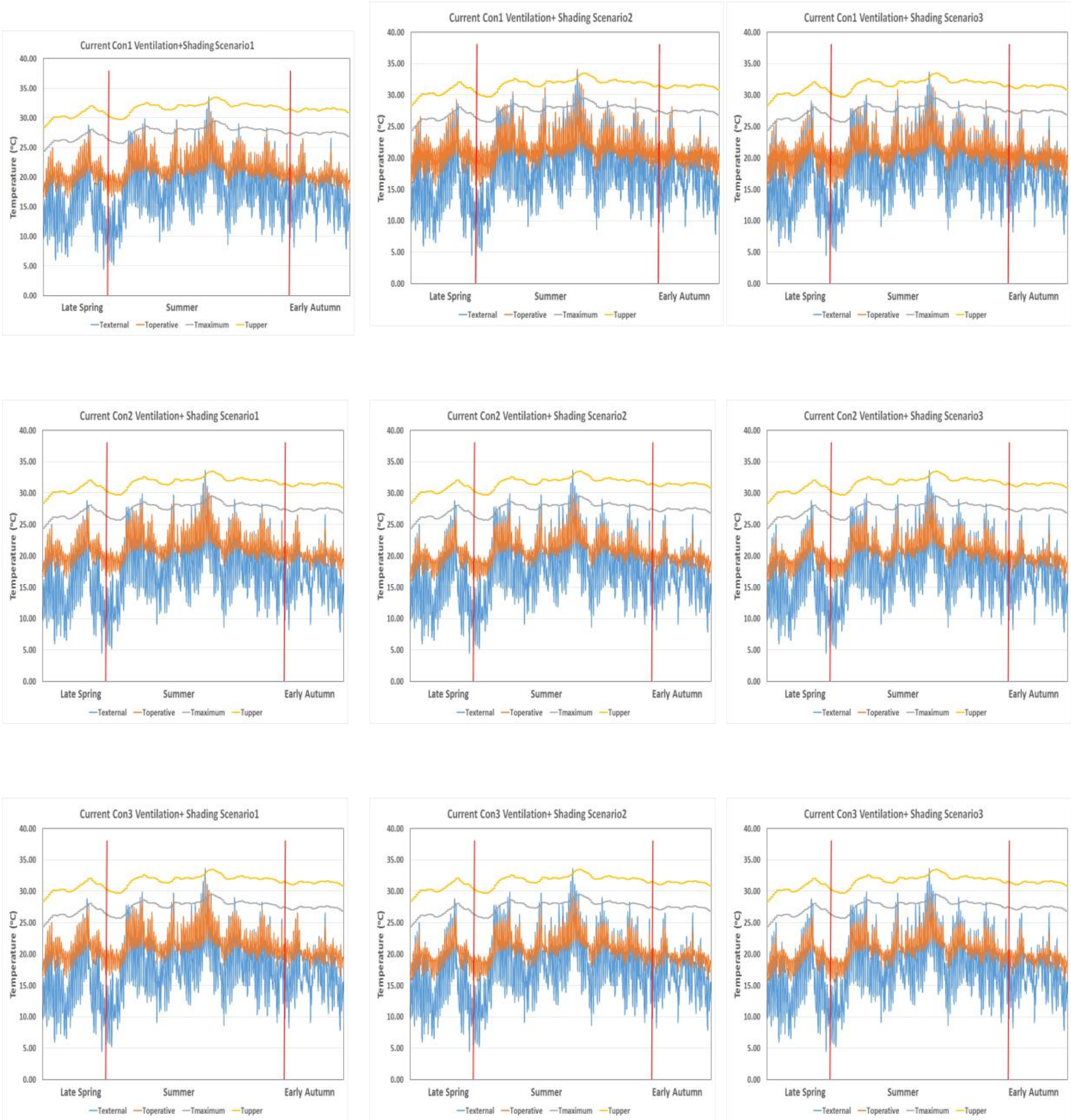
Appendix 8.2 Scatter plot for baseline scenario UKCP09 GTW 2003-2050 Med 50% Night

Appendix 8.3



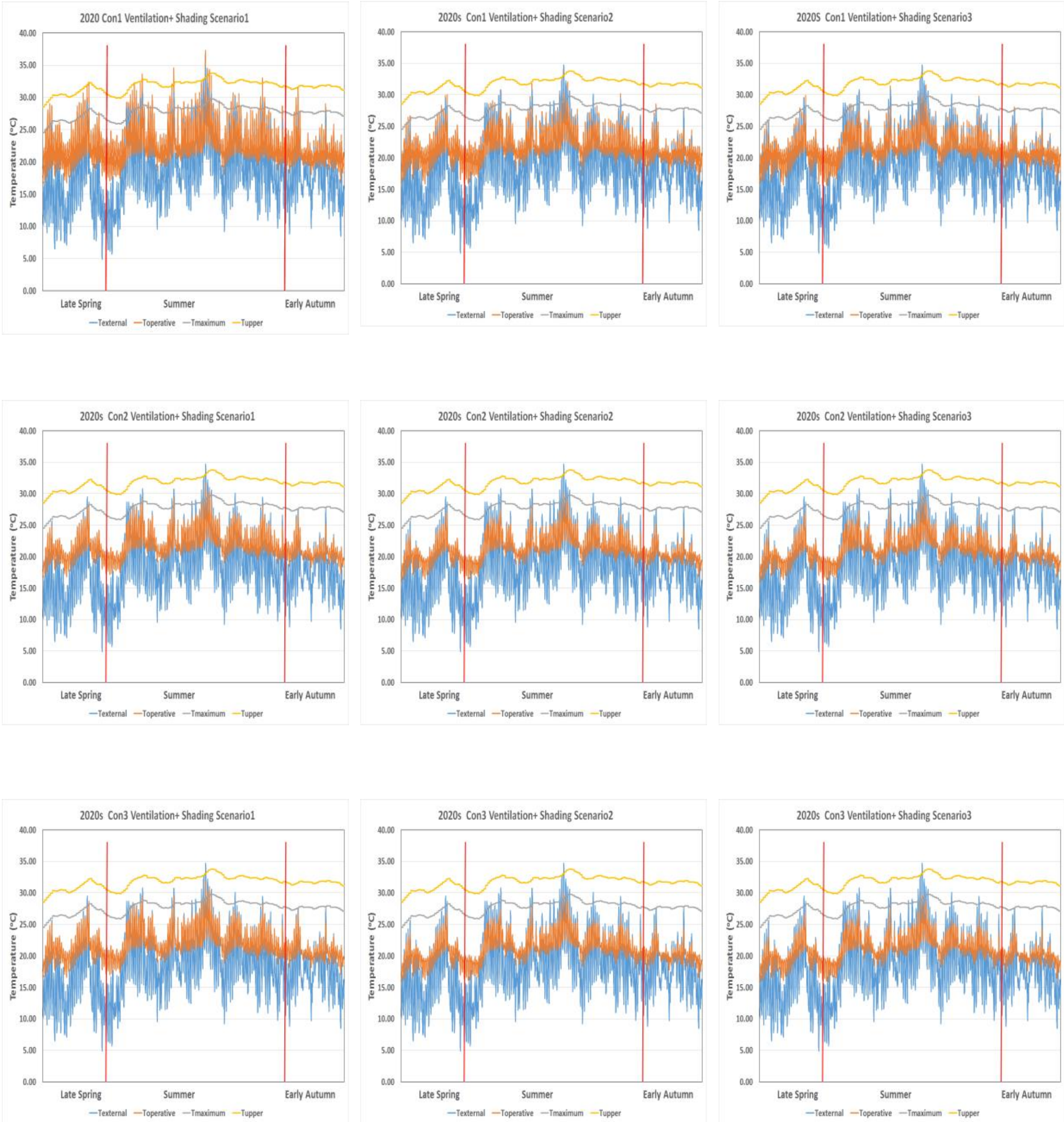
Appendix 8.3 Scatter plot for baseline scenario UKCP09 GTW 2003-2050 Med 50% Night & Shading

Appendix 9.1



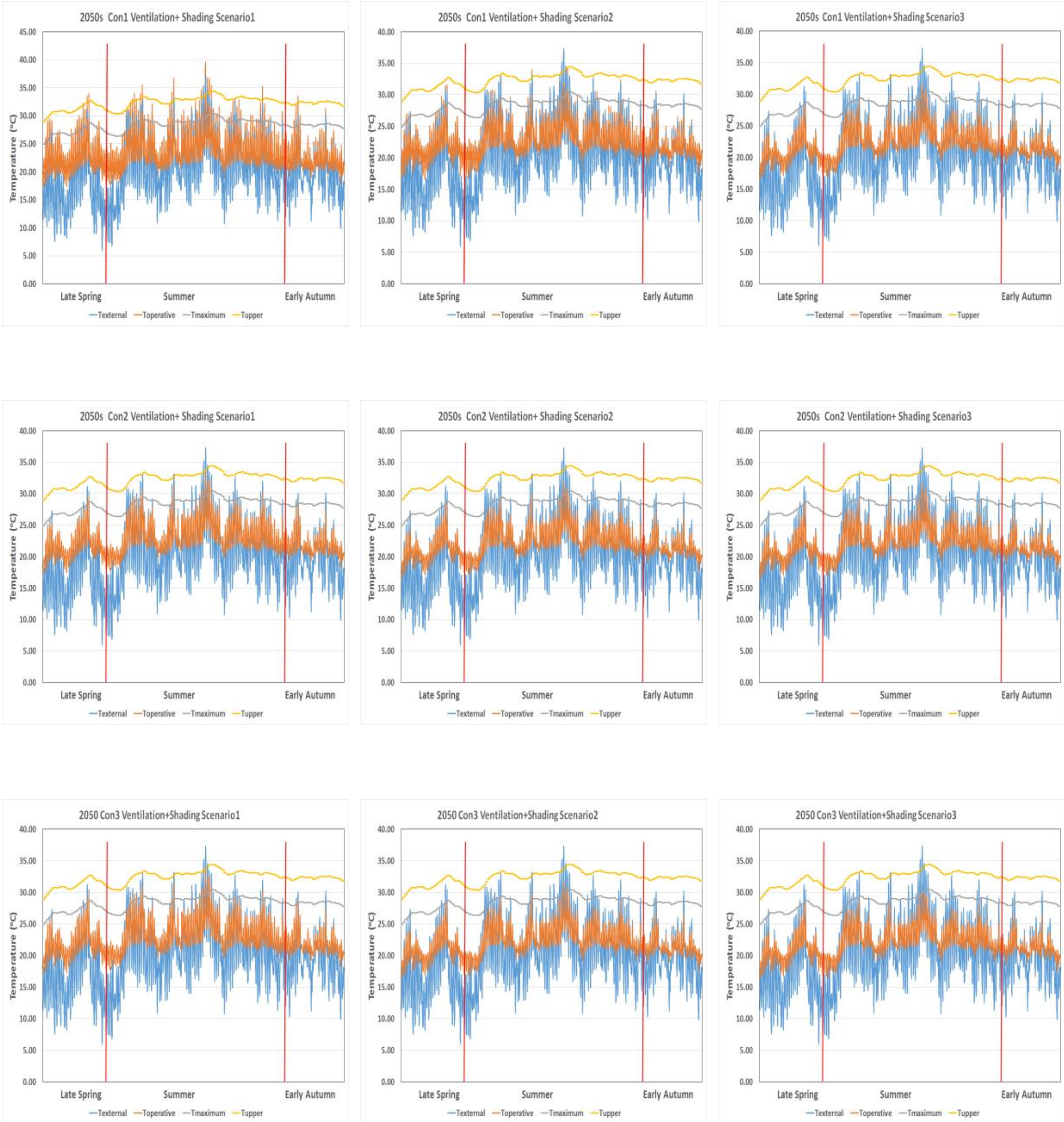
Appendix 9.1 Current weather conservatory non-heating season analysis

Appendix 9.2



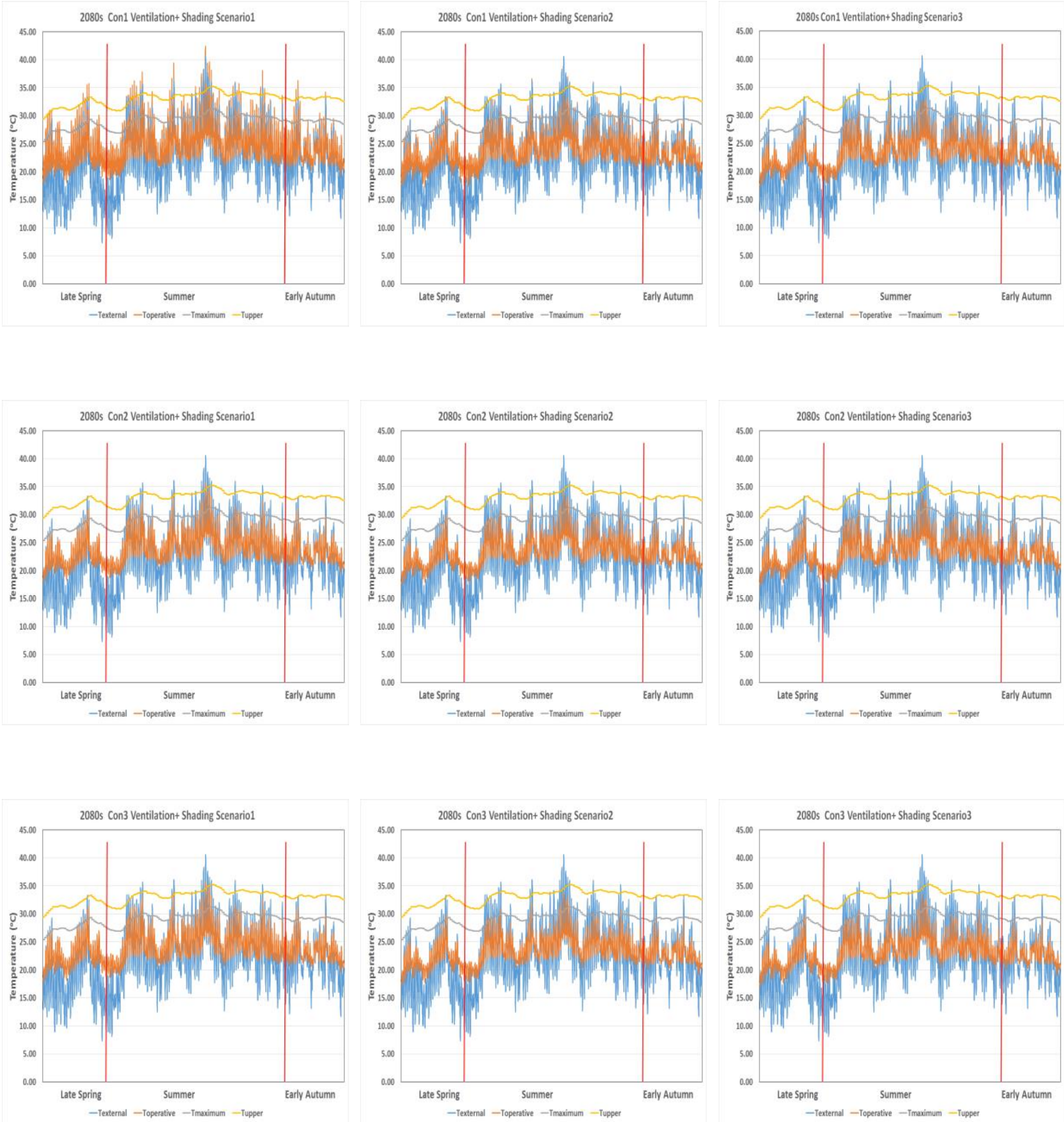
Appendix 9.2 2020s weather conservatory non-heating season analysis

Appendix 9.3



Appendix 9.3 2050s weather conservatory non-heating season analysis

Appendix 9.4



Appendix 9.4 2080s weather conservatory non-heating season analysis