London South Bank University

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Analysis and Comparison of the Thermal Retention Properties of Shading Devices in the Real-World and Dynamic Thermal Models within the UK Built Environment

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A thesis submitted in partial fulfilment of the requirements of the

London South Bank University

for the degree of Doctor of Philosophy

January 2022

Abstract

The built environment accounts for 40% of the UK's carbon footprint, with half of this involving building operations. Additionally, as approximately 50% of the building energy is linked to heating applications, managing thermal loss has become critical in reducing the energy load of buildings. One of the methods to reduce heat loss in buildings is utilising shaded devices. However, most research into the effectiveness of utilising window coverings to reduce heat loss has been carried out in experimental situations within a controlled laboratory, which does not reflect real-life conditions.

To investigate the gap in knowledge in the UK around the use of shading devices, a survey study was conducted with the participation of UK building industry professionals. The results highlighted the lack of awareness of the impact shading devices can have on thermal retention. To assess the effects of shading devices on thermal retention, two real-world case studies were conducted using internal cellular blinds. These studies illustrated the importance of correct installation methods when using shading devices, as well as the effectiveness of sealed blinds in reducing heat loss through windows.

A further survey was conducted to evaluate the effectiveness of BEMS software packages in modelling shading devices amongst UK building energy modellers which indicated that the software databases had insufficient information on shading devices.

To further assess the capability of BEMS software packages illustrating the impact of shading devices, the results from the case study were compared with dynamic thermal model results generated by four software packages. The real-world study demonstrated a positive trend between the correct use of shading devices and the reduction of key energy performance indicators, such as heat loss and heating energy consumption. By comparing this to the results from the simulations, inefficiencies in the software were exposed specifically when assessing the total heating consumption.

Dedication

*To my love, **Morteza***

For his patience, his advice and his faith,

Because he always understood.

Declaration

I declare that this document is my own work and that where any material could be construed as work of others; it is fully cited and referenced.

The research described in this thesis is the original work of the author except where otherwise specified or acknowledgement is made by reference.

This research project was carried out at the School of Engineering, London South Bank University and under the supervision of Prof Deborah Andrews, Prof Issa Chaer, Ass. Prof Elizabeth Newton and Ass. Prof Aaron Gillich.

The work has not been submitted for another degree or award of another academic or professional institution during the research program.

Bahareh Salehi

Acknowledgement

This PhD thesis is the outcome of a long but enjoyable learning process and could not have been completed without the contribution of a number of people to whom I would like to express my gratitude.

I would like to give my special thanks to my supervisors Prof Deborah Andrews, Prof Issa Chaer, Ass. Prof Elizabeth Newton and Ass. Prof Aaron Gillich for their continued guidance and intellectual support as well as personal support throughout this project. I am very grateful to all of my survey respondents and organisations that agreed to be part of the survey, for, without them, this research would not have been possible.

I would like to express my appreciation to the sponsors of this project, their sponsorship is gratefully acknowledged. My thanks also go to the British Blind and Shutter Association for their support during the initial Case Study project. Furthermore, a special thanks go to Mr Bill Thomas for providing the test room for this Case Study.

I owe a great amount of gratitude to my family especially to my husband, Morteza and my mother, Tahereh, for their unconditional love and support throughout my PhD.

I am also grateful to the Built Environment and Architecture School at LSBU and its staff for their assistance and a special thanks to Dr Alex Paurine and Dr Esmail Saber Mahmoudi for their help and support.

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NOMENCLATURE

Symbol	Description	Unit
A	Absorptance	%
A	Surface area	m^2
A_E	Building area envelope	m^2
A_g	Projected areas of window glazing	m^2
A_s	Solar absorption	%
A_v	Visible absorption	%
A_{wf}	Projected areas of window frame	m^2
C	Flow coefficient	$(Pa^{1/n}.m^3)/h$
C_p	Specific heat capacity of a material	J/kg.K or J/kg °C
C_v	Ventilation conductance	W/K
d	Thickness of the material	m
$\bar{E}$	Mean error	/
e_{tot}	Total gap around shading devices	mm
g	Gravity	m/s^2
h	Convective heat transfer coefficient	W/m^2 K
H	Length of the surface or characteristic height	m
k	Thermal conductivity of material	W/m.K or W/m.°C
M	Mass of the material	kg
M_f	Maintenance factor	%
M_t	Measured value	/
N	Number of the variable	/
Nu	A dimensionless ratio between convection and conduction heat transfer	/
P (or CO)	Openness factor or openness coefficient of shading	%
P_e	Air permeability of shading	$m^3/(h.m^2)$
P_t	Predicted value	/
p_{wf}	Length of the perimeter of the window frame	m
Δp	Building pressure differential	Pa
Q	Quantity of energy required to change the temperature and reach the steady-state	J
Q_{50}	Air leakage at 50 Pa	m^3/h

$\dot{Q}_{cond}$	Conductive heat transfer rate or heat flux	W/m^2
$\dot{Q}_{conv}$	Convective heat transfer rate	W/m^2
Q_{rad}	Radiation heat transfer rate	W/m^2
Q_f	Airflow through openings	m^3/h
R	Reflectance	%
Ra_h	Rayleigh number	/
R_{bi} or R_{sh}	Thermal resistance R of the shading product	$m^2.K/W$
R_s	Solar reflection	%
R_v	Visible reflection	%
T_s	Solar transmission	%
T_{surf}	Surface temperature	K or °C
T_∞	Temperature of the surrounding area (gas or fluid)	K or °C
T	Transmittance	%
T_i	Internal air temperature	K or °C
T_v	Visible transmission	%
T_{uv}	Ultraviolet transmission	%
ΔT	Temperature difference	K or °C
U	Voltage output	V
u_{random}	Random errors	/
u_{sys}	Systemic errors	/
u_{tot}	Total uncertainty	/
U_w	Thermal transmittance of window	W/m^2K
U_{wb}'	Thermal transmittance of the window with an internal shading	W/m^2K
V	Room volume	m^3

GREEK SYMBOLS

Symbol	Description	Unit
ρ	Density	kg/m^3
μ	Dynamic viscosity	Pa.s
θ	Light angle	°degree
θ_{ei}	Internal air temperature	K or °C
θ_{ao}	External air temperature	K or °C
γ	The tilted angle of a window	°degree
σ	Stefan-Boltzmann constant	W/m^{2}K^4
ε	Emissivity	/
Φ_t	Total heat loss	W
ψ_g	Linear thermal transmittance of the window glazing and frame	W/m.K
ε	Emissivity	/
$\overline{\sigma s}$	Standard deviation of the mean value	/

ABBREVIATIONS

Abbreviation	Description
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ACH	Air Change per Hour
ACH50	Air Change per Hour at 50 Pa
ADF	Average Daylight Factor
ANOVA	Analysis of Variance
AP_{50}	Air permeability at 50 Pa
ATTMA	Air Tightness Testing & Measurement Association
BBSA	The British Blind and Shutter Association
BEMS	Building Energy Modelling and Simulation
BIM	Building Information Modelling
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CIBSE	Chartered Institution of Building Services Engineers
CFD	Computational Fluid Dynamic
CTS	Calibration Transfer Standard
DSF	Double Skin Façade
EC glass	Electrochromic glass
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
ES-SDA	European Solar Shading Database
ES-SO	European Solar Shading Organization
IES VE	Integrated Environmental Solutions Virtual Environment
IFC	Industry Foundation Class
LBNL	Lawrence Berkeley National Laboratory
LED	Light Emitting Diode
LEED	Leadership in Energy and Environmental Design
NBS	National Building Specification
NPL	National Physical Laboratory
RMSE	Root Mean Square Error
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model

SC	Shading Coefficient
SHGC	Solar Heat Gain Coefficient
SWRF	Short-wave Radiant Fraction
UV	Ultraviolet radiation

CHAPTER 1

Introduction

1.1 Background

The built environment accounts for 40% of the total energy consumption in the UK, with approximately 50% of energy consumption being directly linked to heating applications (Clarke, et al., 2008; BEIS-b, 2020). With statistics showing that more than a quarter of the UK's carbon dioxide is emitted from residential properties, and the fact that the built environment sector contributes to over 60% of global energy consumption, it is clear that more emphasis should be placed on reducing building energy consumption levels (Gledhill, et al., 2016; Anderson, et al., 2015). According to the 2008 Climate Change Act, the UK committed to reducing its carbon emissions by 80% from 1990 to 2050 (Gledhill, et al., 2016), and this was amended in 2019, with the 80% reduction target increasing to 100%, making the UK a 'net zero emitter' (Houses of Parliament, 2019). However, based on the results of the Climate Change Risk Assessment Report of 2017, which indicated that the UK had very few guidelines in place for existing homes to adapt to higher and lower temperatures, more action is needed to find innovative ways to reduce heat loss in buildings and make the existing stock of UK buildings much more energy-efficient (Tink, 2018). In order to improve the energy efficiency of buildings, reducing heat loss (which includes having more efficient insulation and a considerable reduction in infiltration) should be balanced with the solar gains of a building (McLeod & Hopfe, 2013).

One of the main aspects in assessing a building's energy consumption is evaluating its thermal performance and the heat lost through different elements of the building. When heat transfers through a building, there are three mechanisms that dictate the heat loss and gain levels: convection, radiation and conduction (Mulopo & Abdulsalam, 2019). Considering these mechanisms, the total heat loss in a building is the sum of the fabric and ventilation losses (Johnston, et al., 2013). Having assessed the different elements of a typical building in the UK, heat loss is at its highest level within the windows (Palmer & Cooper, 2013). This highlights the importance of windows when considering reducing heating-related energy consumption in buildings. There are various approaches to reducing heat transfer through windows in colder climates. Optimisation methods which include diverse types of glazing optimisation, such as vacuum glazing, gas-filled glazing, triple vacuum glazing and multilayer glazing or frame optimisation, can be effective in increasing thermal retention within a building. Additionally, using solar shading devices can act as an extra layer of insulation for windows, resulting in reducing heat loss whilst maintaining solar gain when needed. The effect of shading devices on thermal retention has been investigated in several studies, but most have been reliant on simulation results or executed within controlled laboratory-like settings, which do not reflect real-life conditions (Wood, et al., 2009; Lunde & Lindley, 1988; Smith, et al., 2012). Inevitably, there will always be some unpredictable variables in a study such as this, including weather conditions, which means the more evidence there is on the effectiveness of shading devices in real-life scenarios, the more accurate research will become.

Despite the proven benefits of using shading devices, such as saving energy and enhancing thermal comfort, the UK's building industry seems to view these devices as an optional add-on for certain buildings, rather than an essential daylight and energy management device (Seguro & Palmer, 2016). In comparison with other European countries, the UK is lagging behind in its use of solar shading. Building regulations and legislation in several European countries specifically encourage the use of shading devices. Seguro and Palmer have investigated the main barriers for their use in the UK and concluded that these are: (i) a lack of awareness around solar shading; (ii) the below-average performance of devices within the UK; (iii) a retrofit approach; (iv) ill-informed building occupants; and (v) regulations and lobbying (Seguro & Palmer, 2016). Reviewing UK building regulations shows that although some parts indirectly recommend the use of shading devices, more explicit inclusion of these devices is required. Only a handful of initiatives have been put in place to influence the regulations; for example, a report produced by the Climate Change Committee in June 2021 directly recommended shading devices as a means to tackle overheating, and consequently reduce the need for cooling in buildings (CCC, 2021). This demonstrates the need for a greater understanding of why those in the UK's building industry do not have sufficient knowledge or awareness of solar shading devices.

Dynamic thermal models are used in the early stages of building design to ensure that energy consumption is controlled and kept at a minimum (Gao, et al., 2019). This is one of the key factors in deciding whether shading devices should be installed in buildings. However, there are often discrepancies between the results generated by Building Energy Modeling and Simulation (BEMS) software packages and real-world data. These differences can be due to several factors, such as weather conditions, the energy systems used in a building, the indoor environment, the maintenance of a building, or the behaviour of a building's occupants (Yoshino, et al., 2017). Additionally, modellers' assumptions and default data are crucial factors which affect the results of these simulations (Mantesi, et al., 2018; Rees, 2017). In order to investigate this further, it is important to at first ascertain which software packages are most commonly used within the UK.

Many studies demonstrate the benefits of using shading devices for the purpose of thermal retention within a building (Yao, 2014; Atzeri, et al., 2014; Liu, et al., 2013; Stazi, et al., 2014; LBNL, 2013). However, this evidence often does not compare simulation results with real-world data. In some studies, experimental data is collected, but it is not directly compared with simulation results, and instead is used primarily as inputs for the simulation. Furthermore, in the few empirical validation studies (those comparing real-world data and simulation results) that exist, data is generally taken from a test cell, rather than a real building (Loutzenhiser, et al., 2008). In 2018, a research paper compared real-world data from a London flat using various built-in shading devices, with the simulated results generated by IES VE. Again, this study highlighted the discrepancies between simulation and reality (Venturi, et al., 2018). Within this thesis, the aim is to examine the effects of installing sealed and non-sealed internal cellular shading devices within buildings and investigate how they affect levels of thermal retention within a real-world setting. The results will then be compared to simulated results from the dynamic thermal models generated by software packages, with the aim of exposing the shortcomings of using software to model shading devices.

1.2 Aims and Objectives

The primary aim of this experimental and simulation research project is to investigate the reduction of heat loss within the UK built environment through the use of shading devices. It will highlight knowledge gaps around shading devices within the UK's building industry, in relation to both practical use and BEMS software packages. The full aims and objectives of the study are outlined below:

1.2.1 Research Aims

This study aims to answer the following questions:

1. How often do building professionals in the UK consider using shading devices in their projects?
2. Which BEMS software packages are used most frequently in the UK?
3. Are modellers satisfied with the existing data on shading devices within BEMS software tools?
4. To what extent are shading devices beneficial for thermal retention within UK buildings?
5. How does the input data of the software influence the simulation results, and consequently impact the performance gap between real-world data and simulation when modelling shading devices?
6. How successful are BEMS software packages in illustrating the benefits of shading devices for energy efficiency and thermal comfort?

1.2.2 Research Objectives

1. To provide a critical review of literature on the mechanisms behind heat transfer when using shading in buildings, the use of shading devices within the UK, and the dynamic thermal models generated by BEMS software packages when modelling shading devices for thermal retention purposes.

2. To assess the knowledge and interest around shading devices and their application amongst UK industry professionals.
3. To identify the most common BEMS software tools used in the UK building industry. The results of this survey will also help to identify the driving factors influencing decision-making in the early stages of building design, and assist in identifying how satisfied modellers are with various parameters of each type of software.
4. To collect data from real-world scenarios, in order to investigate how sealed and non-sealed internal cellular blinds affect the levels of thermal retention within a building.
5. To validate the UK's most commonly used BEMS software packages against real-world data collected from a thermal retention case study, which evaluated the software tools' capability in illustrating the effects of shading devices.

1.3 Thesis Structure

This thesis is comprised of seven chapters which are outlined below:

Chapter 1: The first chapter introduces the subject, and outlines the scope, aims and objectives of the project.

Chapter 2: This chapter presents a critical analysis and evaluation of existing literature and theory related to the use of shading devices as a method for thermal retention within the UK's built environment. After reviewing heat transfer mechanisms used within buildings, similar studies which investigate the effects of shading devices on energy consumption and thermal comfort were also reviewed. Additionally, this chapter explores some of the barriers obstructing the use of shading devices as an energy-saving method in the UK. Finally, the chapter reviews the results of multiple projects exploring the use of dynamic thermal models and shading devices.

Chapter 3: This chapter focuses on the results from a survey conducted with building industry professionals to better understand their use of shading devices. Key factors assessed include how often shading devices are used within building projects, the different applications of shading devices, and the obstacles facing the implementation of shading devices within the UK.

Chapter 4: This chapter assesses the results of two experimental real-world case studies conducted in the UK, which analysed the effects of sealed and non-sealed blinds on thermal retention within (domestic and non-domestic) buildings.

Chapter 5: This chapter presents the results of a country-wide survey with building modellers based in the UK who have experience working with BEMS software tools and shading devices. The most common BEMS software packages used in the UK (IES VE, EnergyPlus, EDSL Tas and DesignBuilder) are identified and assessed in relation to their abilities to accurately illustrate the impact of shading devices on thermal retention. The survey also determines whether the input databases of various software tools are sufficient to influence the decision-making process of building professionals in the early stages of design.

Chapter 6: This chapter investigates the accuracy and capability of dynamic thermal models generated by the four BEMS software packages discussed in Chapter 5, and compares their simulated results with the experimental results (case study 2) outlined in Chapter 4. The key factors that were compared were the temperatures of the windows' internal surfaces, the measure of heat lost through the windows, and the levels of heating energy consumption.

Chapter 7: The final chapter discusses the key findings from the study in relation to its original aims and objectives. The chapter concludes by highlighting the original contribution that this thesis makes to knowledge, and outlines the areas where further investigation is required in the future.

CHAPTER 2

Literature Review

2.1 Introduction

The purpose of this chapter is to provide a review of the relevant literature on the background of the UK built environment energy consumption and the protocols and targets which are the reason that the UK is moving towards developing Net Zero Energy buildings. The chapter includes the heat transfer mechanisms which are causing heat loss in a building. Furthermore, this chapter identifies the importance of windows in thermal retention in a building and review the related literature and studies on reducing heat loss through the windows using shading devices as a method for improving building energy efficiency. This chapter also reviews the barriers and regulations in the UK which result in lower-level use of these devices compared to other developed countries which was further analysed and investigated through surveys conducted in chapters 3 and 5. As the simulated results of dynamic thermal models are effective on the decision made in the early stage of the design regarding the use of various energy conservation methods in buildings including shading devices, comprehensive literature was conducted on the related studies on simulated projects and those comparing the simulated results and measured results.

2.2 Climate Change

Dating back to the pre-industrial period (i.e after 1850), human activities have managed to make significant changes to the earth's climate resulting in the rapid increase of carbon emissions especially through burning fossil fuels (IPCC, 2014). Climate change and its impacts on the population have been highlighted for some time through various global reports and consequently how this issue is dealt with and challenged will determine everyone's future (Stern, 2006). Global temperature rises resulting from greenhouse gas emissions are estimated to be as much as 2 °C by 2035 and in the long term, a 50% likelihood that it could rise over and above 5 °C (Met Office, 2018).

To limit the effects of climate change, a global initiative led by the UN to bring all countries on board to tackle this issue and ensure commitment was put together which resulted in the Kyoto Protocol and the Paris Agreement (The United Nations, 2015; The United Nations, 1998). In turn, the UK as part of the climate change act 2008, committed to an 80% reduction of carbon emissions compared to 1990 levels by 2050 (Houses of Parliament, 2019). Unfortunately, the current trend shows the UK is behind its 2050 target and one of the main areas highlighted that needs more work and effort is the built environment sector where more than a quarter of the UK's carbon dioxide is emitted. The main indicators to achieve the carbon reduction target were assessed in 2019. In the building sector, the main focus for insulation has always been mainly the loft area, cavity walls and solid walls as well as using heat pumps but none of these targets were met by 2019 (Committee on Climate Change, 2019). However, in this assessment, the insulation of windows was not included.

The importance of focusing on energy consumption within buildings is even more prevalent when it accounts for over 60% of global energy consumption and coupled with the potential of temperature rises, it can be seen how vital it is to find novel methods of reducing inherent energy consumption and subjects such as overheating in buildings (Gledhill, et al., 2016). With the UK projections for temperature increases ranging between 1 °C to 6 °C and the Climate Change Risk Assessment Report 2017 highlighting that there are no guidelines and policies for existing properties in the UK to adapt to this higher temperature and combined with increasing prolonged heatwaves in the UK, it is clear why the spotlight is on the building environment to act rapidly on this matter (Committee on Climate Change, 2017).

2.3 UK Household Energy Consumption

In order to better understand the energy consumption trends in UK domestic buildings, which accounts for a large proportion of the total energy consumption in the UK, collected data including population, property types and breakdown of energy usage is a good starting point. One statistic highlighted in the UK housing fact file report in 2013 was that the proportion of carbon emissions that energy usage in buildings contributes to is 27% of the total energy consumption which has increased from 25% in the 1970s. So, the carbon emissions produced by industrial processes are less than those produced by UK domestic buildings (Palmer & Cooper, 2013).

From 2013, the previous schemes including the Community Energy Saving Programme, Warm Front and the Carbon Emissions Reduction Target were changed to the Energy Company Obligation (ECO) and Green Deal (GD). The purpose of these new schemes is to better utilise energy efficiency measures in order to reduce energy bills and in turn increase thermal comfort in homes throughout Great Britain (BEIS-c, 2020). According to ISO 7730-2005, thermal comfort is "the condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ISO, 2005). Another scheme to achieve the carbon reduction target is improving the insulation of building elements. It was estimated that at the end of December 2019, from 28.6 million properties in the UK, 20.1 million have cavity walls, 8.5 million have solid walls and 24.8 million have a loft. It is projected that by the end of December 2019, 70 % of properties with a cavity wall had insulation (14.1 million), 66 % of properties with a loft had insulation (16.4 million) and 9 % of properties with solid walls had insulation (764 thousand) (BEIS-c, 2020).

According to Palmer and Cooper, the rate of newly constructed properties compared to the existing stock remaining in place (27 million) is at quite a slow rate (180 thousand per year) which signifies that by 2050, more than 60% of houses will be one's in use from 2006 (Sustainable Development Commission, 2006; Ravetz, 2008). In addition to the slow rate of new builds, the existing housing stock is quite old and is considered one of the oldest in Europe which contributes to inefficient energy usage resulting in high heat loss rates (Boardman, et al., 2005; Palmer & Cooper, 2013). The energy consumption in domestic buildings was 29% of total energy consumed in the UK in 2017, where 80% of that energy was consumed for heating purposes (BEIS-a, 2019; BEIS-b, 2020). This is significant as it highlights the reasoning behind the focus of this research project which is heat loss and methods of reducing this process to a minimum.

2.4 Building Energy Efficiency

Considering the UK property landscape, the question arises of how the layout of a predominantly older crop of buildings and the slower rate of new more energy-efficient buildings impact the UK's energy transition goals. The link can be seen in two main categories, one being the UK's international commitments made to reduce carbon emissions and the other being what the energy consumption figures show regarding the building environment data.

Firstly, it is essential to review the commitments the UK has made notably the 2008 Climate Change Act whereby the UK committed to reducing carbon emissions by 80% in 2050 compared to the 1990 levels (Gledhill, et al., 2016) but this was amended in 2019 and the 80% target has changed to 100% which will make the UK a "Net Zero Emitter" (Houses of Parliament, 2019). This agreement was born out of the growing evidence of the adverse impact of climate change and how mankind reacts to this issue which will define the future of generations to come with the best way to tackle it is substantial and sustained reductions in carbon emissions (IPCC, 2013). It is to be noted that after countries joined this global initiative and treaty, the targets were brought into operation through the Kyoto Protocol and the Paris agreement which then for the UK soon became official policy under the climate change act (The United Nations, 2015; The United Nations, 1998).

Despite all these commitments, we review the figures that illustrate the core reason behind this research initiative and the specific focus it has on energy consumption in the built environment industry. With the statistics showing that more than a quarter of the UK's carbon dioxide is emitted from residential properties and to add the fact that the built environment sector contributes to more than 60% of global energy consumption, it is clear why the focus is concentrated on this area (Gledhill, et al., 2016; Anderson, et al., 2015).

This concern has grown even more within European countries where the corresponding energy consumption trends within households where more than half of this energy relates to the operational side i.e. how households cool and heat up their spaces in different seasons throughout the year

(European Commission, 2016). To tackle this, building energy performance targets have been assigned as part of the Energy Performance of Buildings Directive by the European Union as policy throughout different countries, so a benchmark is set for any new buildings being designed and built (Fitton, 2013).

The fact of the matter is that the UK is not on the predicted path of having the ability to achieve a carbon emission reduction of 51% by 2025 and in essence not meeting its fourth carbon budget set out by the Climate Change Act 2008. The added results of the Climate Change Risk Assessment report in 2017 showcasing the UK had very few guidelines in place for existing homes to cope and adapt to higher and lower temperatures, the action is needed to find innovative ways to reduce heat loss in existing buildings and make the existing stock of UK buildings a lot more energy efficient (Tink, 2018). In order to improve the energy efficiency of buildings, reducing heat loss (which include having better insulation and reduction in infiltration) should be aligned with solar gains of building (McLeod & Hopfe, 2013).

2.5 Building Heat Loss Methods

One of the main aspects in assessing building energy is the thermal performance especially heat loss through different parts of a building. In order to investigate the heat loss through a building, understanding the heat transfer process is essential. Based on the first law of thermodynamics, heat will transfer from warmer sections to the colder sections (of solid, gas or liquid) and this heat transfer will continue until the body reaches equilibrium which then will be called the adiabatic body. During heat transfer through a building, three main mechanisms are involved which enable heat gain or loss that are referred to as convection, radiation and conduction (Mulopo & Abdulsalam, 2019).

2.5.1 Steady-state Heat Transfer

In this section three main mechanisms of heat transfer including conduction, convection and radiation are described.

2.5.1.1 Conduction

The kinetic energy within a material can cause the molecules of the material to be activated and the movement of the molecules will transfer the heat inside a material. The Fourier's Law can help identify the heat transfer rate through conduction by the correlation between the heat transfer rate per unit area and temperature difference (Whitaker, 1977):

$$\dot{Q}_{cond} = -k\frac{dT}{dn} \qquad \textit{Eq 2-1}$$

Where $\dot{Q}_{cond}$ is the conductive heat transfer rate or heat flux (W/m^2), k is the thermal conductivity of a material (W/m.K), $\frac{dT}{dn}$ is the temperature difference in direction of n, the negative is added to the equation as the temperature difference is negative and heat transfers from higher temperatures to lower ones. The thermal conductivity of a material is based on its molecular structure, temperature difference and direction of heat transfer. In some materials like various metals and aluminium, the capacity of heat transfer is higher than other materials which are used as insulators. Identifying the conductivity of gases and some other materials which are used as insulators is more complicated and therefore are required to be tested in the laboratory (Mulopo & Abdulsalam, 2019).

2.5.1.2 Convection

Convection heat transfer is due to the motion of the fluid or gas near a surface. The movement of a flow (air or fluid) around a surface can be free (natural convection) or forced (forced convection). The equation based on Newton's law on heat transfer through convection is:

$$\dot{Q}_{conv} = hA(T_{\infty} - T_{surf}) \qquad \textit{Eq 2-2}$$

Where $\dot{Q}_{conv}$ is convective heat transfer rate, h is the convective heat transfer coefficient (W/m^2 K), A is a cross-section of a surface area being heated or cooled (m^2), T_{∞} is the temperature of the surrounding area (gas or fluid) and T_{surf} is the surface temperature (K). Convective heat transfer coefficient is related to various parameters such as properties of the surrounding gas or fluid and the pattern of the flow which can be laminar or turbulent flow. (Bi, 2018; Reventos, 2017).

Based on ISO 15099 (ISO, 2003), the convection heat transfer through the internal surface of a window (with natural convection) can be calculated based on a dimensionless ratio between convection and conduction heat transfer called Nusselt number (Nu):

$$h = Nu\frac{k}{H} \qquad \textit{Eq 2-3}$$

Where k is the thermal conductivity of the air (W/mK), H is the length of the surface or characteristic height and h is the convective heat transfer coefficient. If we assume that air velocity inside the room is constant, consequently the Rayleigh number is not required. However, the Rayleigh number can affect the Nusselt number:

$$Ra_h = \frac{\rho^2 H^3 g C_p (T_i - T_{surf})}{(T_i + \frac{1}{4}(T_{surf} - T_i))\mu k} \qquad \textit{Eq 2-4}$$

Where Ra_h is Rayleigh number, ρ is density (kg/m^3), C_p is specific heat capacity (J/kg.K), μ is dynamic viscosity (Pa.s), g is gravity (m/s^2), T_i internal air temperature and T_{surf} is the temperature of the surface. Based on the γ, which represents the tilted angle of a window, the Nu number is calculated and is assumed that internal air temperature is higher than the internal glass surface temperature. For example, for windows inclined from 90˚ to 179˚, Nu is (ISO, 2003):

$$Nu = 0.56(Ra_h sin\gamma)^{1/4};\ 10^5 \leq Ra_h sin\gamma < 10^{11} \qquad \textit{Eq 2-5}$$

These equations are not used in this PhD thesis and are included here to provide some background knowledge.

2.5.1.3 Radiation

Radiation heat transfer is due to the emission of electromagnetics as a result of the vibration of their atoms when two objects are not in physical contact. The Stefan-Boltzmann law indicates the thermal radiation from a normal body as:

$$Q_{rad} = \sigma A_1 \varepsilon_1 (T_1^4 - T_2^4) \qquad \text{Eq 2-6}$$

Where Q_{rad} is radiation heat transfer rate, σ is Stefan-Boltzmann constant which is 5.67×10^{-8} W/m^2K^4, A is the surface area of an object (m^2), ε is the emissivity of an object, T_1 is the temperature of an object and T_2 is the temperature of the surrounding area (Domairry Ganji, et al., 2018).

2.5.2 Transient Thermal Transfer

Regarding the building heat transfer, if the temperature around a building element is changed, the heat transfer is not considered as reaching the steady-state stage. This means the heat flux in different parts of the building element will be different as the heat will take time to penetrate the element (Childs, et al., 1983). Figure 1 shows actual heat flux through a wall compared to the predicted calculated heat flux.

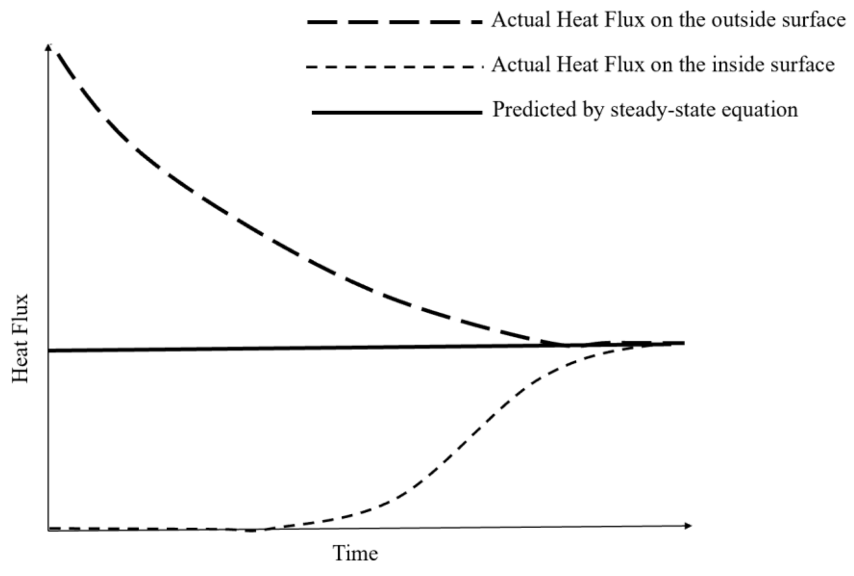

Figure 1: Steady-state heat flux vs actual (non steady-state) heat flux of a wall (Childs, et al., 1983)

By the time a certain amount of energy has been transferred through the wall, the heat flux of the internal and external surfaces of the wall are similar to the steady-state calculated heat flux. The required energy to reach the steady-state can be calculated by the below heat flow equation:

$$Q = mc_p \Delta T \qquad \textit{Eq 2-7}$$

Where Q is the quantity of energy required to change the temperature (J), m is the mass of the material (kg), c_{p} is the specific heat capacity of material (J/kg ˚C) and ΔT is the temperature difference (˚C). Mass can be calculated by multiplying ρ (density of material kg/m^3) and V (Volume m^3) (ASHRAE, 2013).

Two important parameters affecting thermal mass are the Decrement Factor and Time Lag. When the temperature on one side of a wall increase suddenly, the actual heat flux will occur later than the steady-state heat flux calculated. The time it takes for the actual heat flux to reach the steady-state stage value i.e. the stage the predicted and calculated heat flux would be, is called Time Lag (Childs, et al., 1983). This difference in heat fluxes can be seen when the temperature is decreased as well and when actual heat flux occurs later than the calculated steady-state heat flux Figure 2.

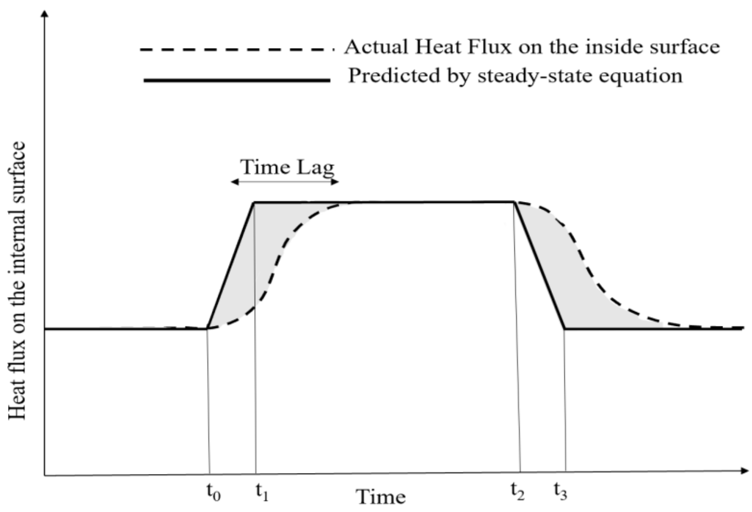

Figure 2: Heat flux on the internal surface of a wall, steady-state and actual (Childs, et al., 1983)

The steady-state calculation is focusing on the thermal resistance (R-value) of the material and not the thermal mass which is the energy storage capacity of the material. So thermal mass affects the duration that energy is transferred through the wall. Furthermore, if the time between t_1 and t_2 is omitted, the heat fluxes will not reach the steady-state. In this case, the peaks of heat flux will be different. The difference is not only the peak in heat flux but the time to reach the peak is different as well. The difference and reduction in heat flux are called Decrement Factor (Figure 3) (Childs, et al., 1983).

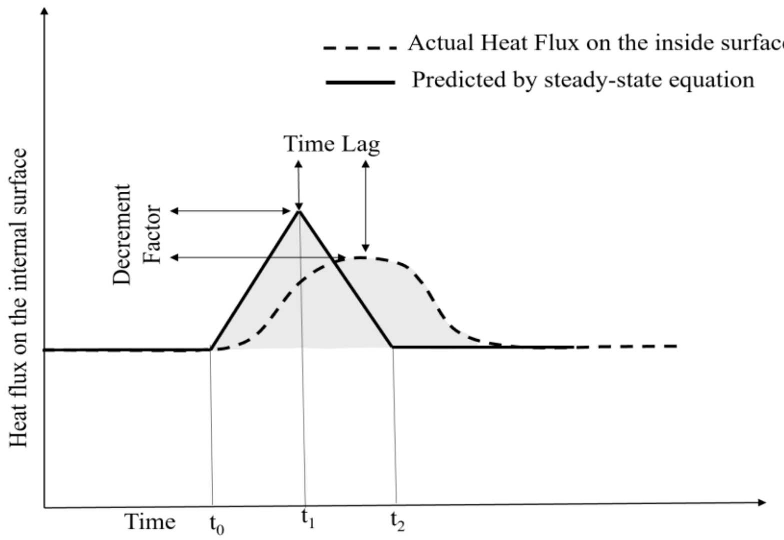

Figure 3: Heat Flux in the wall when the time to reach the steady-state is omitted (Childs, et al., 1983)

2.5.3 Dynamic Thermal Transfer

As the weather temperature varies, reaching a steady-state in reality is not possible, so dynamic or cyclic thermal calculation is required. Several methods are used for assessing the non-steady-state heat transfer. The admittance method is used in CIBSE Guide A for dynamic calculations. BS EN ISO 13786 provides more details regarding this method. In this method, thermal admittance of material (Y-value) is important in addition to the decrement factor (f) and time lag. Specific heat capacity, thermal conductivity (k), density (ρ) and thickness of a material affect the admittance method parameters. Thermal admittance of a building element is the amount of heat transfer through the building element, between internal temperature and environment temperature. In multi-layer elements, the internal surface layer determines the thermal admittance of the element. Another factor considered in the admittance method is the Surface Factor (F) which is the ratio of heat flow readmitted to the space from the surface to the heat flow absorbed by the surface.

Buildings are categorised into two groups; the slow thermal response or fast thermal response which depends on the surface material, type of the heat input, the overall thermal property of the building element, the thickness of the element and the furnishing inside the building. The time delay in thermal response can be related to shortwave radiation or associated with surface to surface or surface to environment thermal transfer. Considering the thermal response in relation to shortwave radiation, the surface factor is defined as:

- ✓ The surface factor of fast response building is 0.8 with a 1-hour delay
- ✓ The surface factor of slow response building is 0.5 with a 2-hour delay

When considering the response to the changes in environmental temperature, the Response Factor is defined as:

$$f_r = \frac{\sum(A\,Y) + C_V}{\sum(A\,U) + C_V} \qquad \text{Eq 2-8}$$

Where f_r is the Response Factor, $\sum(A\,Y)$ is the sum of the surface area products and thermal admittance (W/K), $\sum(A\,U)$ is the sum of the surface area products and thermal transmittance (W/K) and C_V is ventilation conductance (W/K) (Milbank & Harrington-Lynn, 1974; Davies, 1994; CIBSE, 2019). Full details for the calculation of thermal admittance can be found in CIBSE Guide A and BS EN ISO 13786 (ISO, 2017).

There are various types of building energy simulation software packages available to assist with modelling the heat transfer and consequently the energy consumption within a building. This method is commonly used by the building industry. In Section 2.10, the dynamic thermal models are discussed in more detail.

2.5.4 Total Building Heat Loss

The total heat loss in a building is the sum of the fabric and ventilation losses (Johnston, et al., 2013). According to the CIBSE Guide A, total heat loss can be calculated via the equation below:

$$\Phi_t = [\sum(AU) + C_v](\theta_{ei} - \theta_{ao}) \qquad \textit{Eq 2-9}$$

Where Φ_t is the total heat loss (W), $\sum(AU)$ is the sum of the thermal transmittance through the surfaces (W/K), C_v is the ventilation conductance (W/K), θ_{ei} is the internal air temperature and θ_{ao} is the external air temperature. The ventilation conductance can be calculated via the equation below:

$$C_v = {}^{1}\!/_{3}\, N\, V \qquad \textit{Eq 2-10}$$

Where N is the number of room air changes (h^{-1}) and V is the room volume (m^3) (CIBSE, 2019).

2.6 Sources of Heat Loss in Building

With the different types of heat loss identified, the aim is to understand how these different modes of heat transfer translate into areas of heat loss within buildings. Using the Cambridge Housing Model (Palmer & Cooper, 2013) which shows the main sources of heat loss within a building, it is evident that the main cause of heat loss can be attributed to fabric or material loss along with a portion of ventilation losses. Furthermore, windows are having considerably high heat loss compared to roofs and floors (Figure 4).

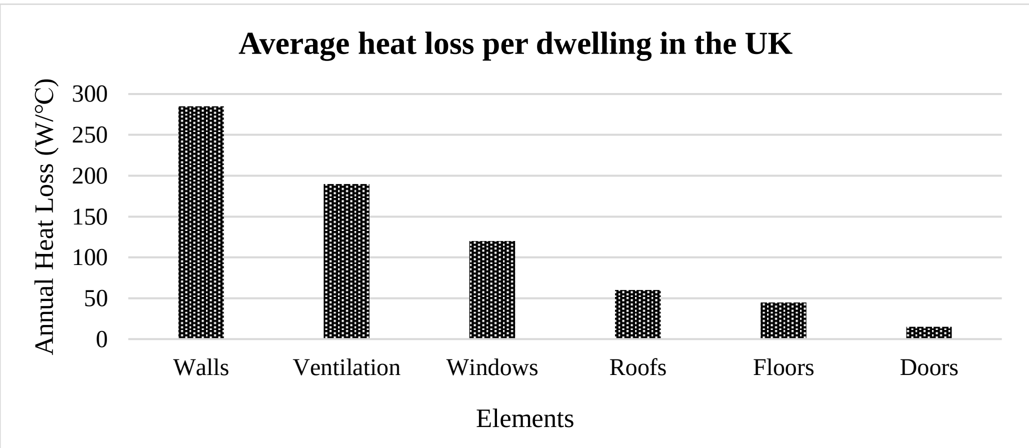

Figure 4: Total heat loss for UK dwellings (Palmer & Cooper, 2013)

As it is shown in Figure 4, the combination of fabric losses contributes the most heat loss in the UK building landscape which is why heat loss can be mainly categorised between fabric and ventilation losses. The statistics show an urgent need to tackle existing infrastructures with varying physical interventions to boost energy efficiency and meet the UK Carbon Emission Reduction Target (CERT). In order to reduce the heat loss in household buildings, the insulation levels in Great Britain (GB) should be improved. In order to reflect more up to date data, the estimation of building insulation levels have been restarted from April 2013. Information from the English Housing Survey 2013 (EHS), Living in Wales Survey 2008 and Scottish House Condition Survey 2013 is the base for estimation of home insulation levels in the UK. Within this estimation, the window glazing insulation and draught-proofing insulation have a 15% reduction effect on energy consumption and carbon emissions (BEIS-d, 2020).

2.6.1 Building Envelope

A building's overall envelope is identified as the separating factor and barrier between the internal and external spaces and is of high importance and a vital factor in energy efficiency and the occupant's comfort. The principles of the building envelope can differ based on the climate where the buildings are situated. There are two main envelope categories, the first one is the non-engaging envelope which is relevant to harsh environments where there are either very low or high temperatures and the barrier and separation is quite stringent and fixed. The second type is an engaging envelope for more moderate climates and allows for more fluid interaction between internal and external spaces via windows and doors. This second type can achieve a lot better energy efficiency and reduction in energy consumption (Oral, et al., 2004; Leifer, 2012).

Research studies have supported this as well where a study of a hotel building in the Mediterranean by Sozer (Sozer, 2010) identified that general energy savings of 40% could be achieved by utilising passive design principles such as relevant thermal insulation, glazing and shading elements. The building envelope is the key factor to recognise levels of daylight, ventilation, comfort and energy requirements for heating and cooling (ES-SO, 2014; OECD/IEA, 2013). The Technology Roadmap report in 2010 has recognised the utilisation of shading devices as a beneficial way to reduce energy consumption and a means of moving towards zero-energy buildings (OECD/IEA, 2013).

2.6.2 Reducing Building Heat Loss through Windows

There are various approaches to reducing heat transfer through the windows in colder climates. Optimisation methods which include glazing optimisation such as vacuum glazing, gas-filled glazing, triple vacuum glazing and multilayer glazing or frame optimisation can make a difference in thermal retention in a building in terms of conduction and convection. Taking into consideration the findings both in the Cambridge Housing model and the published UK housing energy fact file, one of the main pathways of heat loss in all forms are windows within the buildings both due to the large proportion of windows installed throughout buildings and the growing trend of utilising more window/glazing in buildings from a visual point of view (Palmer & Cooper, 2013; Department of Energy & Climate Change, 2015). The Palmer and Cooper report in 2013 shows a steady heat loss contribution for windows of 20% in the last few decades with quite a few fluctuations throughout these years due to slight improvements to frame material and structures and better glazing of the windows. Despite these improvements, a significant proportion of heat loss resulting from windows is seen and varying methods to tackle this have been researched and implemented mainly through either covering such as blinds and curtains or specific secondary glazing each with its own advantages (Fitton, et al., 2017). The challenge is to be able to adopt the retrofit approach and due to the extensive stockpile of older buildings in the UK, implementing a much more expensive option in secondary glazing might not be viable. In this research, the focus will be to utilise internal insulated blinds to identify the extent of their capabilities to reduce heat loss.

2.7 Shading Devices

Solar shading considers all the devices and products which control incoming solar radiation to the built environment (Seguro & Palmer, 2016). The utilisation of shading devices historically did not coincide with the prevalence of windows, and it was quite some time afterwards before the first types of shading were used. This would have been because the first known windows were created during ancient times and were simple slits in thick masonry walls that served purely functional purposes of letting in air and light and allowed inhabitants to see approaching enemies. In fact, the Venetian blinds originate from Persia which is present-day Iran. Then in the early 1760s Venetian trade brought it to Venice from Persia. In the late 1700s, their use spread to France (Cooks, Blinds and Shutters, 2017; Barnes, 2015; Total Look Blinds, 2016).

Window shades began being used widely in the eighteenth century in Holland, France, and England and where at first there were mainly made of cloth or paper with quite primitive decorative design but in the 19th century, the designs and functions evolved into more imaginative designs and were replaced with more stencilled borders and higher quality imagery (Jones, 2018; Olgyay & Olgyay, 1976).

2.7.1 Product Portfolio

There are a wide variety of shading devices currently available in the market which in recent years, depending on the building requirements, new specialised products have been added to the market. i.e. in conjunction with the location and orientation of the building (Seguro & Palmer, 2016). Solar shading devices can be fixed or dynamic/moveable and can be operated both manually and automatically (Bellia, et al., 2014; Olgyay & Olgyay, 1976). Standard BS EN 12216 provides a detailed definition of internal and external blinds (BSI, 2018). Furthermore, the British Blind and Shutter Association (BBSA) Trade Database was evaluated by Seguro and Palmer in 2016 which helped to identify the product portfolio available in the UK presented in Figure 5 and Figure 6.

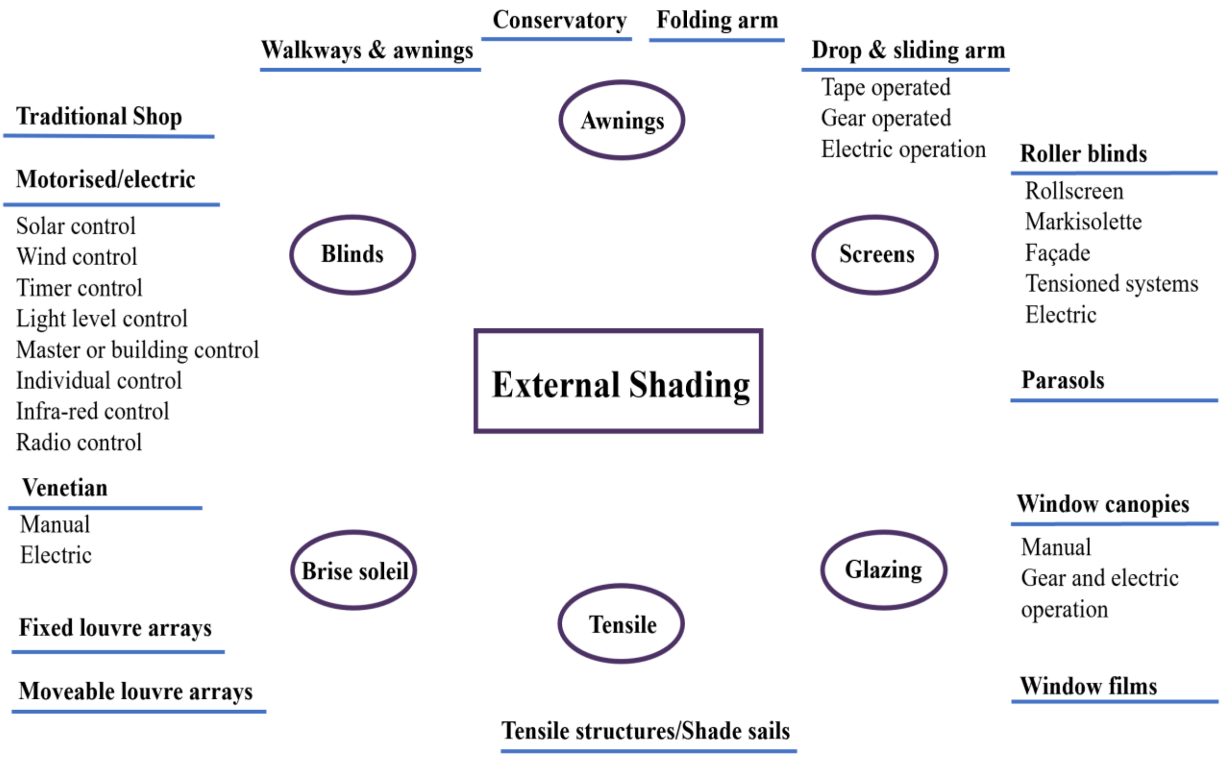

Figure 5: Product portfolio, External shading (Seguro & Palmer, 2016)

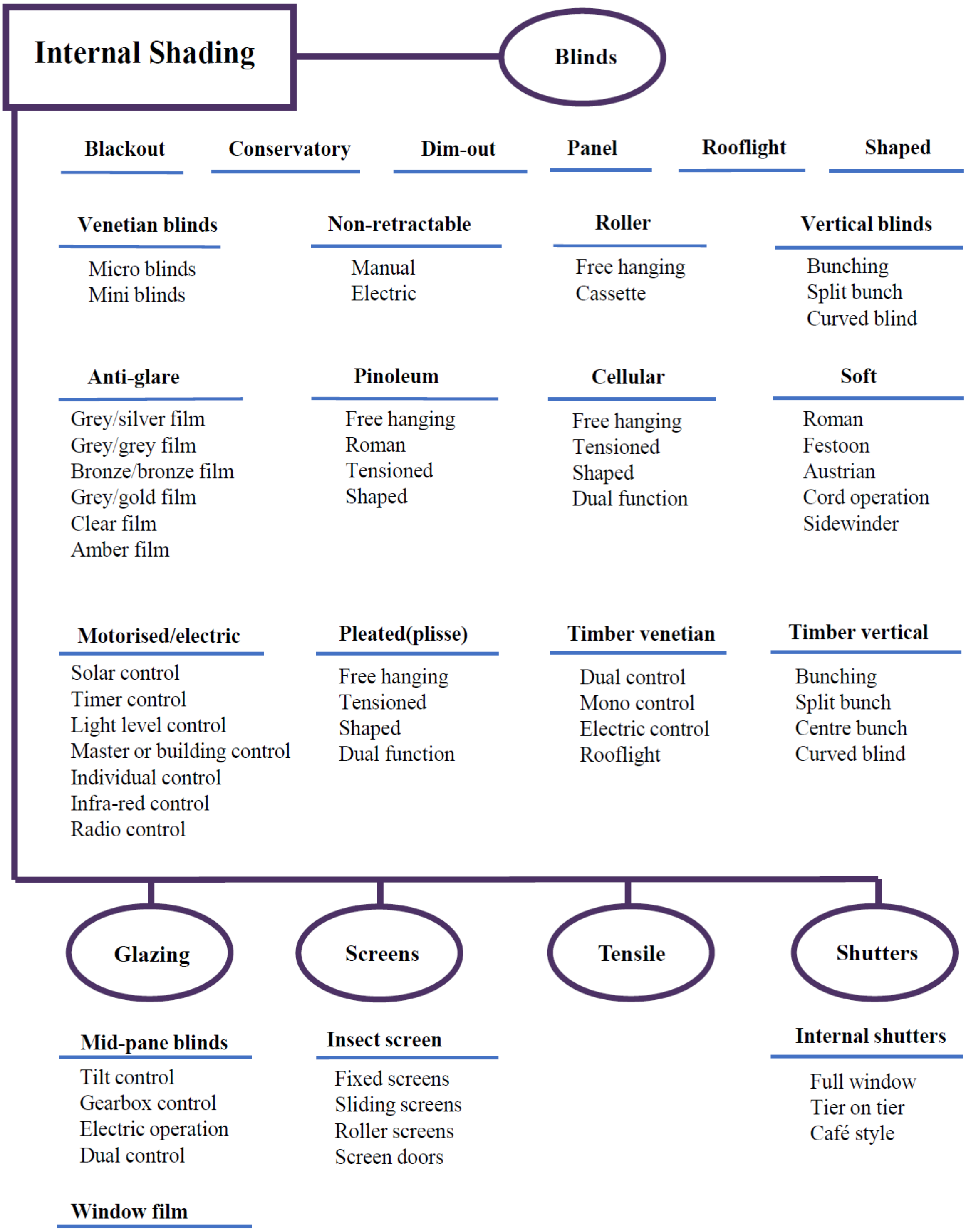

Figure 6: Product portfolio, Internal shading (Seguro & Palmer, 2016)

2.7.1.1 Operating Technology

With more focus being shifted to energy utilisation in buildings, the operation of the shading devices based on where it is used, and occupants' preference become quite important, so consumers' preferences and the optimal energy performance of buildings need to be balanced.

2.7.1.1.1 Manual and Motorised Operation

Manually operated and motorised shading systems can be quite effective, but they are heavily reliant on constant specific consumer attention to reach the most optimum energy performance levels. This method is implemented efficiently when occupants use them in relation to the variable weather conditions. The most vital advantages of using manual and motorised shading devices are the control given to users and the ability to modify the shadings based on their preferences, i.e., privacy, tasks, and visual preferences (Meek & Brennan, 2014; Bellia, et al., 2014).

2.7.1.1.2 Automated Operation

Automated operation of shading devices has the potential of being deployed and retrofitted to systems and limits the need for user intervention. The many advantages of using automated operations in shading devices such as longer periods of effective daylight contribute to increased lighting power savings and longer durations of unobstructed views to the exterior. This method can be most effective when variable direct sunlight is available most periods of the day especially taking into account the dynamic nature of daylight and sunlight, it can provide the longest daylight exposure and most efficient energy performance (Meek & Brennan, 2014). A combined approach can also be taken where manual, motorised and automated controls are implemented. The key is to utilise the automation at critical points considering both energy and daylight performance and also the visual preference is taken into account (Bellia, et al., 2014).

The maintenance and management of control systems after installation is essential to ensure that the systems in place are working to the benefit of occupants and limit interference that could lead to manual overrides and energy-saving losses. Overall, the consensus is shading devices can be balanced between user preferences and efficient energy performance. Manual control can be recommended for use in environments owned or shared by many occupants specifically for privacy or visual comfort purposes whereas automated methods can be suitable in more publicly owned environments to manage the energy performance whilst having the option of being combined with a manual override to bypass the automatic settings (Meek & Brennan, 2014; Littlefair, 2018).

2.7.2 Shading Specifications

The key specifications related to solar shading devices which should be considered and well understood when specifying a shading device are outlined in this section.

2.7.2.1 Solar and Optical Characterisation

In this section, solar and optical characterisations of the shading devices which are mainly related to heat gain, are expanded upon.

2.7.2.1.1 Radiation

The three types of radiation involved in the solar spectrum on the earth's surface (ranging from 280 nm to 2500 nm) are Ultraviolet (UV) from 250 nm to 380 nm, Visible light (Tv) from 380 nm to 780 nm and short wave Infrared (IR) from 780 nm to 2500 nm (see Figure 7).

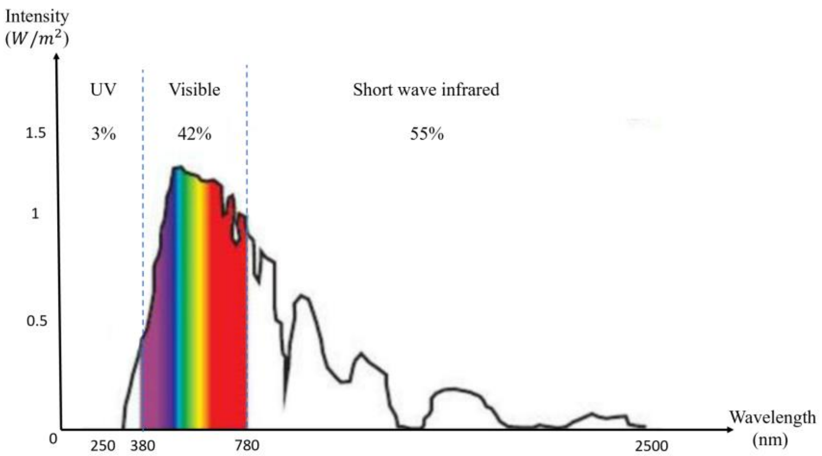

Figure 7:Solar radiation spectrum on earth

The incident solar radiation on a surface splits into three parts; Transmittance (T), Absorptance (A) and Reflectance (R) where the sum of the T+A+R is equal to 100%. Short wave infrared radiation (780 nm to 2500 nm) is within the solar radiation spectrum. This radiation is not visible but will generate heat when irradiance is present on a surface. Longwave infrared radiation (from 2500 nm to 100000 nm) is not within the solar spectrum. This invisible radiation is emitted from a heater or any warm surfaces (ES-SO, 2018).

2.7.2.1.2 Solar and Optical Transmittance

When solar radiation (250 to 2500 nm), irradiates on glazing or material, it splits into three parts including Solar Transmission (T_s), Solar Absorption (A_s) and Solar Reflection (R_s). When visible or optical radiation (380 to 780 nm), irradiates on glazing or material, it splits into three parts including Visible Transmission (T_v), Visible Absorption (A_v) and Visible Reflection (R_v). These characteristics for shading products are measured in the laboratory under the European Standard EN 14500 "Blinds and shutters - Thermal and visual comfort - Test and calculation methods" (ES-SO, 2018).

2.7.2.1.3 G-value and g_{tot}

G-value, also known as the Solar Factor, is the total solar energy or incident flux transmitted into the building through the glass. When considering the solar factor of the glazing and the shading device together, this value is called g_{tot}. G-value has the same value as the Solar Heat Gain Coefficient (SHGC). G-value and g_{tot} have a value between 0 and 1, where 1 indicates that all solar radiation is transmitted and 0 means no radiation is transmitted. These values are usually provided by the manufacturer but if not, the g-value can be calculated using the EN 410[1] method. Furthermore, g_{tot} can be calculated using the simplified method from EN ISO 52022-1[2] or the detailed method given in EN ISO 52022-3[3].

[1] Glass in building – Determination of luminous and solar characteristics of glazing (BSI, 2011).
[2] Energy performance of buildings. Thermal, solar and daylight properties of building components and elements. Simplified calculation method of the solar and daylight characteristics for solar protection devices combined with glazing (EN ISO-s, 2017).
[3] Energy performance of buildings — Thermal, solar and daylight properties of building components and elements — Part 3: Detailed calculation method of the solar and daylight characteristics for solar protection devices combined with glazing (EN ISO-d, 2017).

2.7.2.1.4 Shading Coefficient

A shading Coefficient (SC) is derived from comparing the total solar transmittance through glazing (g-value) with a single 4 mm clear float glass having a total heat transmittance of 0.87. In other words, the relationship between a reference glass with a transmission coefficient of 0.87 and a specific glass combination transmittance. This shading coefficient can be the sum of what is known as the shortwave and longwave coefficients.

The shortwave shading coefficient is calculated via the division of the proportion of shortwave radiation transmitted through the glazing combination at normal incidence by 0.87. Whereas the longwave shading coefficient can be derived from the division of the combined heat convection and radiated from the inner glazed surface to space due to shortwave radiation absorbed within the glazing system, by 0.87 (CIBSE, 2019).

2.7.2.2 Thermal Characteristics

In this section, thermal characterisations of the shading devices which are mainly related to heat loss, are identified.

2.7.2.2.1 Thermal Resistance

2.7.2.2.1.1 Thermal resistance of materials

Thermal resistance (R-value) of a material is a measure of resistance to heat transfer through the material. For homogeneous materials (uniform composition throughout), the heat is transmitted only by conduction. So, the thermal resistance (m^2K/W) is calculated by dividing the thickness of the material (d) by the conductivity of the material (k):

$$R = d/k \qquad \textit{Eq 2-11}$$

This equation does not apply to the non-homogenous materials, so the manufacturer of these materials provides the R-value instead of utilising thermal conductivity (CIBSE, 2019). For more details regarding the thermal resistance refer to ISO 8302 (ISO, 1991).

2.7.2.2.1.2 Thermal resistance of internal shading devices

Air trapped between the window and internal shading devices acts as an insulation layer, which increases the thermal resistance of the windows (Litter & Ruyssevelt, 1984). According to BS EN 13125, this additional thermal resistance (ΔR) depends on the air permeability of shading (P_e) and thermal resistance of the shading (R_{sh}) (BS EN, 2001).

The air permeability of shading devices is expressed from the geometrical considerations in terms of the total gap between shading and the window/surrounding. The total gap is calculated via the equation below:

$$e_{tot} = e_1 + e_2 + e_3$$

Where e_{tot} is the total gap (mm), e_1,e_2 and e_3 are the average gaps at the bottom, top and side of the shading (mm) (Figure 8).

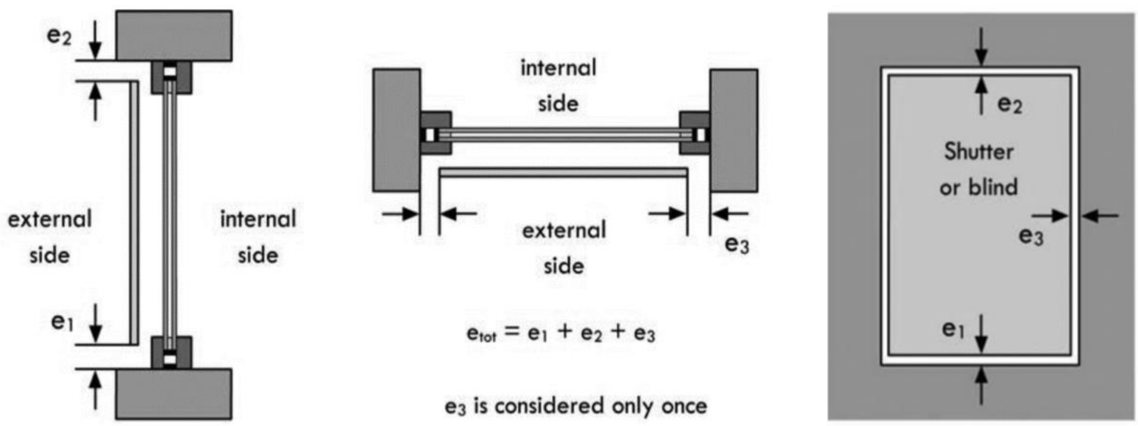

Figure 8: Air permeability of the shading (BS EN, 2001)

The air permeability criterion is calculated by the equation below:

$$P_e = e_{tot} + 10p \qquad \text{Eq 2-12}$$

Where, e_{tot} is the total gap (mm) and p is the openness factor. The openness factor, also known as the openness coefficient (Co), of a shading device, is the ratio between the void area and the total area of shading. So, shading with a tighter weave has a higher thermal resistance and can reduce the solar transmittance as well. Table 1 represents the thermal resistance for external shading devices (i.e. shutters) determined in EN 13125.

Table 1: Additional thermal resistance (ΔR) for shading devices determined in EN 13125

Air permeability of shading devices	**ΔR (m^2K/W)**	
	Internal roller blinds	Shutters
High and very high air permeability ($P_e \geq 35$ mm)	0.08	0.25 R_{sh}+ 0.09
Average air permeability (8 mm≤P_e<35 mm)	0.11	0.55 R_{sh}+ 0.11
Low air permeability ($P_e < \mathbf{20}$ mm)	0.14	0.80 R_{sh}+ 0.14

Although the additional thermal resistance mentioned in BS EN 13125 is still valid, ES-SO (European Solar Shading Organization) considers ISO 15099 as a more up to date reflection of additional thermal resistance (ISO, 2003). Based on this ES-SO will be attempting to update the BS EN 13125 in the future.

2.7.2.2.2 Thermal Transmittance of Window

The thermal transmittance of the window (U-value or U_w) indicates the thermal loss through the window. The lower U-value means better insulation for the window. This is dependent on three elements including glazing centre pane thermal transmittance (U_g), the frame (U_{wf}) and the interface between the frame and glazing. The overall U-value of the window can be calculated using the equation below:

$$U_w = \frac{\sum(A_g U_g)+\sum(A_{wf} U_{wf})+\sum(p_{wf}\psi_g)}{\sum(A_g)+\sum(A_{wf})} \qquad \text{Eq 2-13}$$

Where U_w is window thermal transmittance (W/m^2K), A_g and A_{wf} are projected areas of glazing and frame (m^2) respectively, U_g and U_{wf} are glazing and frame thermal transmittance (W/m^2K), p_{wf} is the length of the perimeter of the frame (m) and ψ_g is the linear thermal transmittance of the glazing and frame (W/mK). When using an internal shading device, due to the additional thermal resistance of the shading, the thermal transmittance of the window can be corrected by using the equation below defined in EN ISO 10077-1:

$$U_{wb}' = \left[\left(\frac{1}{U_w}\right) + R_T\right]^{-1} \qquad \textit{Eq 2-14}$$

Where U_{wb}' is the thermal transmittance of the window with an internal shading (W/m^2K), U_w is the window thermal transmittance (W/m^2K) and R_T is the thermal resistance of internal shading (m^2K/W).

2.7.2.2.3 Emissivity

For calculation of the thermal characteristics of a material, the values related to the long-wave infrared (2500 nm to 100000 nm) are required. These values are categorised as transmittance (T_{IR}), reflectance (R_{IR}) and emissivity (ε or α_{IR}). Emissivity (ε) is a value that shows the ability of a surface to emit energy as heat. So, the ratio of the radiant flux[4] emitted per unit area to that emitted by a black body[5] at the same temperature is known as emissivity (ES-SO, 2018).

2.7.3 Benefits of the Use of Solar Shading Devices in Buildings

The benefits of shading devices are categorised into three main areas inclusive of comfort, energy and occupant implication by Seguro and Palmer in 2016. Suitable design and installation will help to highlight the benefits of shading devices. The core functional benefits of utilising blinds and shutters can be categorised as below (Seguro & Palmer, 2016):

- Occupant comfort improvement: Visual, thermal, and acoustic
- Energy efficiency: operational saving for heating and cooling
- Building regulation compliances, such as the legislation to tackle overheating

[4] The radiant flux is defined as the radiant energy per unit time which is emitted, transmitted, reflected or received by an object.
[5] Blackbody, in physics, a surface that absorbs all radiant energy falling on it.

- Possibility of having highly glazed buildings

2.7.3.1 Energy Saving and Daylighting

The energy-saving capabilities of shading devices are one of their main strengths as they can assist in both reducing heat loss in the winter and preventing heat gain in summer and as a result, reduce the need for use of heating and cooling systems throughout the year. In addition, the use of blinds and shutters facilitates natural lighting and reduces the need to use artificial lighting in buildings. The combination of these factors can result in sizeable financial savings whilst adhering to government legislation regarding reduction in energy use as a significant proportion of energy use is related to buildings (BBSA, 2016).

Currently, most of the related studies and their results are based on modelling and simulation. This is because performing real-time data collection studies is both expensive and time-consuming, so researchers tend to do either the modelling or collection of real-time data in an experimental zone with no habitants. Regarding the benefits of shading devices on energy saving, there are supporting evidential research showcasing this. One of them is the study executed by Hutchin.M which illustrates how shading products reduce energy consumption utilising the ES-SO model. In this study, it is shown that utilising shading devices during winter can be beneficial for thermal retention. Shading can add additional layers to the window which can cause higher thermal resistance (higher R-value) and improve thermal transmittance (lower U-value) of the window (Hutchins, 2015). Shading devices are widely used and known for their heat rejection properties (g_{tot}), but they are beneficial for cold seasons and heat retention (U-value) as well. Several studies have been conducted to illustrate the effect of shading devices to reduce heat gain/heat loss in the summer and winter months. For example, CIBSE Guide A has identified using shading devices in buildings as a beneficial tool to prevent heat loss and excess solar gain (CIBSE, 2019). Furthermore, the evaluation of the shading efficiency was investigated by Pacheco et al (Pacheco, et al., 2012).

2.7.3.2 Comfort Enhancement and Wellbeing

One of the elements that can be overlooked by designers or in general within the building industry is how the building design has a direct or indirect effect on the occupants' wellbeing. One of the key satisfaction factors within both domestic and commercial buildings is the comfort level of the individuals residing within the building and many factors can influence this. The use of blinds and shutters can have a positive impact on people's wellbeing via the thermal and visual comfort it can create. There is a certain body temperature threshold that needs maintaining and by having the control factor of heat gains and losses, this can be balanced quite well without the need of having the fluctuations when using heating and cooling systems. From a visual aspect, the use of blinds and shutters can prevent glare and provide a better view for the occupants and better natural lighting which all go hand in hand to provide all-round balanced comfort both from a psychological and physical point of view (Nicol, et al., 2012; Boyce, 2014; ASHRAE, 2013; CIBSE, 2019).

2.8 Window / Shading Heat Loss Mechanisms

The thermal retention effect of shading products is an important element for buildings to consider especially within a cold climate. In the process of heat transfer through a building, there are three main mechanisms that enable the gain or loss of heat which are referred to as convection, radiation and conduction (Mulopo & Abdulsalam, 2019). In the context of heat retention, the total heat loss in a building is the sum of the fabric and ventilation losses (Johnston, et al., 2013). So, the heat transfer occurring in windows from travelling from inside (higher temperature) to the outside (lower temperature) is via radiation, convection, conduction and ventilation losses. In night-time cases and cold climates, only longwave radiation is involved within the radiation heat transfer mechanism. Utilising an insulating shading device can reduce the amount of heat loss through the window. Figure 9 represents the heat transfer mechanism in a window with internal shading (i.e. blind)

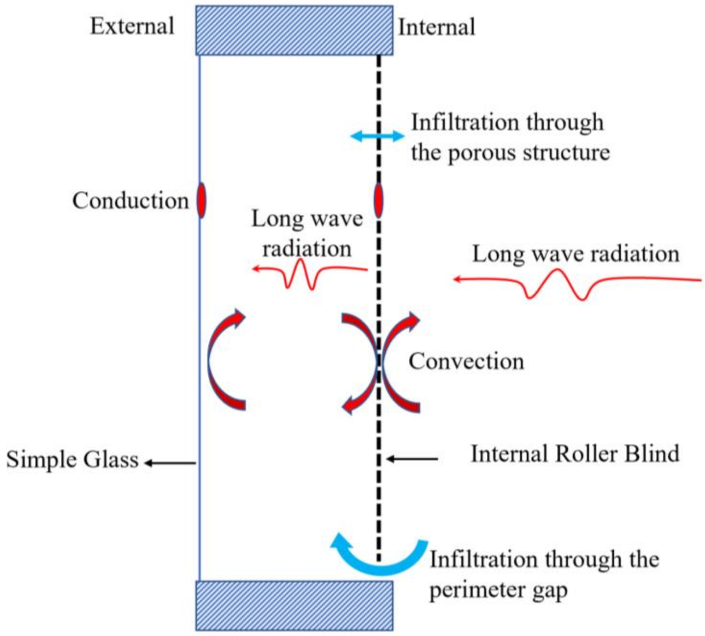

Figure 9:Night-time heat loss mechanism through the internal blind

The type of fabric (or material) used, and its thermal characteristics affect the heat transfer through the shading device. Additionally, to enable the increase of the insulation properties of shading devices, reducing air permeability is an important factor that needs to be considered. Shading products predominantly have high air permeability which is mainly the result of the openness factor of its structure or its openings around its edges (ISO, 2003).

2.8.1 Studies on the Impact of Shading Devices on Thermal Retention

The effect of shading devices on reducing heat loss has been investigated in a steady-state model by Hutchins in 2015 which considers the various types of shading in combination with different types of glazing. The results show that if a 50:50 split between cooling and heating is considered, solar shading can reduce the required heating energy by 14% (Hutchins, 2015). Many research reports have been published throughout the years focusing on window coverings in experimental tests which have stated the effectiveness of utilising varying window coverings but most of them like in the cases of Wood et al and Lunde & Lindley are executed in very controlled laboratory-like settings which are very far from real conditions (Lunde & Lindley, 1988; Wood, et al., 2009). Table 2 represents the previous studies assessing the impact of shading products on thermal retention.

Table 2: Previous studies on shading devices' effect on thermal retention (Wood, et al., 2009; Garber-Slaght & Craven, 2012; Lunde & Lindley, 1988; Fitton, et al., 2017; Smith, et al., 2012)

Shading Product	Percentage of heat transfer reduction	Methodology	Authors	Year
Curtains Insulated blinds	38% 15%	Real-time test in the cold season	Garber-Slaght & Craven	2012
Insulated blind Curtains (heavy) Roller blind	68% 39% 37%	Hotbox method[6]	Wood, et al	2009
Roller blind Different types of curtain materials	6.3 to 38% 3.8 to 9.5%	Hotbox method	Lunde & Lindley	1988
Roller blind Curtain	12-24% 26-27%	Controlled real-time condition	Fitton, et al	2016
Secondary glazing	R-value increased from 0.15(m^2K/W for single glazing) to 0.57 m^2K/W	Guarded hot box and modelled in WINDOW	Smith, et al	2012

Furthermore, another study was conducted by Feather in 1980 which showed the possible energy savings by adding various types of shading and curtains to the window. The key finding in this study was not only the U-value and type of the curtains utilised but the way that curtains were fixed to the window. Fixing a sealed blind to the window can create an air layer between the shading and window which can act as an extra layer of insulation (Feather, 1980). A study conducted in 2000 shows that

[6] Based on the Hot Box Test Method, a specimen is located between two chambers: the metering chamber and the climatic chamber. The metering chamber is used to simulate the interior environment (hot side), while the climatic chamber is used to simulate the exterior environment (cold side). Heating and cooling systems are used in the metering chamber and climate chamber, respectively, to create the temperature difference (Lu & Memari, 2018).

having a sealed blind with a stationary air layer between the window and shading can improve the U-value of the window by 19% compared to when the blind is not sealed (Table 3).

Table 3: Comparison of U-value and R-value between loose and sealed blind (Fang, 2001)

	Loose curtain		Sealed curtain	
	R-value (m^2K/w)	U value (W/m^2K)	R-value (m^2K/w)	U value (W/m^2K)
Single Glazed	0.23	4.44	0.27	3.66
Double glazed	0.39	2.58	0.46	2.16

Using an equation from the CIBSE Guide A, the corrected U-value of a window utilising a shading device can be calculated as below:

$$U_{wb} = [\left(\frac{1}{U_w}\right) + R_{bi}]^{-1} \quad \textit{Eq 2-15}$$

Where U_{wb} is the corrected thermal transmittance of window (W/m^2K), U_w is the thermal transmittance of window (W/m^2K) and R_{bi} is thermal resistance R of the shading product (m^2K/W). CIBSE Guide A has also provided the data for the U-value and R-value of the shading devices according to the experiment conducted by Wood, et al (Wood, et al., 2009; CIBSE, 2019).

A recent study was conducted in 2017 by Fitton, et al to show the effect of shading on thermal retention in a real-world scenario within an unoccupied test house. They had monitored the heat flux through the window similar to the controlled condition test conducted by Wood et al. Another aspect of their project was replicating the real-world conditions by assessing the heaters/emitter's location and airflow inside the rooms (Fitton, et al., 2017). Although this approach can give an overview of the product utilised relative to the window used but can often show optimistic and far from reality results as at the end of the day without having a real-world setting where elements and variables such as the occupancy behaviour/movement, then it will be very difficult to justify the retrofit approach for existing buildings and ultimately show what the real energy efficiencies are.

In a simulation study conducted in China, the heat loss was reduced when using Double Skin Façade (DSF) with Venetian blinds by 14% and 72% compared with when using the common fabric and when using double-glazed facades (Wang, et al., 2020). The Lawrence Berkeley National Laboratory (LBNL) has been researching the effect of shading on heat transfer for many years. However, these studies are mainly conducted in an environmental chamber. Robert Hart investigated the zero solar loads thermal transmittance of internal cellular (honeycomb) blind in an environmental chamber using the Calibration Transfer Standard (CTS) method (Hart, 2018). The results were validated by simulating the simplified correlation from ISO 15099 and software packages WINDOW and THERM, developed by Berkeley Lab, were used in addition to CFD analysis. This study shows that wave type surfaces of the honeycomb blind have less than 5% of natural convection of the room-side surface. During this study, it was also shown that the distance between the window and the blind is different between the top and bottom of the blind. This is due to the structure and weight of the blind which is shown in Figure 10. This difference between assumption and reality can affect the thermal transmittance calculations and should be replicated through simulation software packages as well.

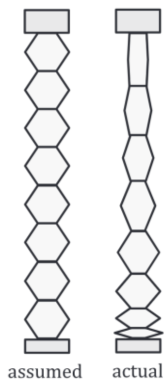

Figure 10:Honeycomb cell geometry assumed and actual (Hart, 2018)

2.9 Use of Solar Shading in the UK

The functional benefits of shading are often disregarded and are deemed second to its aesthetic and appearance appeal (Beck, et al., 2010). Within the UK, solar shading use is approached as an optional item for buildings rather than an essential daylight and energy management device (Seguro & Palmer, 2016). In comparison with some European countries, the UK is lagging behind in the use of solar shading which can be attributed to many reasons. Building regulations and legislations in some of the European countries motivate the use of these devices in buildings.

For example, as France had a target and aim to have energy-positive buildings from 2020, according to the RT2012[7], it had been instructed that from 2013 the annual energy consumption in residential buildings should be less than 50 kWh/m^2 whilst highlighting the use of solar shading as a recommended method to this initiative (GBPN, 2013). In Austria, there is a restriction on the use of air conditioning and the size of the windows to limit the solar radiance, this can be overcome by using solar shading products which will help buildings to maintain larger windows. In Italy, for some types of buildings, the use of external shading is compulsory, whilst a 65% income tax break (Eco Bonus 65) of the total cost was introduced in 2018; this can be paid over ten years for buying or replacing external shading products (European Commission, 2018). In Denmark, according to the BR 10 (Danish Building Regulation 10), the total building annual energy consumption should be less than 20 kWh/m^2 for dwellings and 25 kWh/m^2 for non-dwellings. So, applying a conservation factor to cooling systems will lead to the use of solar shading in order to reduce the solar gain in buildings (DECA, 2010).

However, within the UK there is no mandatory or incentivised legislation such as tax reduction or subsidies to increase the use of solar shading in buildings (Seguro & Palmer, 2016). Also, there are several barriers in the UK that prevent the use of solar shading at its optimal level.

2.9.1 Barriers for the UK Shading Industry

The main barriers preventing the more widespread use of shading in the UK, which were investigated with Seguro and Palmer in 2016, are listed below:

[7] Réglementation Thermique - RT2012 (GBPN, 2013)

2.9.1.1 Solar Shading Recognition and Devaluation of its Benefits

The benefits of solar shading are not well recognised and the scientific knowledge behind it is not well understood amongst building specifiers, stakeholders and customers within the UK which results in devaluing shading products and identifying them as optional items rather than essential devices. It also seems that the shading industry itself in some cases is not aware of its benefits (Seguro & Palmer, 2016). This devaluation can impact and influence the decisions at the building design stage even more. For instance, the National Building Specification (NBS) considers shading as a general fitting which can be misleading to building professionals as this is not its core and primary purpose. Also, the SKA rating, which helps occupants fit-out projects against specific sustainability criteria, has identified very few credits for use of shading devices (RICS, 2013) and has yet to be updated. Whereas BREEAM, WELL and LEED which are environmental building labelling schemes, consider the use of solar shading devices as a valued method in improving glare control and therefore are examples of solar shading recognition (Littlefair, 2018).

2.9.1.2 Below Standard Performance

The optimal performance of solar shading devices is vital for more widespread use in buildings. However, several factors are causing the below-par performance of shading devices. The main reasons for this sub-standard performance are:

- Manufacture and specification: lack of knowledge within the shading industry can cause the development of products that perform below best practice guidelines. Furthermore, lack of knowledge and training amongst building professionals results in underestimating the benefits of shading. For example, the lack of inclusion of solar shading solutions and devices within building services engineering projects can act as a prohibiting factor for specifying solar shading in buildings. This impact is heightened as building service professionals are paid based on the traditional building services that they provide whereas shading devices are sometimes not included in their pay structure. In addition to that, building energy modelling and simulation software packages are not normally designed to accommodate shading information in its entirety (Seguro & Palmer, 2016).

- Installation and maintenance: shading devices are considered as an afterthought and installation for a building and shading will be used only when required. This causes the installation of shading products to be below expectations and standards and consequently makes them expensive. Also, due to the lack of strategic planning for maintenance, there is mostly either a reactive approach to fix the issues such as overheating or glare or no action at all.
- Design: Since shading is still only considered as a stand-alone device its attributes are mostly considered in isolation as opposed to being the main part of a building. Added to that are the inefficiencies and bias at the design stage which is caused by misunderstanding and underestimation of solar shading performance in compliance tools and building energy modelling software packages.

2.9.1.3 Retrofit Approach

Considering solar shading devices when the façade is being completely replaced or in the early stages of design, a new building is known to be the best approach. Many elements influence the type of shading used for the retrofit approach which includes building aesthetics and window specifications. Taking this into account, the retrofit approach will result in a less cost-effective approach compared to if shading is considered at the early stages of the design process (Littlefair, 2017-b). However, poor knowledge and understanding of the window and glass specifications (with and without shading) are a factor that affects the retrofitting process.

2.9.1.4 Ill-informed Occupants

Occupant behaviour, which is unpredictable, and related to the individuals' thermal comfort, culture etc., is an element that impacts the operation of shading devices and can reduce their benefits. In most cases, as the occupants do not have enough knowledge regarding shading devices, they neglect the advantages of shading (Seguro & Palmer, 2016). For example, during warmer days occupants can reduce the risk of overheating by using solar shading which causes a reduction in solar thermal gain. In addition, in colder climates, they can use insulated internal blinds overnight to keep the heat inside the building and not use it during the day to receive as much solar radiation as possible to reduce the energy requirements for heating and lighting. However, occupants may not use solar shading products at the most optimal times which will minimise its advantages and also increase energy consumption.

2.9.1.5 Regulations and Lobbying

In comparison with other industries related to construction such as glazing, insulation material, frame and building services, it seems that the solar shading industry has been less successful in influencing government legislation and lobbying in general. The EPBD (Energy Performance of Buildings Directive) recognised solar shading and protection systems as an effective tool to reduce cooling energy consumption and increase the thermal performance of the building. The Committee on Climate Change has published a report in 2019 for UK housing which has identified shading (External shading for new build homes and internal shading for existing homes) as a beneficial element to achieve a low carbon and sustainable home (Committee on Climate Change-a, 2019). However, the importance of shading systems in buildings is still not highlighted or reflected in UK regulations where the focus is mainly on reducing overheating and glare and not other benefits such as heat loss (Seguro & Palmer, 2016).

2.9.1.5.1 UK Building Regulations and Environmental Labels with regards to Solar Shading

2.9.1.5.1.1 Part L Building Regulations

In the UK, building regulations are setting standards for energy conservation and performance in existing and new buildings. Approved Document L is regarding the conservation of fuel and power, covering dwellings and non-dwellings. In building regulations, the main points and necessities are stated in short and direct sentences. There is a statement within the building regulation related to solar shading: “Reasonable provision shall be made for the conservation of fuel and power in buildings by limiting heat gains and losses through thermal elements”. Within this statement, as windows and transparent parts of the buildings have been considered as the “thermal elements” therefore it can be concluded that reducing heat gain and loss through windows is included as part of the requirements (HM Government (L1A), 2016).

Guidelines are provided by the government to allow a better understanding of compliance known as Approved Documents. These documents which cover both existing and new buildings are not mandatory to follow but if not used then compliance needs to be reached through other means. These documents are categorised as:

- Approved Document L1A for new dwellings (HM Government (L1A), 2016)
- Approved Document L2A for new buildings other than dwellings (HM Government (L2A), 2016)
- Approved Document L1B for existing dwellings (HM Government (L1B), 2018)
- Approved Document L2B for existing buildings other than dwellings (HM Government (L2B), 2016)

As in reality the guidelines for solar shading mainly apply to new buildings, for example, approved Document L1A (new dwellings) and Part L2A (new buildings) outline the need for passive measures to be implemented to reduce heat gain in summer, regardless of the addition of cooling apparatus. This is to avoid non-essential additional air conditioning instalment which will result in higher energy use.

Currently, the main tool at a building designer’s disposal to predict internal temperature increases is a method/calculation present in one of the appendices of the UK Standard Assessment Procedure (SAP). This prediction method takes into account various factors such as the window size and positioning, ventilation rate in addition to shading where mainly simple factors are considered for the different types of shading.

It should be noted that the Approved Document L2A also provides guidelines and recommendations related to the total energy usage of a building especially in relation to the maximum value reference point which is dependent on the size and spaces within the building. The selection of shading can be vital here as it can have a direct impact on various factors such as cooling energy usage, daylight prevalent in the space and any heat gains in winter. The energy usage values are computed using dynamic thermal modelling software packages or the Simplified Building Energy Model (SBEM). It should be noted that adhering to these guidelines present in Approved Documents concerning overheating or solar gain does not mean that the building will not overheat as there may be equipment within the building that can contribute to these gains despite the solar gain values of the building itself being low.

2.9.1.5.1.2 BREEAM

To be able to assess and ascertain the sustainability of any development whether it is new or refurbished, an internationally renowned method has been established in the UK called the Building Research Establishment Environmental Assessment Method (BREEAM). This method covers sustainability of all stages of the supply chain, design phases and construction of the buildings regarding specific categories such as energy, wellbeing, ecology etc. Every category covers key factors such as carbon emission reductions, climate change, durability both in design material and many other subjects whilst being assigned specific points for each of these areas with their final tally determining their overall rating (BRE, 2018).

Now some of these categories are key in terms of shading and can have a direct impact on the points given and the overall rating. Some examples are visual comfort and daylight provision where shading and glare control is a factor and also carbon emissions and energy reduction which shading can play a part in and assist in improving the energy performance of a building.

2.9.1.5.1.3 LEED

Another widely used international rating system for performance and sustainability of buildings established in the USA is called Leadership in Energy and Environmental Design (LEED) which again covers all the different stages of the building process whilst distributing points based on energy savings aspects and also occupant well-being.

As with BREEAM, some of the compliance categories relate to shading such as thermal comfort where the design of the building is considered in providing optimal thermal conditions. Daylight is also considered where the use of glare control devices such as shading is examined in addition to energy usage and even more interesting the integrative process meaning if and how shading has been implemented at the initial design stages of a building.

2.9.1.5.1.4 WELL Building Standard

When considering wellbeing in occupants, there is a specific standard focused solely on the health of inhabitants with the goal to improve their overall wellbeing i.e., nutrition, sleep, mood, comfort etc established in the USA is called the WELL Building Standard v1 (WELL) developed by the WELL Building Institute (WBI). This guideline has some pre-requisite conditions which are needed for certification and some optional points which all add up to the overall WELL score in relation to seven main categories: air, water, nourishment, light, fitness, comfort, and mind.

Similar to the previous rating systems, concepts like light and comfort can be fulfilled partly by solar shading, for example, glare control which makes use of shading is a pre-requisite that can assist with better sleep, increased productivity and avoiding computer glare which is an optional point part of the daylight credit limiting extreme lighting in working environments. As part of the comfort criteria, there is a pre-requisite for thermal comfort which can be assisted by the use of solar shading in line with ventilation methods (International WELL Building Institute, 2020).

2.9.1.5.1.5 NABERS

With a specific focus on operational energy performance in buildings, the National Australian Built Environment Rating System (NABERS) was established more than 2 decades ago in Australia which has helped buildings meet the energy targets consistently and in the last year has been introduced in the UK. This six-star rating system focuses on the measured energy usage within a building over a year as opposed to the traditional Energy Performance Certificate (EPC) which focuses on predicted or design performance (NABERS, 2020; BRE, 2021).

When considering the building model needed to assess the energy performance by the NABERS guidelines, it is vital that elements such as shading, insulation, glazing systems, lighting and ventilation are considered. This highlights how significant shading device inclusions are in these standards and rating systems as they ensure these key energy loss mitigators such as shading devices are considered early on in the building design (BRE, 2021).

2.10 Building Energy Modelling and Simulation

One of the issues regarding the use of shading devices in buildings is the results of the dynamic thermal modelling software tools which have an important role in the early stages of the building design on the decision making regarding the use of shading. In the 1960s, building energy performance simulation was initially introduced. With the rapid increase in energy consumption within buildings and the prevalence of more glazed buildings in recent years especially with the rise in population and growing economies, the importance of energy savings in buildings becomes more critical. One of the key factors in ensuring energy consumption is controlled and kept at a minimum is to utilise Building Energy Modelling and Simulation (BEMS) at the very early stages of the design (Gao, et al., 2019). During the design phase of construction, modelling software can be used to estimate a building's projected energy consumption, as well as the building performance. Previously, as the input for the project was not available, the BEMS was used in the final stage of the design phase. In the final stage, the building design decisions were already made, so making changes at this stage was not possible due to the amount of time and money spent on it (Zhu, 2014). So, using BEMS in the final stage of the building design was an inefficient process to follow (Ahn, et al., 2014).

Growth in the use of building modelling software packages opens the door for improvements in design and also in the modelling itself by introducing novel methods such as building information modelling-based software packages which promote conventional building energy modelling into the digital building design process (Garwood, et al., 2018). BEMS software tools can produce building thermal simulation which is a dynamic thermal model of a building created by energy performance software analysis in the early stages of the building design (Bahar, et al., 2013).

2.10.1 Software Packages

Over 100 tools are available for dynamic thermal simulation in buildings, which are either free or have commercial versions (Zhu, et al., 2012). Some of these software tools are listed below:

- Integrated Environmental Solution Virtual Environment (IES VE)
- Energy Plus, which is a code-based software with a simulation engine and input/output of text files
- DesignBuilder, which is a simplified EnergyPlus thermal model and uses the EnergyPlus engine for simulation
- EDSL Tas, which has a modular design
- IDA Indoor Climate and Energy (ICE), which is a simulation platform for modular systems
- Environmental Systems Performance – Research (ESP-r), developed by Energy Systems Research Unit (ESRU)
- Transient System Simulation Tool (TRNSYS) with a modular structure
- eQUEST (the Quick Energy Simulation Tool), accomplished by combining a building creation wizard, an energy efficiency measure (EEM) wizard, and graphical reporting with a simulation "engine" derived from the latest version of DOE-2 (Building Energy and Cost Analysis Tool developed by LBNL).

Based on the input and output data file, the output of software can be used as an input for another software. Bahar et al, has provided a summary of the data exchange between some of the software tools considering only gbXML (Green Building XML) and IFC (Industry Foundation Class) files, shown in Figure 11. In addition to the 2D software packages which can model the whole building energy simulation, there are some 1D software tools as well such as WINDOW, THERM (developed by Lawrence Berkeley National Laboratory (LBNL)) and Early Stage Building Optimisation software (ESBO) which only simulate the one-dimensional heat transfer in the window area.

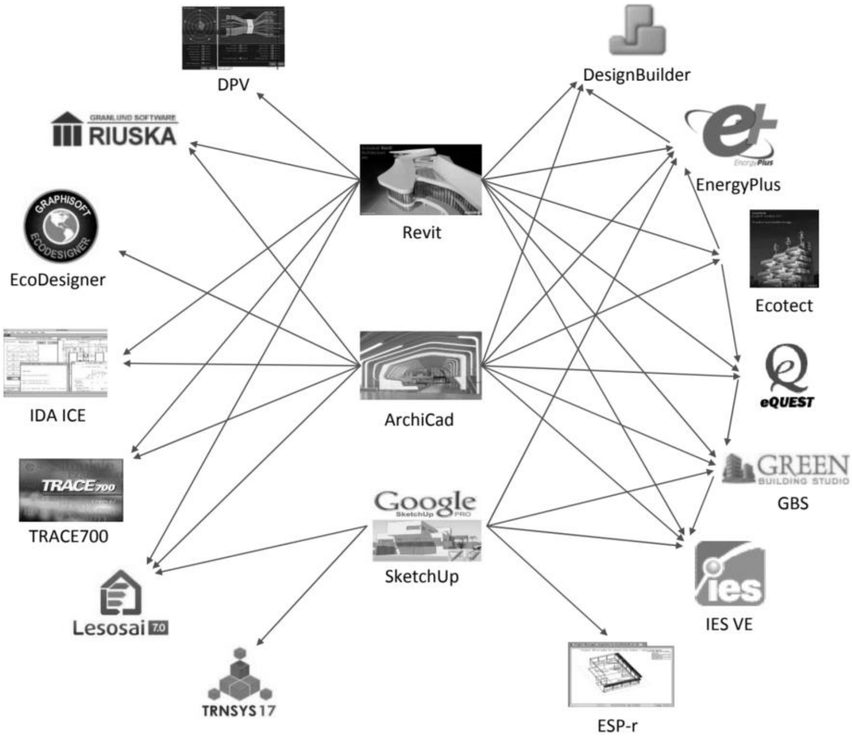

Figure 11:Summary of input/output exchange between thermal and modelling simulation tools (Bahar, et al., 2013)

Due to the increasing number of building energy modelling software packages developed in past decades, it is beneficial to understand previous studies conducted whereby these software packages have undergone a comparison analysis. One of these such studies was conducted by Crawley et al whereby twenty software packages and their tools and functionality were compared against each other (Crawley, et al., 2008). Users were encouraged to select their desirable software tool based on what they would like to see in practice. Furthermore, Jaric et al have reviewed several software packages and concluded that EnergyPlus, IES VE, IDA ICE and TRNSYS are the most common software packages in the world for building modelling. As these are the most complete and complex software packages, they require more expertise to use (Jarić, et al., 2013).

2.10.2 Dynamic Thermal Modelling and Performance Gap

Dynamic thermal simulation is beneficial to predict the performance of a building as it provides the closest prediction to reality. The thermal simulation results of BEMS software packages influence the building professional's decision on different elements in the buildings such as utilising shading devices. However, there is sometimes a discrepancy between dynamic simulated results and real-world data. This difference between design/virtual and real buildings can be due to weather, energy systems used in building, indoor environment, maintenance of the building and occupant behaviour (Yoshino, et al., 2017).

One of the factors in analysing these BEMS packages is to identify their shortcomings and gaps, especially when compared with the real-world data. Occupant behaviour is one of the factors that affect the dynamic thermal models. A study conducted by Gram-Hanssen in 2012 illustrated the effect of user behaviour on energy consumption in buildings which can lead to discrepancies between reality and simulation (Gram-Hanssen, 2013). This discrepancy which is caused by occupant behaviour is considered in IEA EBC Annexe 53 as a social factor (Andre, 2013). Annexe 53 also identified six main factors which influence energy consumption in a building, shown in Figure 12.

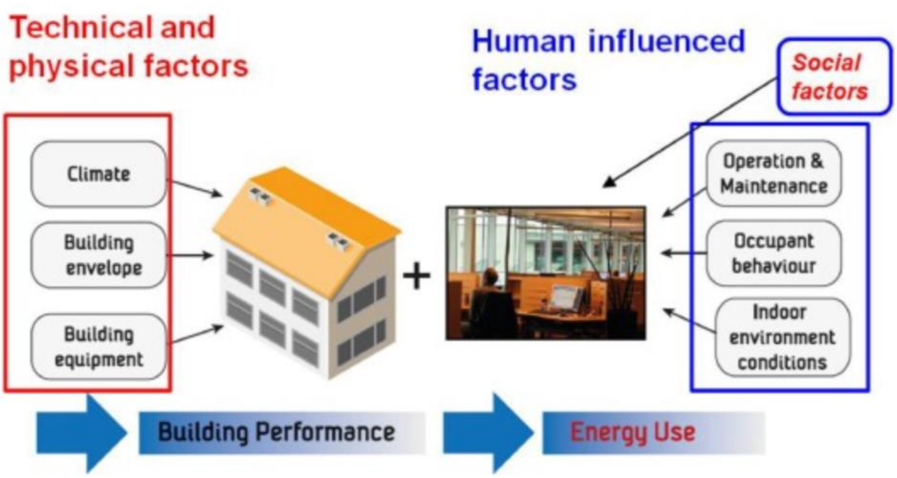

Figure 12: Six main factors which affect energy consumption in a building (Yoshino, et al., 2017; IEA EBC, 2016)

Another reason that can cause a discrepancy between real-world and thermal dynamic models is the user expertise and decisions. A study was conducted in 2014 showcasing how user decision making can have a major impact on the outputs. In this study, a similar project was given to 12 professional energy modellers to complete a model on eQUEST. The results varied between -11% to +104% for total annual electrical energy consumption and for gas consumption, it was between -61% to +1535%. These results illustrate how significant the decisions made by a modeller for software inputs can be (Berkeley, et al., 2014). Furthermore, according to Simon Rees, one of the main factors causing the performance gap is parameter uncertainties in building modelling. This is because the modellers use the default data available in the software which can be uncertain (Rees, 2017). Regarding the building heat transfer modelling, the common assumptions are (i) the room's air is completely mixed, (ii) the conduction heat transfer is one-dimensional and (iii) the effect of moisture on heat transfer is ignored (Rees, 2017).

In another research the main sources of uncertainty in the building energy simulation results are categorised as:

- Related to inaccurate specifications and input for the building parameters (specification).
- Related to modellers incorrect assumptions of physical aspects such as zoning (modelling).
- Related to the numerical errors in the simulation model (numerical).
- Related to the external conditions around the building such as occupant behaviour or weather condition (scenario) (Wit & Augenbroe, 2002; Dronkelaar, et al., 2016).

In a research study performed in 2016, discrepancy caused by simulation weather data was illustrated where real-time experiments were carried out in an unoccupied refurbished building in London with the IES VE model to illustrate the performance gap in relation to overheating issues in buildings. In this research, the lack of extreme weather scenarios in the weather file was one of the main reasons causing the discrepancy between the thermal model and real-world data (Venturi, et al., 2018).

When using various BEMS tools, discrepancies can occur between the results of the different software packages. Modelling uncertainties can cause these discrepancies and also reduce confidence in the building energy simulation results (Hopfe & Hensen, 2011). Another study shows that up to 26% of differences in the results of the simulation are due to the modelling uncertainties. The software assumptions and default data are important factors affecting the results of the simulation and users have no control over them (Mantesi, et al., 2018). Dronkelaar et al have reviewed the energy performance gap in more than 60 case study buildings in 2016. In this study, the specification uncertainties can affect 20% to 60% on energy use in software results which can cause deviation between measured and predicted energy used (Dronkelaar, et al., 2016).

Regarding specification uncertainties, Salehi et al in 2013 showed that specifications of lighting and equipment were not correct when using IES VE (Salehi, et al., 2013). Also, underestimated value for fan power in IES VE default values was shown by Burman et al in 2012 (Burman, et al., 2012). The modelling uncertainties were identified in a study conducted in 2011 where mechanical systems are oversimplified (Wetter, 2011). Furthermore, Salehi et al, Burman et al and Crawley et al, confirmed the limitations of the software that the users are unable to model some specific requirements (Salehi, et al., 2013; Burman, et al., 2012; Crawley, et al., 2008).

A recent inter-model validation study was conducted in 2019 for overheating prediction during summertime within a house located in the UK. In this study, four experienced modellers used two different types of dynamic thermal modelling software tools which are approved by ASHRAE 140 and comply with CIBSE AM11. The simulation with two software packages was completed at two levels: The blind phase (when the modellers are not aware of assumptions made by other modellers) and the open phase (when the modellers share their assumptions with each other). The results show that even when the input data is very similar or “near-identical”, two different software tools can produce different results and predictions of overheating. It should be noted that the name of the software packages was not mentioned in this study (Robert, et al., 2019).

Although inter-model comparisons are relatively easy to conduct and different parameters can be tested in the study, however, as results are not validated against the real-time data, there is the criticism that there is no true standard in such tests (Judkoff & Neymark, 2006). Intermodel validation is particularly useful to test new models against the well-established ones (Clarke, 2011). On the other hand, in empirical validation, the building energy simulation results are validated against the measured data from a real building. This method can validate the predicted simulation results in the highest level of accuracy but gathering high-quality experimental data is expensive and time-consuming (Im, et al., 2020). Previous empirical validation studies are revies by Neymark & Judkoff in 2002 (Neymark & Judkoff, 2002). An empirical validation study was undertaken in 2015 to compare the experimental results of a full-scale building with dynamic thermal simulation results with various software packages such as IES VE, TRNSYS, IDA-ICE, EnergyPlus, ESP-r, EES, eQUEST, etc. The experiment was undertaken from August to September 2013 (two months). Most of the modelling results are similar to the experimental data. Some of the software tools produce very similar results to the experiment data however, one software package produced the worst results but is not clear whether it is caused by the modellers' assumptions or it is due to the embodied calculations and deficiencies in the software (Strachan, et al., 2016).

Another research exercise was carried out to compare simulation results of two commonly used software tools in the UK which are IES VE and EnergyPlus and their effect on overheating prediction in nine naturally ventilated flats located in London. The results of these simulations were dramatically different as in IES VE all the flats had a low risk of getting overheated but in EnergyPlus, seven out of nine flats had a high risk of overheating. This could be due to two reasons; one could be due to differences in the natural ventilation modelling approach in the software packages and the other one is because of the higher surface temperature due to the higher internal surface convection factor in EnergyPlus. In conclusion, as the simulation results are not validated against the real-time experimental data, it is not clear which software is producing the more accurate data hence the comparison of simulated results with real-time experimental data is recommended (Petrou, et al., 2019).

2.10.3 Guidelines and Manuals for the Building Energy Modelling and Simulation

The main approaches/guidelines that identify the three main factors for thermal retention analysis (inclusive of thermal comfort, energy estimation and plant sizing) available in the UK are CIBSE

AM11, CIBSE TM54, CIBSE TM52, CIBSE TM59, SAP, SBEM, CIBSE Admittance Method, NABERS[8] and ASHRAE 90.1[9].

CIBSE AM11 is an Application Manual for providing guidance but it is not a standard. Many of the issues of building simulation and its compliance with building regulations are covered within this AM11 Building Performance Modelling (BPM) (Awbi, et al., 2015). CIBSE TMs are the Technical Memoranda that outline upcoming technologies or provide a specific view in a very detailed and clear manner on certified systems. CIBSE TM54 provides guidance for building owners and designers on how to assess operational energy consumption at the design stage (Cheshir & Menezes, 2013). CIBSE TM52 is used to inform building professionals and designers regarding the indoor building environment and provide techniques to predict the chance of buildings getting overheated (Nicol, 2013). CIBSE TM59 provides a methodology to assess overheating in homes and limit its risk (CIBSE, 2017). These guidelines and technical manuals are useful for modellers however there is a need for a straightforward approach for modelling shading devices.

2.10.4 Solar Shading Devices: Modelling and Simulation

There are some one-dimensional software packages such as WINDOW, THERM and WIS (Window Information System) for determining the solar and thermal characterisation for window systems including shading, glazing and frame. However, these software tools are not appropriate for use in a whole building dynamic thermal model. The 2-D software tools which are acceptable for Level 5 EPC (Energy Performance Certificate) are used for whole-building energy modelling such as EnergyPlus, DesignBuilder, IES VE, ESDL TAS, etc. Several research studies were conducted regarding the building energy simulation with shading devices. Datta in 2001 used TRNSYS to model external horizontal fixed louvres with different slat angles and lengths in warm climate cities to propose the best shading device for investigated cities in terms of the building thermal performance (Datta, 2001). Tzempelikos & Athienitis in 2007 investigated the effect of automated external roller

[8] National Australian Built Environment Rating System
[9] American Society of Heating, Refrigerating and Air-Conditioning Engineers

shade on whole building thermal performance. In this study, TRNSYS was used for hourly simulation of solar irradiance for one year and a reduction of lighting and cooling energy requirements were seen when the shading device was used. Furthermore, in this study, the importance of using shading devices at the early stages of the building design, where the main decision regarding the use of shading devices is made, is highlighted (Tzempelikos & Athienitis, 2007).

In another study conducted in 2005, using DOE-2 for prediction of energy-saving utilising Electrochromic (EC) glazing with overhang in both cold (Chicago) and warm (Houston) climates yielded interesting results. The results showed that EC glazing and overhang reduce the annual energy consumption in hot climates considerably. However, as overhangs can not block the low angle sunlight which is mostly in a cold climate, an internal shading system is required to be used with EC glass to create better energy-saving results (Lee & Tavil, 2007). In a study in 2010, the effect of external horizontal and vertical louvres on energy saving in an office building in Abu Dhabi was investigated using IES-VE, where in the south, west and east faced façade, external dynamic shading was used, 34%, 30% and 28% energy saving was seen, respectively (Hammad & Abu-Hijleh, 2010). A research project in 2013 investigated a comparison between the effect of fixed shading devices and electrochromic glazing in hot weather conditions. For this study, an office building in Arizona is modelled using DesignBuilder with the different types of shading used within this study being fixed overhang (1.5 and 1.0 m projection) and side fins. The results of this study show that EC glazing is more effective in reducing yearly solar heat gain in comparison with the shading devices used in the simulation study. It is also concluded that well designed vertical side fins and overhangs are important to reduce cooling energy and the risk of overheating (Aldawoud, 2013).

Yao in 2014 investigated the impact of external roller blinds on energy saving, visual and thermal comfort of domestic buildings in Ningbo, China. The real-time illuminance and solar radiation were measured on one day only (due to the lack of equipment) in summer and the annual building performance was simulated using Energy Plus. Within this simulation study, during summer the shading system is fully closed in the daytime and fully open at night-time. Also during winter, shading is fully open during the daytime and fully closed at night. Therefore, it was concluded that using external dynamic shading can significantly improve building energy saving, visual and thermal comfort in both winter and summer in China (Yao, 2014). In another study, an office located in Rome, Italy was simulated with EnergyPlus 8 in order to compare the performance of internal and external shading in terms of visual and thermal comfort and primary energy use. The results show that having an external shading causes reduction in cooling energy requirements and slightly increases the heating energy but adding internal shading can increase the cooling energy requirement and decrease heating energy needs (Atzeri, et al., 2014). Lawrence Berkeley National Laboratory (LBNL) provided a report for the US Department of Energy in 2013 including a simulation study on the various types of shading products using EnergyPlus and WINDOW. The results of this study show benefits of shading on energy-saving applications. However, this study is only simulation-based and the results are not compared with reality (LBNL, 2013).

Liu et al in 2013 investigated the effect of nighttime insulation on a double glazing façade and developed a simplified method to calculate it. By adding the nighttime insulation (internal shading), the comfort performance (by measuring the internal surface temperature) and thermal performance (by measuring U-value) are measured and calculated. The experimental real-time data has been collected from two test rooms within the Alborg University in Denmark. The calculated results show that having the night insulation with a double glazing façade can reduce U-value by 30% compared to when there is no insulation. BSim which is a building simulation software developed in Denmark is used for simulation in this study. The comparison between the simulation and experimental results show that BSim can simulate the building energy performance and show the effect of night insulation. However, this software is not capable of calculating the internal surface temperatures so it is recommended to conduct an experimental data collection test and compare the results with other simulation software tools to find out the ability of other software tools (Liu, et al., 2013).

Tian et al in 2014 conducted an experimental and simulation study using two different software tools, Radlink and DOE2 whilst utilising a Venetian blind. Also, Radiance simulation software is used as reference data to be compared with the other two simulated data. Comparing the results of the simulated and measured illuminance data showed that Root Mean Square Error (RMSE) in Radlink and DOES2 are 80% and 48% in the cloudy sky and in the clear sky 68% and 75%, respectively. It is concluded that the assumption made by the modeller in these two software tools caused errors in the simulation results (Tian, et al., 2014).

In another study, with experimental monitoring and analytical simulation using EnergyPlus in two periods in summer and winter, the effect of different external solar shading systems on thermal comfort and energy saving in a Mediterranean climate is investigated. The comparison between three different types of external louvre shading devices shows that the aluminium shading products have similar behaviour but having the wooden louvre due to its heat capacity, can maintain a higher temperature than the other two aluminium variants. The results also show that the various sizes, angles and the material of the shading do not affect energy requirements (Stazi, et al., 2014).

The ability of EnergyPlus for heat transfer through window frames is investigated in a research study in 2018. To reduce the simulation time, some simplifications are required to be made. At the time of this study, EnergyPlus calculates the heat transfer through the frame with a 20% error. This was due to a one dimensional model on a 2D simplified geometry. An algorithm was suggested in the study to overcome this problem (Gastines, et al., 2019).

Seguro and Palmer have conducted a simulation study using EnergyPlus on the effect of the internal and external roller and Venetian blinds. From this study, it is predicted that using internal shading can reduce energy consumption by 7% to 16% and using external shading can reduce annual energy consumption by 30% to 33%. Furthermore, Seguro and Palmer have reviewed other studies regarding the simulation of shading products which highlighted that some of the BSM software packages do not value shading products and are under-assessed (Seguro & Palmer, 2016).

So, it is observed several research studies are available on building dynamic thermal simulation with regards to shading devices, however, there is a lack of evidence and studies showcasing the comparison between the simulation results and real-time data. In some of the studies mentioned in this section, the experimental data were collected from the site, however, these data were not directly compared with simulation results and were used as inputs for the simulation. Furthermore, in those few empirical validations focusing on shading devices, the real-time data were mostly measured from a test cell rather than a real building (Loutzenhiser, et al., 2008). Following this, a research paper has compared the real-time data with simulation results regarding the use of shading devices. A London flat was selected as an experimental test location whereby the effect of various types of shading was investigated to reduce overheating and it was modelled with IES VE. The real-time data shows that solar shading can significantly reduce the heat gain through the window which lead to reducing overheating. However, the simulated results show a minor impact of solar shading on the internal temperature changes (Venturi, et al., 2018).

2.11 Conclusion and Research Gap

The critical literature review identifies that the UK building stock is one of the highest energy consumers within the UK. With climate change and the new protocols, the UK is moving towards developing Net Zero Energy buildings. In order to achieve that, the energy efficiency of buildings and reducing heat loss during cold seasons should be considered as the initial step. Windows are one of the elements of a building that play an important role in energy loss in cold weather conditions. However, to improve the energy efficiency of buildings, reducing fabric heat loss (which include having better insulation) and reduction in infiltration should be aligned with the solar gain of buildings. In this case, utilising solar shading devices can be the best way to mitigate heat loss while allowing solar gain when it is required.

However, the use of solar shading devices within the UK is lower than in other developed countries and the benefits of shading devices are devalued as the use of solar shading is approached as an optional item for buildings rather than an essential daylight and energy management device. With regards to shading devices, several issues have been identified in this literature review including the lack of recognition of the benefits of solar shading among both building and shading professionals and occupants, lack of sufficient standard shading performance, difficulties during shading retrofit approach and limited inclusion of shading devices in building regulations and environmental schemes. The literature review shows that there is a need to evaluate UK building professionals' and stakeholders’ knowledge regarding solar shading devices and their benefits which can help to identify the building professionals’ knowledge gap on solar shading.

One of the key elements affecting the building regulation and professionals’ knowledge regarding the advantages of shading devices is the results of Building Energy Modelling and Simulation (BEMS) software packages at the early stages of building design. However, the literature review highlighted the discrepancies between the simulated and experimental results which is sometimes referred to as the “Performance Gap”. There are many reasons for this discrepancy, which include errors due to the users' assumptions or due to the software itself. To investigate this, it is important to initially identify the most common BEMS software packages in the UK, then validate their results to highlight the issues especially the insufficient shading input data of the software tools which can cause the devaluing of shading devices in the dynamic thermal models. To validate the BEMS software tools and show the discrepancy, real-time data collection is required for comparison with the dynamic thermal model.

The impact of shading devices on thermal retention has been covered in a few experimental studies, however, most of these research studies have been conducted in a controlled environmental chamber or Hotbox. Insulated internal cellular blinds are one of the most effective window attachments available in the UK market as they can affect both fabric heat loss and ventilation heat loss through the window. As the benefit of using insulated internal cellular blinds on thermal retention within real-time conditions in the UK has not been investigated before, there is a need to show this in this PhD.

Validation of BEMS software tools with real-time data collected from the experimental test will assist in identifying the best software package for thermal retention purposes when using shading devices. This will provide stakeholders and building professionals with robust scientific evidence of the advantages of using shading devices for window insulation and the attention required when modelling shading devices in software tools.

CHAPTER 3

The Status of Shading Devices within the UK Built Environment

3.1 Introduction

Following on from the discussions and statements made within the literature review, utilising shading devices has the potential to be a driving factor in improving energy efficiency in buildings. The use of shading devices as a key component in reducing energy usage for heating and cooling purposes, thermal comfort and reducing glare within buildings is on the rise in Europe. However, the UK is still lagging behind other developed countries in utilising shading devices within buildings despite the known effectiveness of solar shading devices in reducing operational energy consumption within buildings. As discussed in CHAPTER 2, there are several barriers for the UK shading industry that prevent the wider use of shading in the UK built environment. One of the main barriers is the apparent devaluation of the benefits of shading due to the lack of recognition of shading devices by building professionals, building specifiers, stakeholders and even the shading industry itself. This can result in identifying shading devices as an optional item for buildings rather than an essential one (Seguro & Palmer, 2016). This devaluing can impact and influence the decisions at the building design stage even more which may result in costly re-work later on. Consequently, in comparison with other industries related to building such as glazing, insulation material, window frame and building services, it seems that the solar shading industry has been less successful in influencing government legislation and lobbying in general.

To better understand the knowledge and experience of the people working with various shading devices (i.e. blinds and shutters) in both domestic and commercial buildings, a survey regarding shading devices was distributed to relevant professionals. The survey was targeting building specifiers, stakeholders, and shading industry professionals. This Chapter describes the status of shading devices within the UK built environment. In Section 3.2, the distribution and Ethics Approval Letter of the survey are included and in Section 3.3, the qualitative results are analysed and discussed. The last section presents a summary of the chapter.

3.2 Data Collection Method and Survey Distribution

The survey, which can be found in Appendix , was reviewed by the supervisory team who are proficient in this field before being distributed to the external parties. For confidentiality and ethical reasons, the survey responses were collected anonymously. The survey was approved by the London South Bank University Ethics Committee with the approval form available for review in Appendix . In the online survey, the participants were provided with the Information Sheet (Appendix) and Consent Form (Appendix) before starting the questions and the Debriefing Form (Appendix) appeared once the survey was completed at the end.

Before the distribution of the survey, a list of the relevant manufacturers, organisations and individuals were compiled through web-based searches performed and through contacts obtained via previously attended events and conferences. The survey was then presented in an online version using the Qualtrics survey tool to enable distribution to participants around the UK. This research study was undertaken between July 2020 and November 2020. The main focus of this research study was to cover construction sectors including *Building Services Engineering, Facade Engineering, Sustainability Engineering, Architectural Practice, Academia and Research, Manufacturers and retailers*. Several companies and organisations within the building industry were identified and targeted for this data collection. Despite the existence of many organisations and communities for each of the aforementioned groups across the UK, due to the focus of the survey being around participants who are directly linked to the shading industry in some shape or form, this narrows down the participants that were approached to 350. The final number of participants that were contacted for this survey are not considered to cover the full spectrum of all relevant stakeholders but this is the number reached through extensive engagement, networking and recommendations of various groups. It must be noted that although the survey was tailored towards shading products and taking into account the reasons outlined in the literature review stating relatively low levels of engagement and knowledge of these stakeholder groups related to the shading industry in the past, receiving a total of 72 responses exceeded expectations.

Most of the studies conducted that focus on surveys related to shading products, predominantly cover user feedback and not professionals in the building industry or key decision-makers like architects or even academia. For example, a study was conducted by analysing the responses of 50 survey questionnaires received from the building occupants of a university building in Qatar in relation to their perception of thermal comfort levels resulting from the external shading (Al-Mohannadi & Furlan, 2019). Additionally, another survey investigated the factors affecting the occupants' comfort within a residential building in Denmark which received 645 responses (26% response rate) from the occupants themselves (Monika Joanna, et al., 2012).

There have also been studies whereby the survey responses are received from the building industry professionals related to building and construction performance. One recent example was a survey conducted in Russia, regarding the perception of green architecture and constructions in cities with 52 responses (Leontev, 2019) while in another study conducted in 2015, regarding the awareness and barriers of sustainable construction in Kuwait, there were 504 completed questionnaires received and analysed (AlSanad, 2015). A similar study was conducted in 2017 in Cambodia whereby 104 responses were received from architects, engineering and construction professionals (Durdyev, et al., 2018). In 1996, a questionnaire distributed amongst the building industry sector in Hong Kong was completed by 78 participants. The results were used to evaluate construction time performance within the building industry and the reasons behind the delays in construction (Chan & Kumaraswamy, 1996). So based on the various studies, the number of participants can vary but there are very few examples found whereby the focus has been on shading products and the industry professionals' perception and awareness of these products especially in the UK.

Table 4 represents the field of work and years of experience of the participants. To better group and categorise some of the fields together, a reference category is shown below specifying the reference names used throughout this chapter.

Table 4: Participants' field of work and years of experience

Field of work	**Reference Name**	**Frequency**	**Years of experience**	
Building Services Engineering, Facade Engineering and Sustainability Engineering	Building Services	33	Fewer than 5 years	10
			5-10 years	15
			11-20 years	7
			More than 20 years	1
Architectural Practice	Architects	9	Fewer than 5 years	4
			5-10 years	2
			11-20 years	2
			More than 20 years	1
Academia and Research	Academia	11	Fewer than 5 years	4
			5-10 years	3
			11-20 years	3
			More than 20 years	1
Manufacturers and Retailers	Manufacturer	19	Fewer than 5 years	1
			5-10 years	2
			11-20 years	4
			More than 20 years	12
Total		72	Fewer than 5 years	19
			5-10 years	22
			11-20 years	16
			More than 20 years	15

Nearly half of the participants work in the *Building Services Engineering, Facade Engineering and Sustainability Engineering* sectors (Figure 13). More than a quarter of participants are manufacturers/retailers and the rest (about a quarter of participants) work in academia or architecture. It should be noted that despite the pivotal link between the use of shading devices and the role of architects, the number of participants who completed the survey is much lower than expected. As the architects are one of the key decision-makers at the design phase of building projects and can determine the application of shading devices in their design, because the criteria of this survey were to have some level of involvement with shading devices in their projects, only a low number of the responder's considered themselves in this category which will be highlighted in the analysis later.

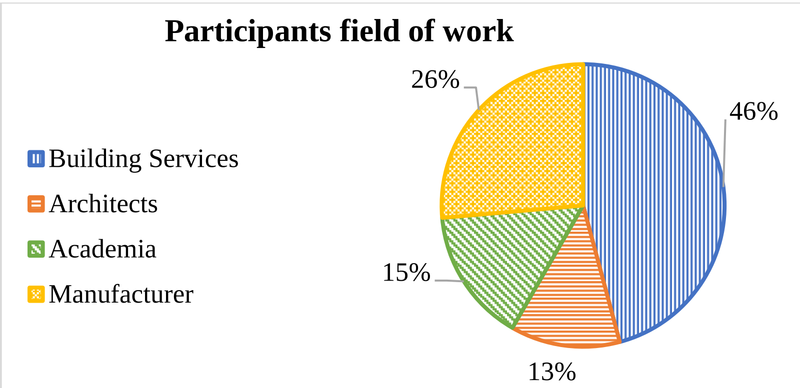

Figure 13:Participants' field of work

Regarding the participants' years of experience, nearly half of the participants who work in building services (45%) have five to ten years of experience whilst 44% of architects have fewer than five years of experience. The majority of the manufacturers (63%) have more than 20 years of experience (Figure 14).

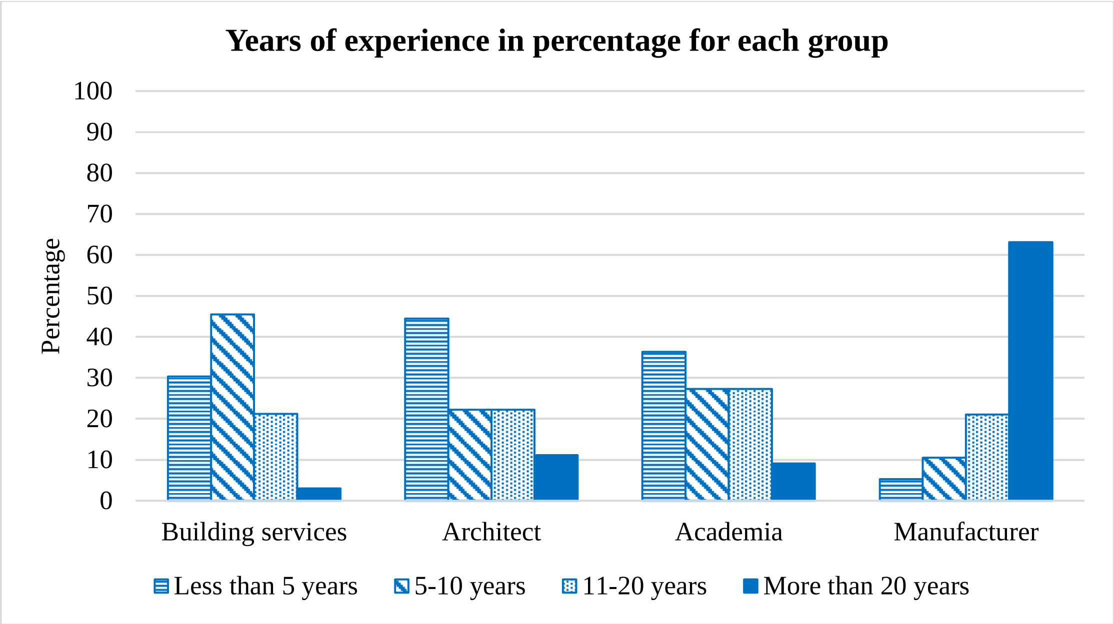

Figure 14: Years of experience in percentage for each group

3.3 Results and Discussion

The results of this survey and the relevant discussions are presented in this section. Each sub-section includes an investigated topic.

3.3.1 Type of shading devices commonly used/designed/installed

The survey options focused on three main types of shading devices; internal, external and interstitial shading. Interstitial shadings are another name for integrated blinds, integral blinds or inter-pane blinds. They are Venetian, roller or pleated blinds sandwiched between two panes of glass in the form of a sealed double glazed unit. The results presented in Figure 15 show that building services engineers and manufacturers have both selected internal and external shading as their main choice (73% and 84%, respectively) while architects and academia have selected external shading more than internal shading. In addition, interstitial shading is the least popular option chosen within all four groups of expertise. This can be due to the difficulty of repair and maintenance of interstitial shading as a result of being fitted within the double-glazed windows which can result in costly repairs as in many cases where access is limited, the whole window will need replacing (Dardalis, 2017). Internal and external shading usage is fairly similar across all groups of expertise with the exception of architects and academics using/designing external shadings more often. This is based on an assumption that architects and academics will not necessarily consider cost when designing, and will base their recommendations on theoretical data whereas the building services engineers and manufacturers are involved more in the practical side of things hence use both types frequently.

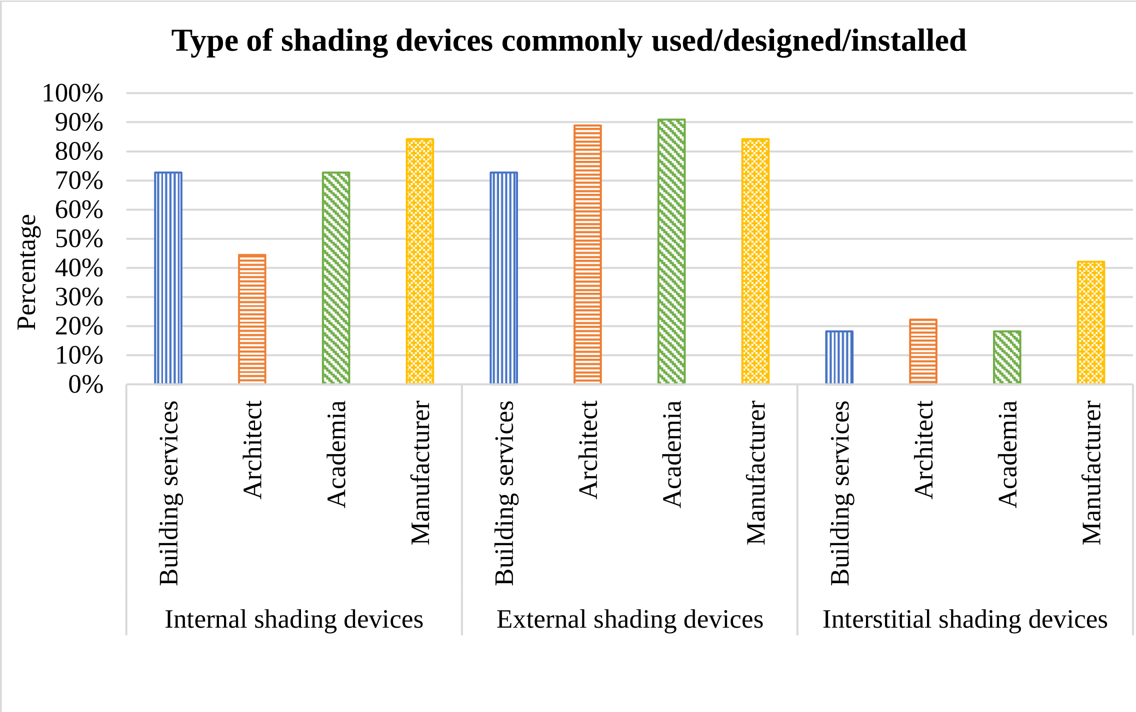

Figure 15: Type of shading devices commonly used/designed/installed

3.3.2 The Frequency of Specifying or Recommending Shading Devices for Buildings/Projects

Summarising the results presented in Figure 16 shows that manual shading is more frequently recommended than all other shading types by all four groups of participants. As this question relates to the final stages of the design for a commissioned project or building, consideration of cost, ease of installation and using known solutions applies even more so this can be a factor in why most groups normally specify the use of manual internal shading compared to other variants. Furthermore, manual shading is more recommended than motorised and automated shading types for both internal and external shadings for all groups excluding manufacturers. This can be due to the cost-effectiveness of using these types of shading and manual variants being quite known and used historically more often in the industry which can result in initial lower overall costs. This is also mentioned in the BRE information paper that motorised shading devices are generally more expensive than manual types (Littlefair, 2017-a). In addition, automated shading types are even more expensive than manual and motorised shading devices as they utilise a complex control system to sustain the constant shifting of shade positions and relevant angles (Yao, et al., 2016). On the other hand, manufacturers recommend automated and motorised shading more than manual shading especially for external shading in comparison with the other three groups of participants. This may be the result of the manufacturers' more in-depth knowledge of the products and technology and better understanding of the benefits of automated and external shadings which can drive a change in the market in terms of industry culture in general towards using more automated solutions which may be more cost-effective in the long run and not so much in the short-term. In some situations where the occupants do not tend to operate the shading devices to their optimal application, having a fully manual operation mode may not be the most energy-efficient solution. This can be due to the fact that the manual mode is quite reliant on human behavioural patterns which aren't necessarily consistent. For instance, some of these inefficient activities can be when, during the day, the shading device is left down whilst having the lights on and also when there is no sun or during the cold season, shading devices are left up during the night. In these circumstances, it is recommended to consider additional automatic control to improve and optimise energy consumption and be less reliant on human intervention which as explained in some circumstances can lead to energy inefficiencies (Littlefair, 2017-a). A BRE study has simulated the energy consumption of heating and cooling purposes in a UK office when comparing the use of internal manual blinds and automated variants with a manual override. The results showed that the automated blind control provided significant heating and cooling energy savings where in southern England the total energy consumption was about 3% lower when using automated shading control (Littlefair, et al., 2010). Based on the studies' findings, it's evident that using adaptive controls has the potential to be a more widely used option in buildings within the near future as the system can learn from occupant overrides to establish individual users' preferences which will reduce the use of manual control even more (Littlefair, 2017-

a; Gunay, et al., 2014; Gunay, et al., 2017). Regarding selecting external shading, although all types of shading devices are effective in reducing heat gain and glare to some extent, external shading is usually more effective than internal shading (Littlefair, 2018). As the industry becomes more aware of the benefits of shading in relation to thermal retention, they may tend to recommend internal shading more than external shading.

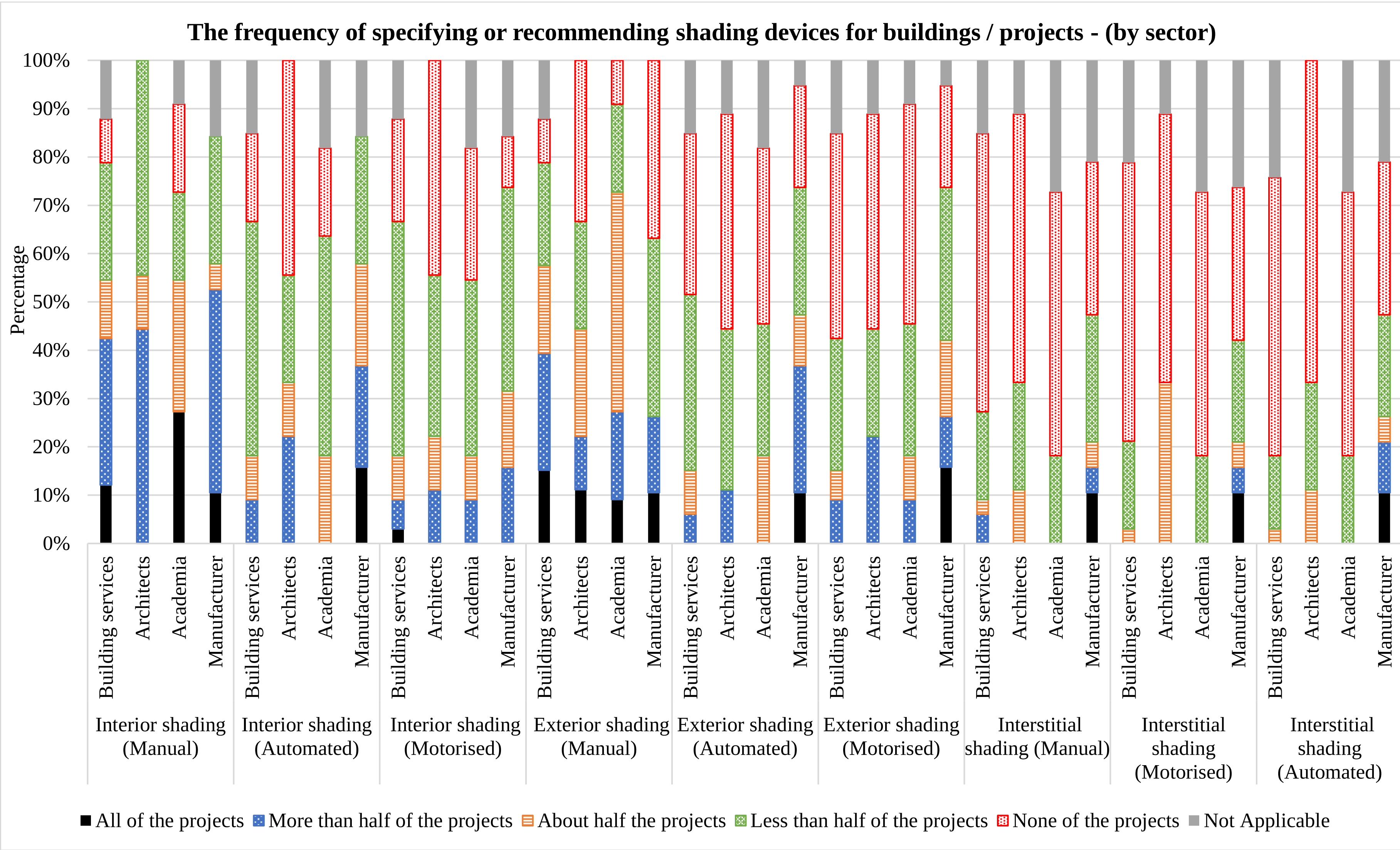

Figure 16: The frequency of specifying or recommending shading devices for buildings/projects - (by sector)

3.3.3 Reasons that Shading Devices are Installed in Buildings

More than 70% of participants in each sector have selected external shading as an energy-saving method for cooling and reducing overheating. This is in line with recent research studies and technical reports within the industry that external shading is more effective in reducing excess solar gain by preventing sunlight from reaching the window (Zero Carbon Hub, 2015; Littlefair, 2018). In contrast, the effect of shading devices in reducing heat loss is less recognised in all four groups of participants compared to the impact on reducing overheating. This may be down to the perception of shading being predominantly used for tackling overheating and historically shading being more widely used in warmer climates (Dwyer, 2018; MakeMyBlinds, 2018). Based on the responses received, it is the participants' thinking and perception that internal shading is more effective in reducing heat loss which is in line with the general industry expectations and studies.

More than 70% of participants have selected internal shading for providing privacy whereas for security there seems to be more of a mix and a shift to external shading by some groups. This can be based on privacy being considered as more of an internal/visual issue whereby internal shading has more flexibility to adjust whereas security is more subjective. Architects and academia perceive external shading as an external deterrent for security breaches whereas building services and manufacturing that are more involved in the practical side of the industry seem to consider all types of shading as having the potential to provide more security.

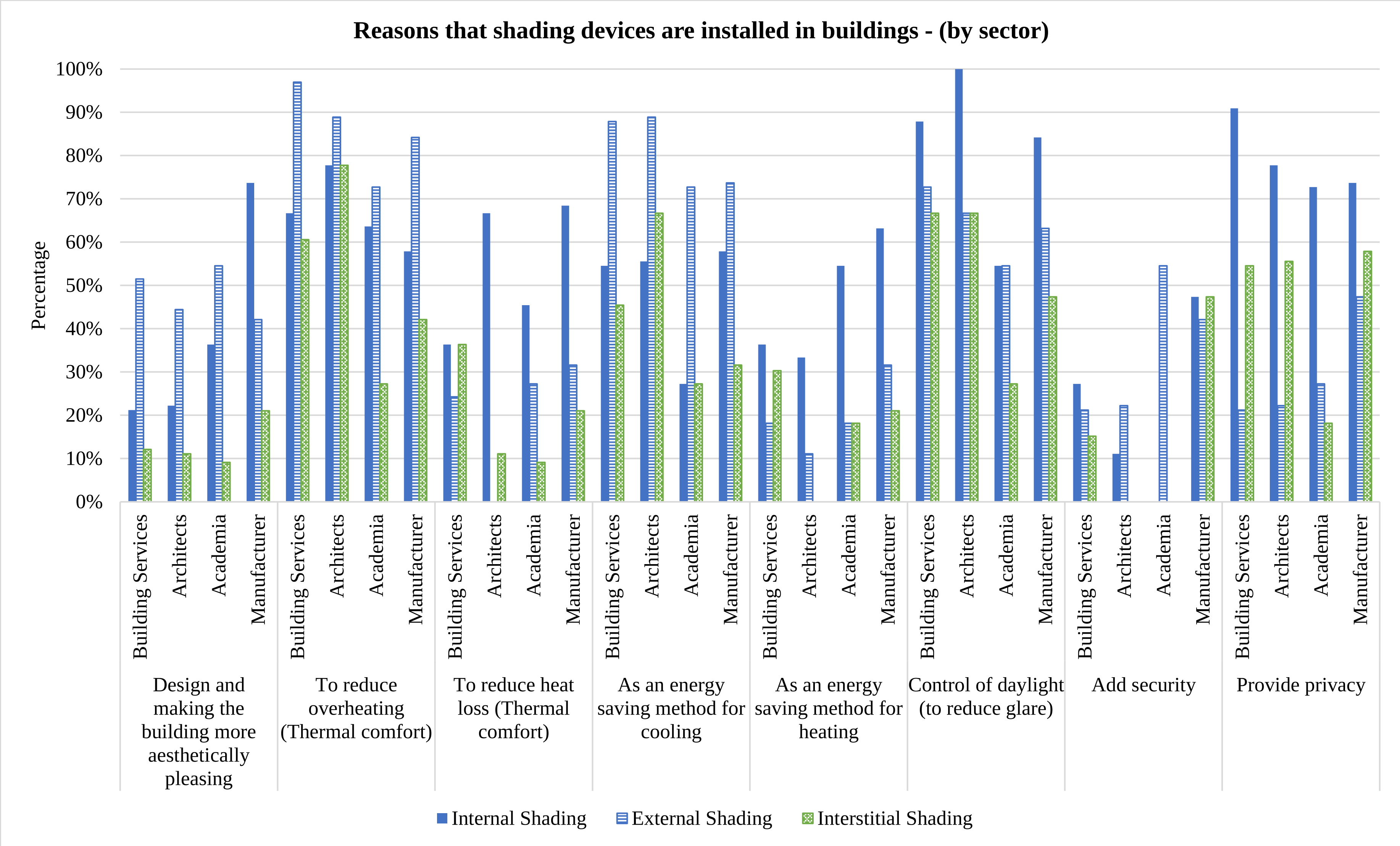

Figure 17: Reasons that shading devices are installed in buildings - (by sector)

3.3.4 Increase or decrease in the use of shading devices during the past 5 years

There is a clear trend and pattern within the results of this survey showing a perception that the use of motorised and automated shading has seen an increase in the past five years for all three types (internal, external and interstitial) of shading, especially for internal and external shading. Whereas manual variants have been quite stable or seen a slight decline in their use. This can be attributed to a shift in the industry and market towards smart buildings and consumers' desire to have more automated / digitalised solutions for ease of use and flexibility. It is important to note that this shift is also a result of the desire to implement more energy-efficient solutions as part of the Net Zero Energy Building initiative as studies have shown that occupants tend to adjust manual blinds less frequently than motorised/automated variants which will result in inefficiencies whereas modern facilities can adjust heating, cooling and lighting in a more digitalised manner which can maximise the energy efficiency in buildings. For example, research studies conducted by BRE shows that occupants alter their manual blinds once every three days on average (Littlefair, 2017-a). Another study in Switzerland found similar results as people alter their manual blinds an average of 1.74 times per week (Paule, et al., 2015) whilst a study conducted in France, concluded that occupants operate motorised blinds three times more than manual blinds which mean people are more willing to alter their blinds and shading devices if they are easier to operate (Sutter, et al., 2006).

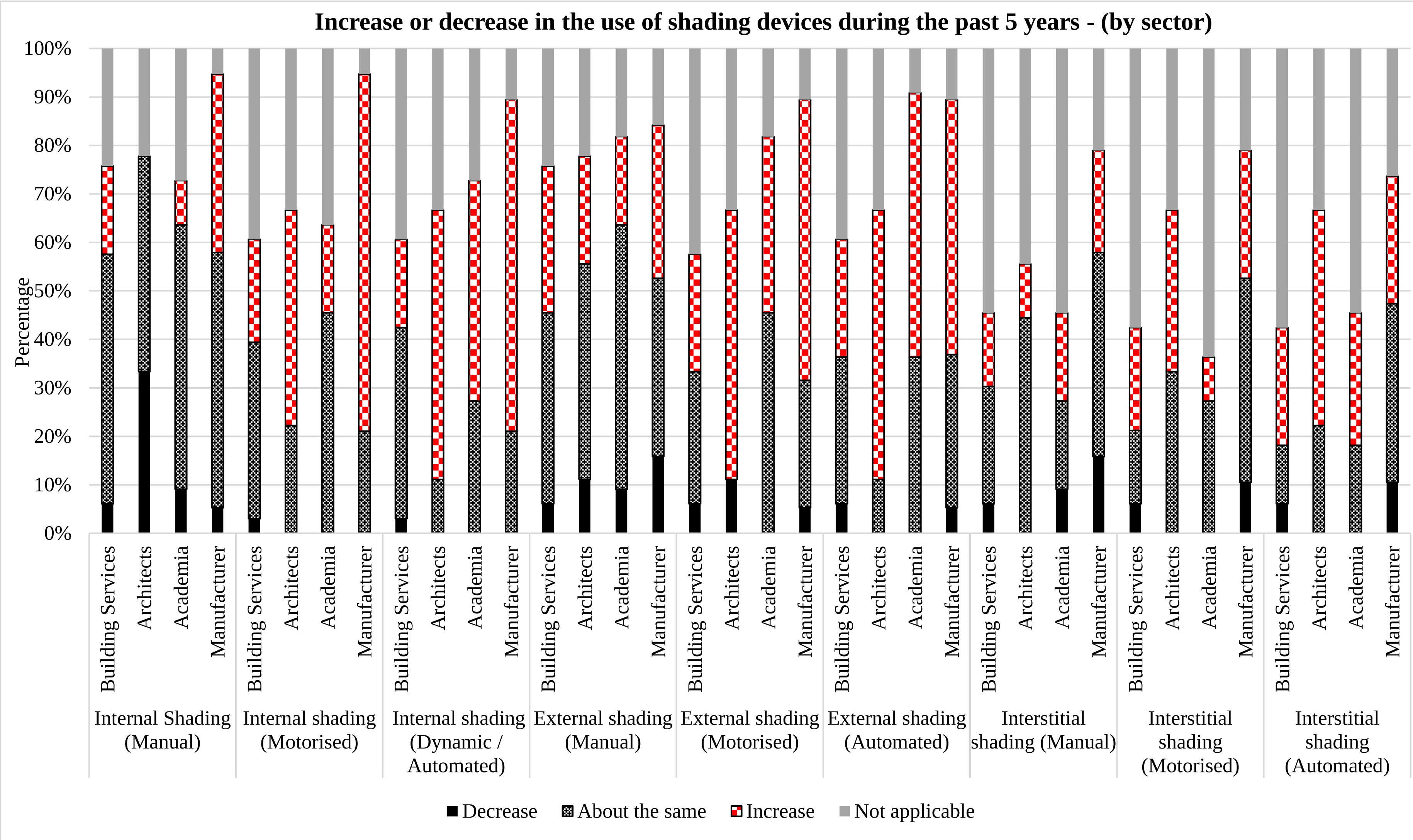

Figure 18: Increase or decrease in the use of shading devices in the past 5 years by sectors

3.3.4.1 Reasons for the Increase in Using Shading Devices

Following Section 3.3.4 regarding the increase in using shading devices, the reasons for this are investigated further in this section. The results show that while the effect of shading devices in reducing overheating is the most selected (two-thirds) reason for increasing the use of shading devices, the effect of shading in reducing heat loss and also changes in regulations are the least selected (fewer than 17%) reasons. This is in line with the current thinking and the same reasons mentioned previously meaning a potential gap in understanding the general benefits of shading in reducing heat loss and the perception that shading devices were used historically in warmer climates for cooling purposes.

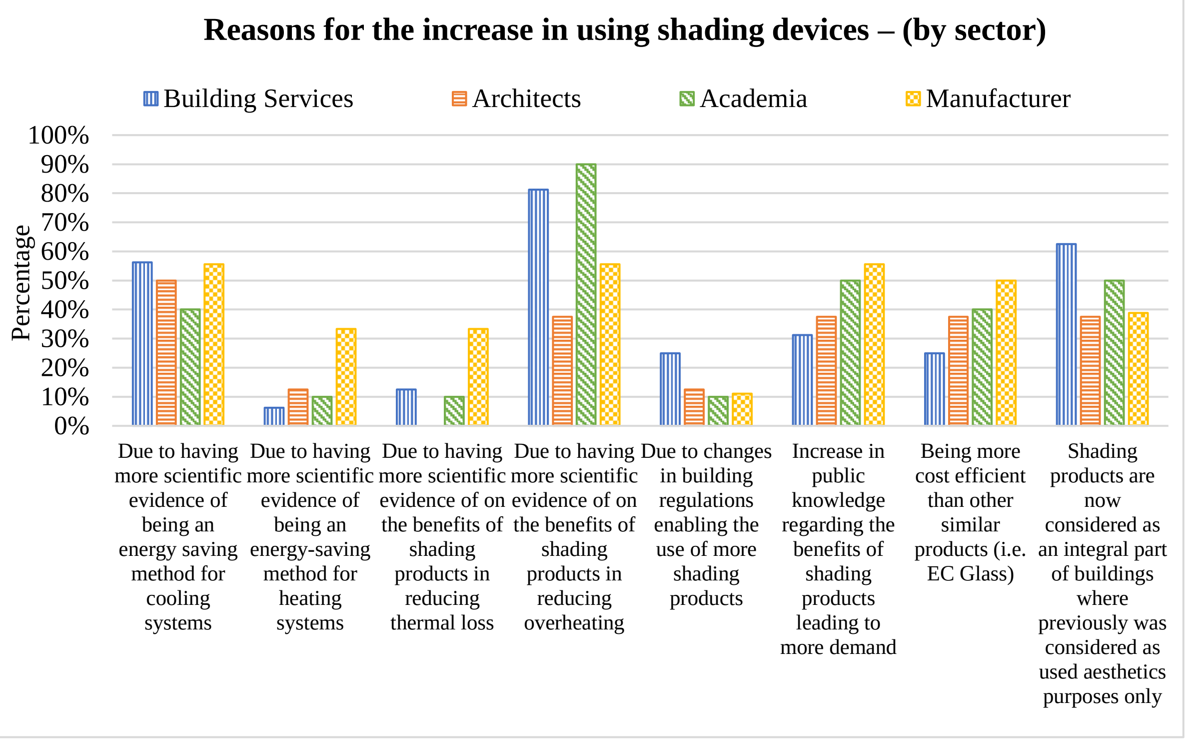

Figure 19: Reasons for the increase in using shading devices – (by sector)

3.3.4.2 Reasons for the decrease in using shading devices

Regarding the reasons for the decrease in the use of shading devices (following Section 3.3.4.2), all of academia and 83% of manufacturers believe that having more innovative products such as EC glazing, kinetic, intelligent façade etc on the market is the reason for the decrease in the use of shading devices which can be linked to a perception amongst engineers that these methods use more advanced technology and can have more of an appeal to the public. This can also be due to manufacturers being more aware of the competing technology markets as they need to be up to date with the latest innovations and academics who are more research-based are always assessing new and upcoming technologies, so they have selected this option more than the other groups. Furthermore, more than 50% of architects and building services engineers believe that shading devices are less cost-efficient compared to other similar products (i.e. EC Glass) but only 17% of manufacturers think this way. This means that architects and building services engineers may tend to use EC glass more than shading devices but as manufacturers have more up to date practical knowledge in this area and maybe as the EC glass development is seen as direct competition to the shading manufacturers business, they prefer shading over other solutions. Another factor specifically highlighted by the building services engineers that they believe have contributed to this decrease, is the public's desire to have more open and less obstructive views in buildings. Ultimately these contradicting opinions from key stakeholders in the industry can also be a factor in the decrease and decline of shading device use consequently showcasing the benefits of shading devices amongst broader groups and not just manufacturers can potentially assist in these conflicting situations.

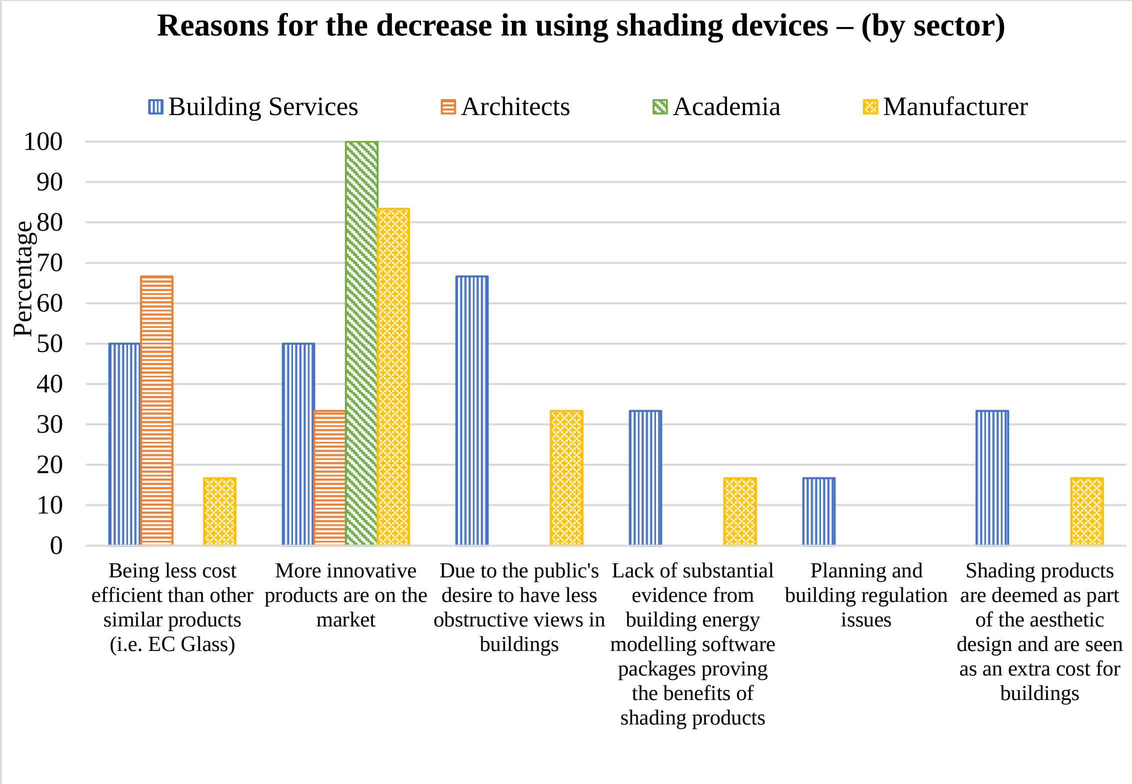

Figure 20: Reasons for the decrease in using shading devices-(by sector)

Regarding the innovative products in the market which have influenced the potential decline in the use of solar shading devices, from ten participants who have selected this option, it is observed that only one-fifth of manufacturers think EC glazing is being used more than shading, whilst all of the other three groups think that EC glazing is being used a lot more frequently than shading devices and is a contributor to the decline in shading device use. Manufacturers being the only group that does not agree with this line of thought may be attributed to the fact that they are directly competing with EC glazing and don't believe that they're as frequently used as shading devices.

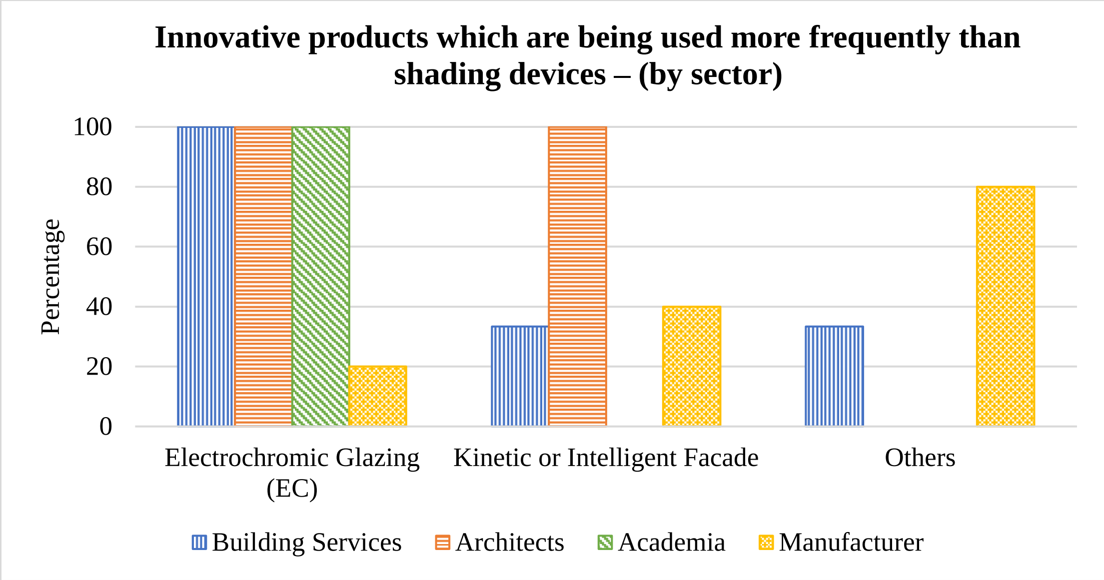

Figure 21: Innovative products which are being used more frequently than shading devices - (by sector)

In this section, three participants, who are all working as manufacturers, have stated "any other types of innovative products" which have not been included in the options. One of the participants is of the opinion that high-performance glasses, in general, is being more frequently used in buildings in comparison with shading devices. Two other participants believe that motorised and automated devices are being used more frequently compared to manual products: "*Clients are more aware of the benefits of motorised and automated shading, being not only more convenient but more efficient at controlling solar heat gain and glare*". This is in line with the results provided in Sections 3.3.2 and 3.3.4 as motorised and automated shading devices are being more used in recent years. Also, this statement highlights that the participant is only paying attention to reducing solar gain and glare, not the benefits of thermal retention of shading devices which are discussed in more detail in Sections 3.3.3 and 3.3.6.

3.3.5 Impact of local planning and building regulations on the use of shading devices over the past 5 years

The results based on the field of expertise (Figure 22) show that participants who are aware of changes due to planning and regulations put in place in the past five years believe that external shading has been influenced more by these regulations compared to internal and interstitial shading devices. Manufacturers and academia believe that local planning and building regulations had significantly affected interstitial shading, but the other two groups do not agree whilst most of the participants believe that interstitial shading was not affected at all. Regarding internal shading, the majority of all groups believe that building regulations have little or no impact on internal shading. The perception that planning and building regulations have more impact on external shading than internal shading can potentially be attributed to the results seen previously in Section 3.3.4 whereby the consensus by the participants was that in the past five years there has been a steady increase in using external shading devices which can mean more activity and consequently more regulation and planning imposed compared to internal shading which has its use be quite stable or seen a slight decrease, this may be an indication of a shift in focus within the industry to external shading applications.

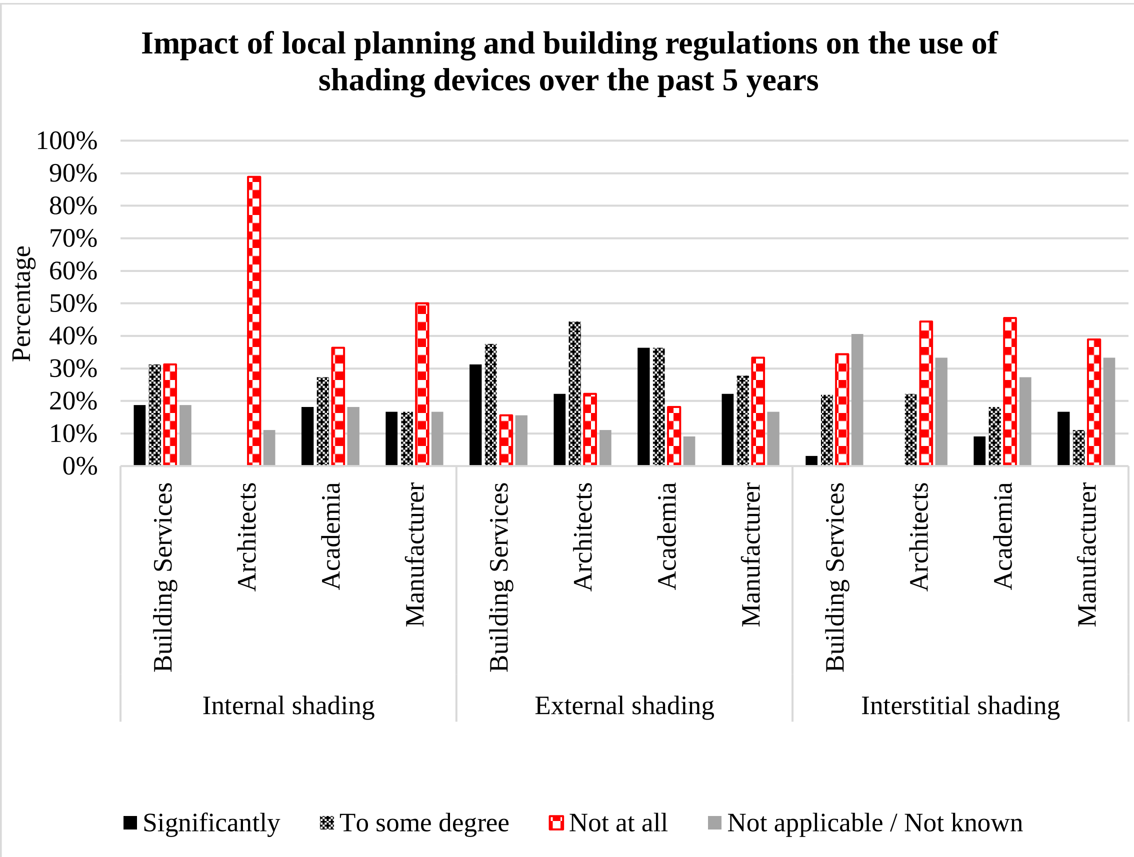

Figure 22: Impact of local planning and building regulations on the use of shading devices over the past 5 years

3.3.6 Areas of performance data that assist in specifying shading devices

When specifying a shading device for a building, it is important to know the performance data of the proposed device. Taking into account performance data is vital because lack of consideration can result in use of incorrectly specified shading devices and consequently inefficiencies in the building and potential re-work later on. The graph in Figure 23 illustrates that in this survey all four groups use the performance data in a fairly similar way. It is clear that solar gain (g_{tot}) and visual comfort (T_v) are the main areas that the groups use to specify shading whereas U-values which are related to heat loss is lagging behind these two areas. This again re-iterates the perception within the different sectors that blinds are mainly beneficial for reducing overheating and occupants' visual comfort than having an impact in reducing heat loss. T_{uv} is the least selected performance data by three groups but 72% of manufacturers have selected it which means UV control is mostly recognised within the manufacturers' sector. As UV control in most cases does not have a direct impact on temperature and energy consumption, the building professionals (excluding shading manufacturers) do not value this performance data as much as others. This is in line with the more in-depth knowledge of manufacturers and their specific attention to detail when specifying a product which links quite closely to a statement provided by one of the participants of this survey working as a manufacturer, explaining their thoughts on why manufacturers have selected the different performance data options more than the other groups:

"Every environment/ building is different. Buildings have different exposure to direct sunlight or reflected sunlight and all of the above data performances must be taken into consideration. In addition, you will need to understand what the space is used for, what interior will be fitted and what will be the building sustainability targets, following that you can then put forward the ideal shading solution products".

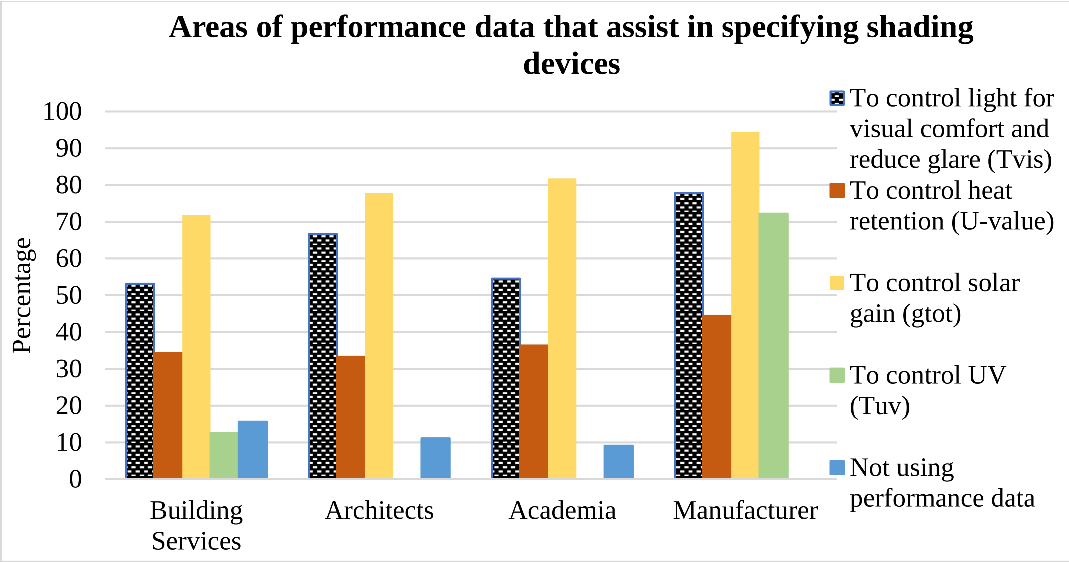

Figure 23: Areas of performance data that assist in specifying shading devices

3.3.7 Source of shading device performance/design data

It was observed that 81% of participants who use performance data (50 out of the 62 participants) get their data from manufacturers' data or company catalogues whilst 39% of them get the performance data from modelling software tools. Fewer than 20% of them use the European Solar Shading Database and other resources. This highlights the importance of the results of modelling and simulation software tools when using shading devices in buildings.

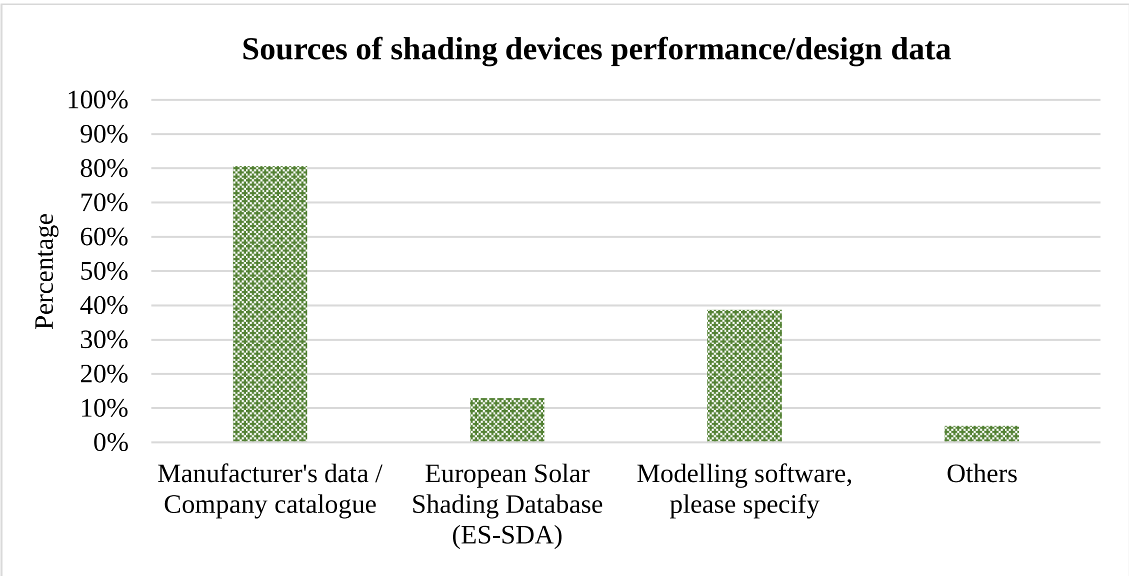

Figure 24: Sources of shading device performance/design data

The software tools which are used by the participants (who use modelling software tools for obtaining shading performance data) are represented in Figure 25. IES VE is the most popular software for retrieving the shading performance data as 50% of them rely on these software packages. Energy Plus (18%), EDSL Tas (9%) and DesignBuilder are also common in this area. Other software tools which are stated by participants are either static software or bug software for EnergyPlus. These software tools are Rhino 3d, Grasshopper, lBNL Window, Optics and Radiance.

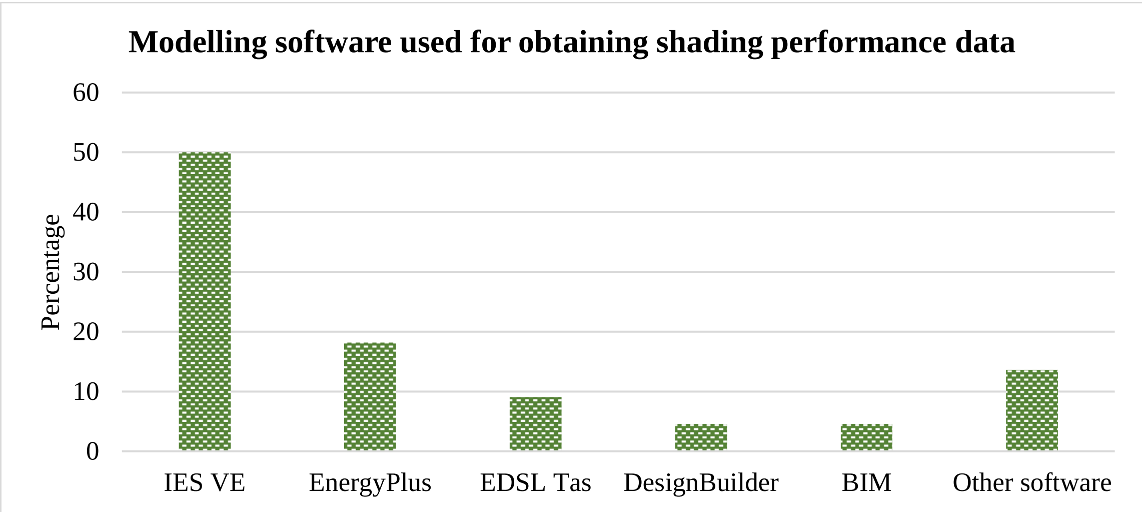

Figure 25:Modelling software used for obtaining shading performance data

3.3.8 Comparison of shading devices with high specification glass, air-conditioning or heating

This section highlights the differences between the key performance indicators of shading devices and other alternative methods such as the use of high specification glass, air-conditioning and heating.

3.3.8.1 Energy saving comparison

Figure 26 demonstrates that architects have performed this comparison less frequently than the other three groups (only 22% for each queried comparison) whilst 45% of academia have gone through this comparison for cooling systems and fewer than 10% for the other two comparisons. Building services and manufacturers are two groups that have performed a comparison for all three options more frequently than the other groups.

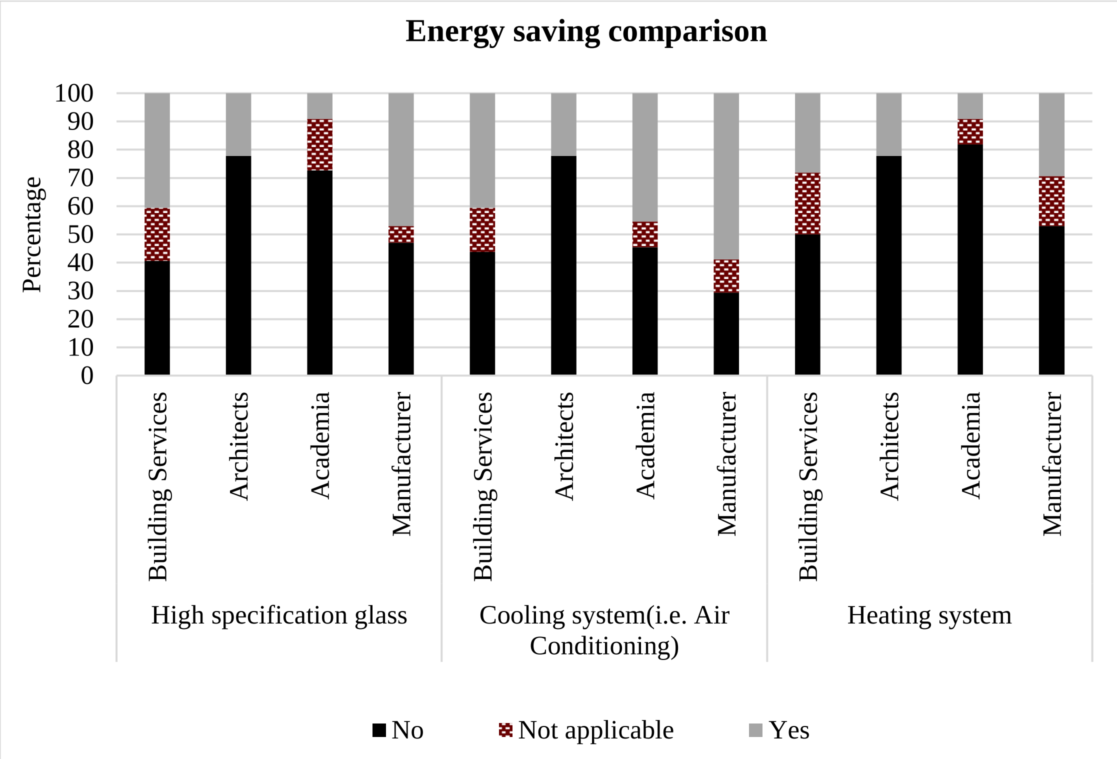

Figure 26: Energy saving comparison

3.3.8.2 Carbon reduction comparison

More than half of the participants have never compared the carbon reduction of shading with "high specification glass", "air-conditioning" or "heating" to demonstrate the benefit of shading devices.Whilst 36% have performed this comparison with cooling systems, 30% with high specification glass and 23% with the heating system.

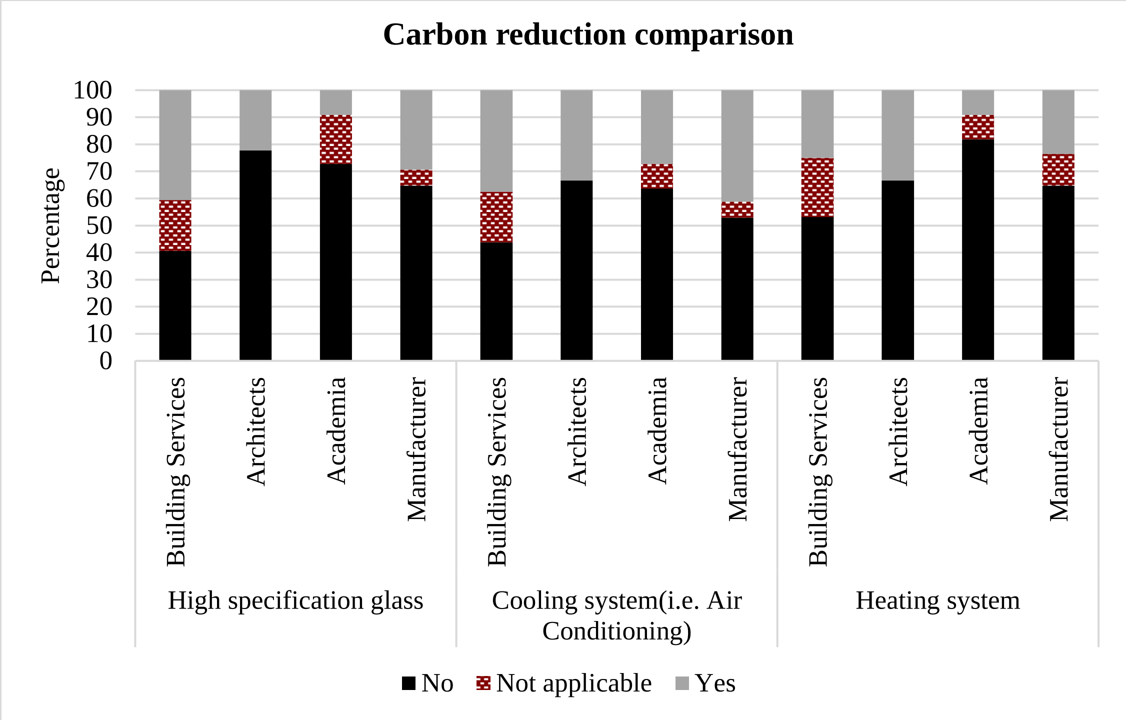

Figure 27: Carbon reduction comparison

3.3.8.3 Information used to perform this comparison

For those participants who had compared energy cost savings and carbon reduction effects of shading with "high specification glass", "air-conditioning" or "heating" to demonstrate the benefit of shading devices, the majority (69%) of participants use software/simulation tools to compare the impact of shading devices with other methods. This shows the modelling software packages are one of the main source tools for the different sectors which re-iterates the need to assess these software packages in more detail.

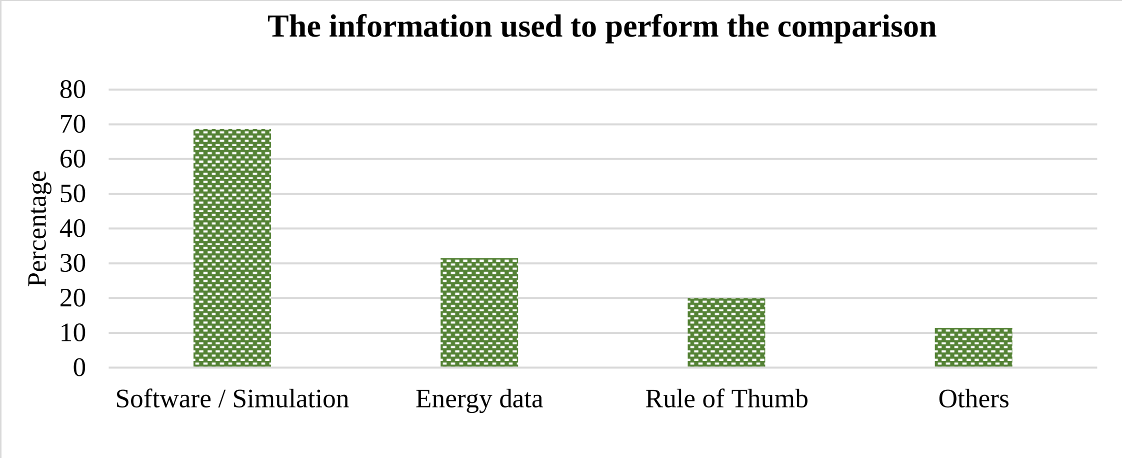

Figure 28:The information used to perform the comparison

Furthermore, IES VE, EnergyPlus and EDSL Tas are more widely used than the other software packages so a particular focus on them is vital.

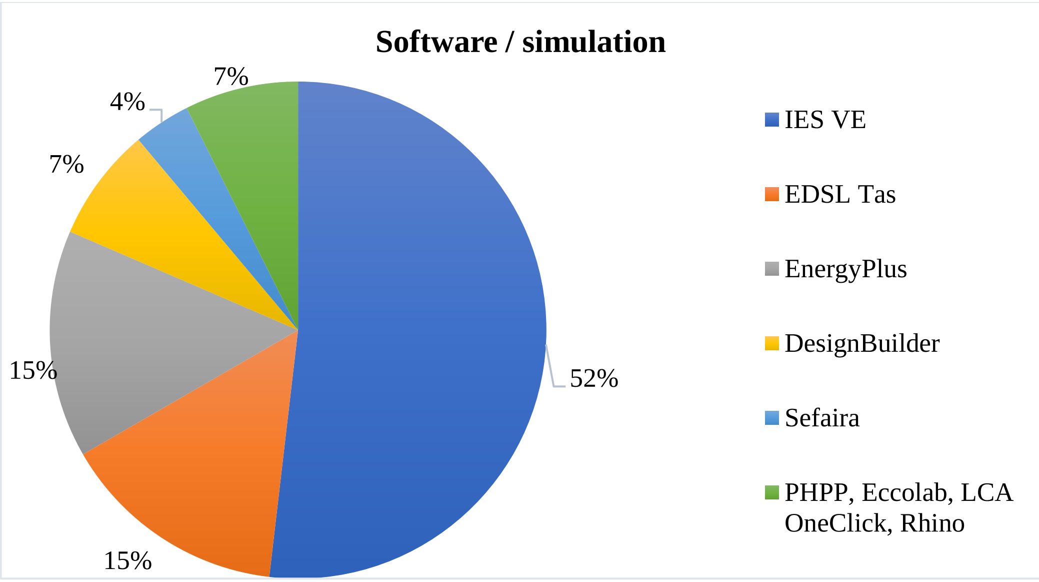

Figure 29:Software / Simulation

3.3.9 Additional Participant Feedback for the Shading Industry

At the end of the survey, participants were asked to provide their feedback for the industry (Table 5). Reviewing the comments shows that the focus when using shading devices is mainly on reducing solar gain as was argued throughout this chapter. From the comment provided by participant number 3 (Building Services Engineer), it is evident that they believe that architects are at the forefront of the decisions being made related to the design of the building which includes the application of shading devices. In contrast, building services engineers will only use the confirmed design from the architects at a later stage for either compliance modelling (building regulations) or heat gain calculations and they are rarely directly engaged with shading manufacturers. Participant number 5 (Building Services Engineer) stated what has already been emphasised in this chapter, i.e. that specifying shading devices should be considered in the early stages of the design rather than being postponed to when the building is completed. Therefore it is also the responsibility of the architects to consider shading devices at the early stages of the design and before planning permission is granted.

Despite the fact that most groups highlighted and emphasised the importance of architects' knowledge and interest regarding the use of shading devices in buildings, unfortunately, most of the architects who were requested to complete this survey did not go on to complete it because the criteria for participating in this survey was being involved with shading devices in their projects. This is a key point as it potentially highlights the broken link between shading topics, their application and how they're perceived with the very individuals who have a say in how they're used and implemented within buildings at the design phase.

Table 5: Participant feedback for the shading industry

ID	Field of Expertise	Feedback/Comments
1	Manufacturer	The understanding of shading is far more prevalent across the rest of Europe compared to the UK with Architects continually designing glazed buildings without proper consultation regarding solar gain.
2	Architectural Practice	There needs to be a real drive to persuade clients and developers of the benefits of **external shading** in **reducing the risk of overheating** in **new**

		homes (as well as commercial buildings). For the most part, I see external shading used quite frequently in commercial buildings, but its use is not yet commonplace in housebuilding. Given the extent to which we already know that new housing is overheating in the current climate, there needs to be a focused effort to see shading become a key architectural feature in new homes.
3	Building Services	Whenever I think of external shade - I always think... ok **the form will generally come from the architect -** and I will use this as a basis to model in the IES model for either compliance modelling (building regulations) or heat gain calculations. **I have never actually engaged (as a mechanical engineer) with a shading product manufacturer**.
4	Building Services	Coming from a warm country, I am aware of the importance of **external shading**. In the UK people still have to face a change in perception of this, as they mainly consider balconies for this option, rather than external blinds. As the climate changes, this perception will probably modify as well, but not sure if fast enough. Although engineers can suggest introducing shading, this **is mainly down to architects and clients**, so still a tough battle for us.
5	Building Services	The introduction of overheating risk analyses as part of the planning process would make a huge difference (eg CIBSE TM52 & TM59). Many buildings suffer from **overheating** issues due to excessive glazing, ill-conceived shading strategies or no shading at all. All too often these are addressed as retrospective problems, using fans, air-conditioning and solar films etc, when a far superior solution could be achieved if the issue were given more thought. **Once the aesthetic of the building is granted planning permission, the ability to introduce shading measures is**

reduced, so it must be accounted for before planning permission is granted.

3.4 Conclusion

The UK built environment professionals are predominantly aware of the impact of shading in reducing overheating however, they seem to lack up to date knowledge regarding the benefits of shading devices with regards to reducing heat loss in buildings. Considering the predominantly cold weather in the UK and the impact of climate change which is introducing extremes of colder and warmer weather, it is important to insulate windows as well as the other parts of the buildings. So, educating the professionals and building specifiers regarding this matter can be the initial step to enhance the energy efficiency level of buildings both in new buildings and retrofitted projects. Building energy modelling software tools also play an important role in specifying shading devices in a building especially during the early stages of the building design. So, investigating and evaluating the dynamic thermal models generated within these software tools should be considered to eliminate potential errors as a result of discrepancies between the real-world data and simulated results which has been highlighted in previous research studies (Dronkelaar, et al., 2016; Venturi, et al., 2018; Mantesi, et al., 2018).

Reviewing the thoughts of industry professionals across the board, it is clear that more focus and effort is needed in bridging the gap in understanding and perception of the impact of shading devices on heat loss especially at the early stages of the design so it is embedded in the process itself and not an afterthought. At the heart of this, is the detailed understanding of the complete portfolio of shading devices and their operational modes to ensure the most suitable is selected so knowing the application of the various types of shading is also a key factor in having a more widespread appreciation and ultimately use of shading devices in buildings. In addition to ensuring a better understanding of shading devices, this study has highlighted that the reliability of the modelling software tools that can enable building designers and specifiers to utilise shading devices more regularly needs to be assessed and improved. Increasing the reliability of the modelling software database and values, with less discrepancy between the software values and real-world data, will increase confidence in their use and similarly more accurate tools will ensure a more appropriate selection of shading devices. This illustrates the need for further analysis and studies into the performance of software modelling packages and real-world tests to verify and validate the software tools. Furthermore, a key takeaway from the results is the ability of the shading industry to compete and keep up with the latest innovations and technology will also determine its presence in the market especially as we move towards a more digitalised approach in buildings and how the public is shifting towards smarter methods then its vital that the shading industry moves with the times and does not lag in this area.

As the final point, it is vital to focus on educating and enhancing the interest of architects regarding the use of shading devices in buildings as their decisions in the early stages of the design can play a significant role in correctly specification of shading devices in buildings. From this survey, it was seen that architects are not really involved within the shading industry and they either have no knowledge or interest in this area as most of the architects who did not complete the survey did not meet the criteria for participation which involved use of shading devices in their projects.

3.5 Summary

This chapter outlined the data collection method to investigate the status of shading devices within the UK built environment. The survey was completed by 72 individuals including building professionals and other relevant stakeholders. The results of the survey were discussed in this chapter and the main findings are listed below:

- Internal and external shading is still quite commonly used but there is a shift towards increased use of motorised and automated variants
- The beneficial impact of adding shading devices in buildings in terms of reducing the risk of overheating and consequently, reducing energy consumption required for cooling and improving thermal comfort due to reducing the high temperature, were known by all groups of participants. However, the impact of shading devices on reducing heat loss which results

in lower heating energy required and improved thermal comfort was not known by building professionals and stakeholders within the UK.

- Building energy simulation software tools' results illustrate the important role they play within the industry by having a direct impact on how and where to utilise shading devices in buildings. This highlights the importance of accuracy and validation of the results of these software packages when modelling the shading devices. The most common software tools in the UK for this purpose are IES VE, EnergyPlus, EDSL Tas and DesignBuilder.

CHAPTER 4

Measuring the Thermal Retention Effect of an Insulated Blind in a Real-World Building

4.1 Introduction

The effect of internal shading devices on the window heat transfer process has been investigated predominantly in dynamic thermal models or hotbox experimental chambers within a completely controlled environment. As discussed in the literature review, hotbox tests are not a true representation of real-world conditions i.e. variable weather conditions. In addition, various discrepancies have been found in the results of research conducted in the past when comparing dynamic thermal model tests and real-world data (Venturi, et al., 2018). This is because many factors can affect the building performance and its heat transfer such as uncontrolled weather conditions and the use of different materials. Attempting to replicate real-world conditions can pose its own challenges as the installation of the test equipment within the real-world setup can be difficult and finding suitable equipment and buildings can be both challenging and expensive. Furthermore, specifying the correct shading type and method of installation of the shading devices should be considered to achieve the optimal results.

This research project aims to investigate the effect of having an internal sealed and non-sealed cellular blind on window heat transfer within real buildings which are assessed in two separate case studies. The initial case study was conducted in a conservatory within a domestic building located in London and real-time data were collected from September 2019 to March 2020. For the second case study, an office room within the London South Bank University building was selected and real-time data were collected during the heating season in March 2021 for the duration of 22 nights.

This chapter contains two main sections including the two case studies. Each section begins by describing the test rooms, their locations, geometries, constructions and modifications applied to the rooms. It also includes the air leakage test conducted for the second case study according to the requirements of ATTMA (Section 4.3). In Sections 4.3.2 and 4.2.3, the methodologies are outlined whilst Sections 4.2.4 and 4.3.3 describe the equipment used for measuring internal parameters such as temperature, heat flux, energy consumption and external weather condition. Sections 4.3.4 and 4.3.4 relate to the results and discussion and Sections 4.5 and 4.5 provide a conclusion and a summary of this chapter.

4.2 Case Study 1: Non-sealed Blind

This section covers descriptions of the test location, geometry, construction, methodology and results of the real-time data collection test conducted within a conservatory.

4.2.1 Project Description

4.2.1.1 Site and Location

A north facing conservatory (Figure 30) within a domestic building in Holborn, London (51°31′22.6″N, 0°06′56.8″W) was selected to conduct the thermal retention test over the winter period 2019 to 2020. Due to the lack of insulation, north-facing orientation (345º) and reduced solar irradiance because of the surrounding buildings, the conservatory experienced quite low temperatures during the cold months.

Figure 30: Conservatory within a domestic building

4.2.2 Layout and Construction

Figure 31 shows the conservatory layout from the top and side views. The 3.2 m walls were adjacent, and the 10.4 m wall and the glazing area were exposed. There was a utility room inside the conservatory which the occupant used every month but the rest of the time, its door was closed.

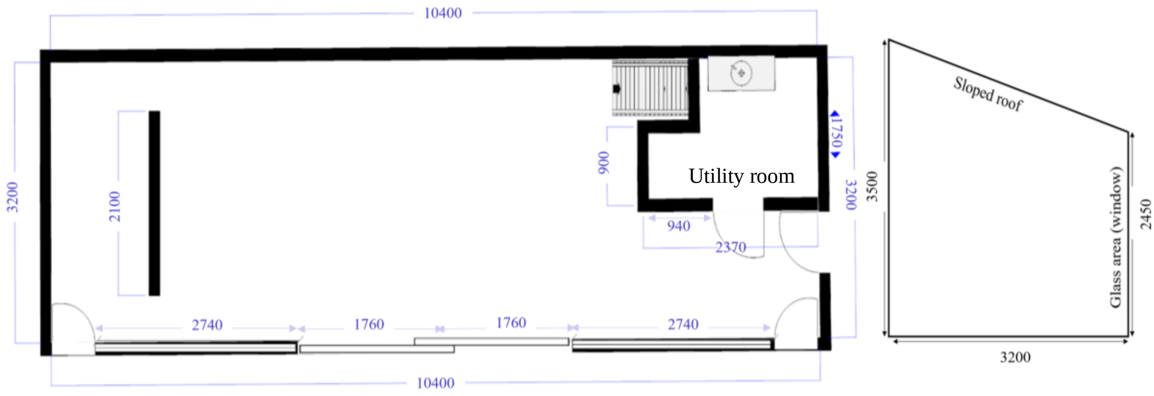

Figure 31: Conservatory layout (mm)(Layout on the left is showing the top view and on the right, showing the side view)

The conservatory was added to the main building in 1998 and the construction report including the layout was provided by the occupant but missing data were estimated through observation. The sloped roof of the conservatory was made from clear 5-wall Thermoclear (polycarbonate) with 20mm thickness. The Thermoclear sheets were connected with non-insulated aluminium frames. The closest specification of the Thermoclear was taken from a similar product manufactured by LEXAN according to the product specifications, the U-value of this product was 1.69 (W/m^2K), the light transmission (T_v) and shading coefficient (SC) of this product was 58% and 0.76, respectively. Although the low U-value of this product makes it beneficial in reducing heat loss, in terms of solar gain during winter it is considered a drawback. The orientation and location of this conservatory already reduced the amount of solar gain which with the addition of the Thermoclear roof, the heat gain during the day (during colder seasons) was very low. From a lighting perspective, having 58% light transmission and 0.76 shading coefficient, the conservatory received adequate light. Based on BRE guidelines, the Average Daylight Factor (ADF) is defined as "the ratio of total daylight flux incident upon the working plane, expressed as a percentage of the outdoor luminance on a horizontal plane due to an unobstructed CIE Standard Overcast Sky" (Littlefair, 2011). So, based on the equation below, daylight factor and illuminance in a room has a direct relationship with the light transmission (T_v):

$$ADF = \frac{TM_f A_g\, \theta}{A(1-R^2)}\ \% \qquad \text{Eq 4-1}$$

Where T_v is light transmittance, M_f is the maintenance factor which includes the effect of dirt on the surface, A_g is the glazed area, θ is the light angle, A is the total room surface area and R is reflectance (Littlefair, 2011). Considering 58% light transmission and the dirt factor of the Thermoclear (as this conservatory was built 22 years ago), receiving lower internal illuminance compared to the external illuminance was expected.

The exposed wall was a non-insulated double brick wall with the U-value of 1.92 (W/m^2K) and the adjacent walls were non-insulated single brick. The suspended floor was covered by timber (4cm thickness) with an average of a 15cm air gap to the ground. The lack of insulation and 1-2mm gaps between each timber increase the infiltration rate in the conservatory. The north faced glazed part of the conservatory was made from two hinged doors at the ends, two sliding doors in the middle and two fixed glass panels, all single glazed with 10 mm thickness (Figure 32).

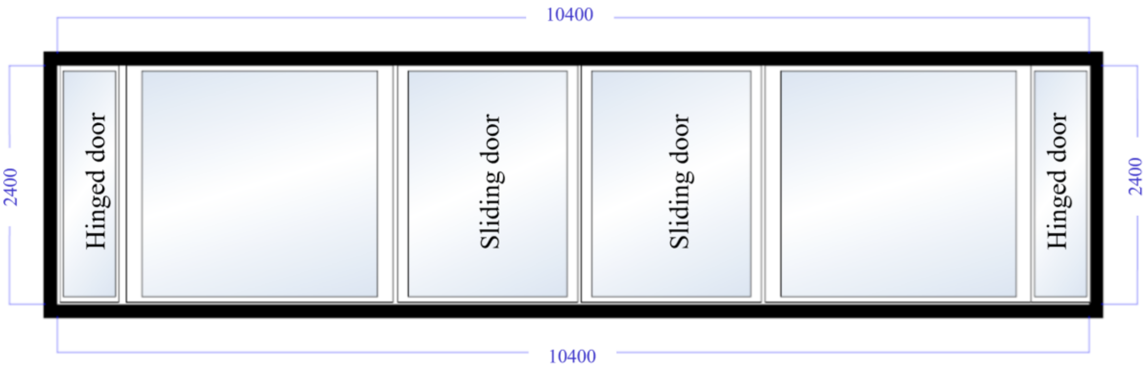

Figure 32: Glazed area of the conservatory (mm)

The frame of the glazing area was a non-insulated metal (steel) frame with a U-value of 6.9 (W/m^{2}K) (CIBSE, 2019) but the panels of the glass itself had no specific frame. There was only a layer of plastic in the gap between the hinged door, the fixed glass and between the sliding doors. However, this was not sufficient as the doors were never completely sealed/closed which caused higher infiltration and air change on an hourly basis. Furthermore, instead of a handle, there was a hole in each glass door which was filled with corks during the winter. These were quite loose and unstable causing them to fall out and in turn result in higher infiltration rates. The construction details of the conservatory are presented in Table 6.

Table 6: Conservatory construction elements

Building Element	**Description**	**Area (m^2)**
Floor	Suspended timber floor	approximately 33.28
Ceiling	Clear 5-wall Thermoclear (polycarbonate)	35.03
Internal wall	Single brick	17.34
External wall	Double brick- without insulation	36.4
Door	Plywood- 20 mm thickness	1.70
Window	Single glazed (10 mm thickness) with non-insulated metal frame	25.48

4.2.2.1 Shading Specifications

The shading device utilised in this project was an internal cellular blind. The decision on the selection of the blind, sizing and installation method was made by a professional shading association covering the UK shading industry. So, the blinds were installed in a similar way to which internal shading products are installed in UK households. The hexagonal shape of the blinds' cell when extended creates the air pocket and an extra insulation layer within the blind (Louvolite, 2018). The technical data of this blind provided by the manufacturer are presented in Table 7.

Table 7: Specifications of the internal cellular blind used in the conservatory

Name	**Value**
Name Tag	DUA
Colour	Pure White
Visible Transmission	16
Visible Reflection	75
Visible Absorption	9
Solar Transmission	16
Solar Reflection	72
Solar Absorption	12
gtot	0.19
Shading Coefficient	0.30
G-value with Single Glass	0.313
U-value with Single Glass	3.20

The g_{tot} is defined as solar transmittance through the window and according to the EN 14501 standard, it is a value between 0 and 1 (EN 14501, 2005). A g_{tot} closer to 1 means less efficiency whereby all the solar radiation is transmitted but when the number is closer to zero it means the shading is more efficient in reducing the transmitted solar radiation. The thermal properties of a shading device are defined by the thermal transmittance U-value (W/m^2K) which is related to the thermal resistance R-value (m^2K/W) of a material. According to CIBSE Guide A, single glazing with 6mm thickness has a U-value of 5.7 W/m^2K (CIBSE, 2019). Based on the shading manufacturer data, by adding this blind to a single glazed window, the U-value should improve to 3.20 W/m^2K. However, the effect of the frame is not considered in this calculation.

4.2.3 Methodology and Data Collection

To investigate the effect of having a shading device on reducing window heat transfer during the heating season, an internal cellular blind was selected and mounted on the window. Figure 33 shows the heat transfer mechanisms through the single glazed window using an internal blind. Figure 33 shows that the glass is considered to have an external surface (S1) and an internal surface (S2) and then situated in the middle is the air gap whilst the blind is considered to have an external surface (S3) and an internal surface (S4). Generally, the U-value of the glass including the blind itself would be derived from the reciprocal of the S1 to S4 resistance of the fabric plus the surface resistance.

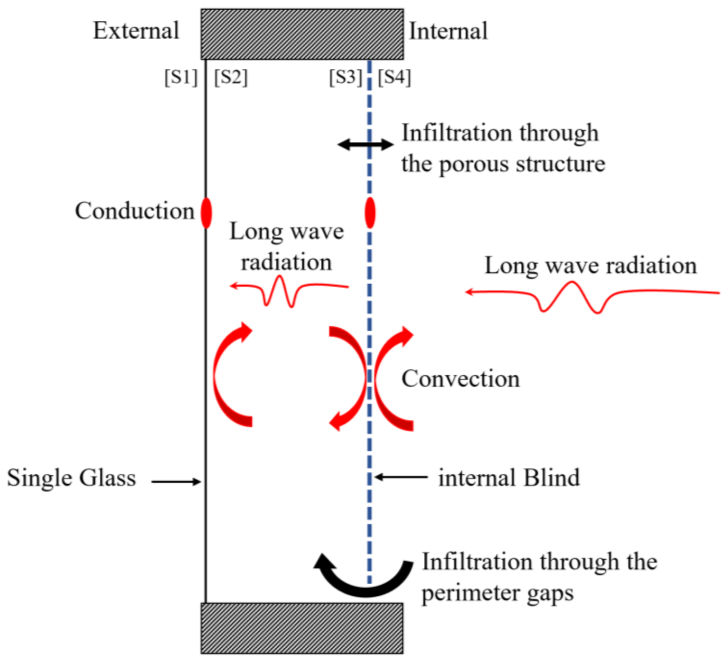

Figure 33: Heat transfer mechanisms through the window, focusing on heat loss.

Figure 34 shows the position of the conservatory in relation to the sun during winter where the glazed area (window) of the conservatory could not receive any direct solar radiation and the roof will not receive direct solar radiation in winter either and will receive diffuse solar radiation which will not contribute to heat gain as much as direct solar radiation.

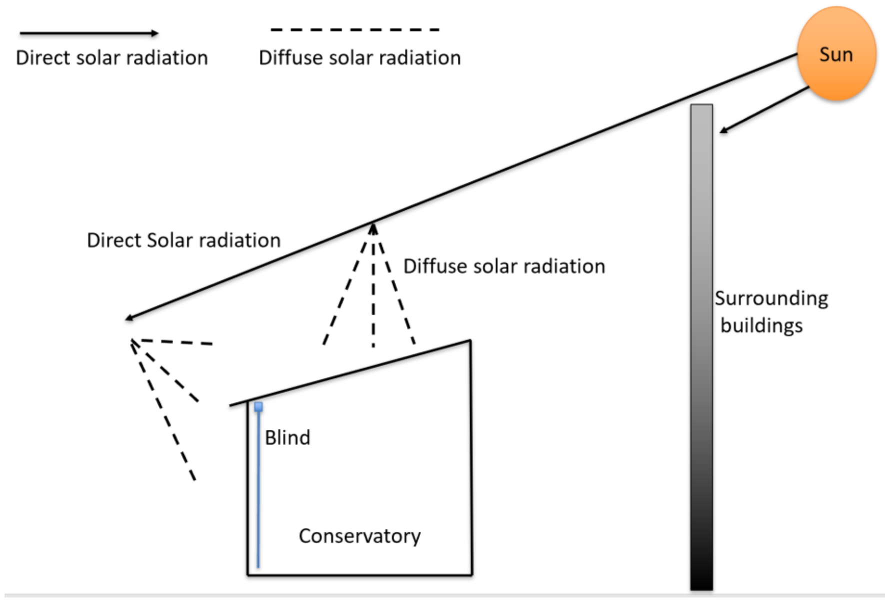

Figure 34: Conservatory position against the sun

To facilitate the collection of the data in winter, internal and external sensors were installed in the conservatory. During this project, the internal and external temperatures, illuminance, and solar radiation were monitored daily at 10-minute intervals. As the intention was to find the effect of the internal cellular blind in normal (daily life) situations, no modification or insulation were applied to the conservatory during the test. Furthermore, there was one occupant who used the conservatory regularly; this was monitored continually with occupancy and door sensors. Additionally, this test was conducted in natural conditions so no heating system was utilised continuously.

4.2.4 Measuring Parameters and Equipment

The sensors and equipment used in this study are described in this section. All the indoor sensors were connected to a Datataker DT500 data logger to store the data.

4.2.4.1 Indoor Operative Temperature

The internal operative temperature was measured using 40 mm globe thermometers with a thermistor inside and accuracy of $< \mp 0.2$ ˚C measuring between 0-70 ˚C, which can measure the combined effect of radiance and air temperature. When this sensor is used inside a building (with an air velocity of less than 1 m/s) and away from direct sunlight, it can measure the operative temperature (Humphreys, 1977; CIBSE, 2019). The two globe sensors were located in the middle of the room, two meters from the floor (Figure 39) and six globe sensors were located between the glass and blind (Figure 35 and Figure 38).

Figure 35: Thermocouples on the glass, globe sensors between blind and glass

4.2.4.1.1 Globe Sensors' Calibration

The globe sensors were calibrated against two mercury thermometers which were inserted into two globes to mimic the temperature reading by globe sensors. All globe sensors were connected to the DT500 data taker. The calibration process was conducted in an office room at London South Bank University which was heated by a radiator and a fan heater. The temperature was measured for 15 minutes with 30-second intervals and the thermometers were read every five minutes. The sensors were all positioned next to each other with 5cm distance in a line and thermometers were at the end of the line. Figure 36 shows the layout of the sensors and Figure 37 shows the sensors during the calibration process.

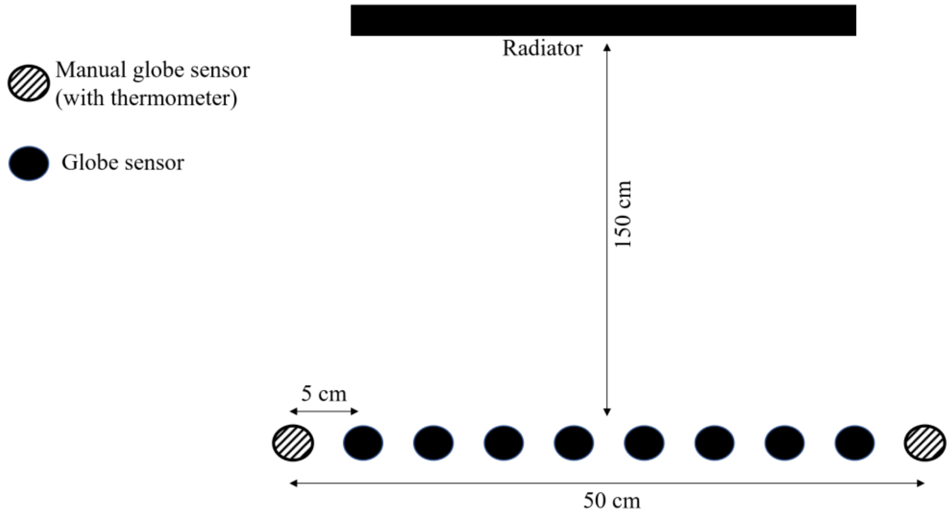

Figure 36: Schematic of the position of globe sensors during the calibration process

Figure 37: Position of globe sensors during the calibration process

The sensors were calibrated at four different temperatures (from 10 to 22 ˚C). Then the readings from each sensor were plotted against the average result of the thermometers (manual globe sensors) and a polynomial equation was obtained for each sensor. The equation is then used to calibrate the sensors and will be applied to the measurements in the real-time study. The graph and equation for each sensor can be found in Appendix A.

4.2.4.2 Window Glass and Blind Surface Temperature

The window glass surface temperature was measured using type TX-1/0.3 mm PFA insulated thermocouples with an overall uncertainty of ±0.08 °C (refer to Section 4.3.3.3.1.2 for more details) mounted on the internal surface of the glass at six different locations to get an average surface temperature (Figure 35). The blind surface temperature was also measured using type TX-1/0.3 mm PFA insulated thermocouples with an overall uncertainty of ±0.09 °C (refer to Section 4.3.3.3.1.2 4.3.3.3.1for more details) attached to the internal surface of the blind at six different locations to get an average temperature (refer to Figure 35 and Figure 38).

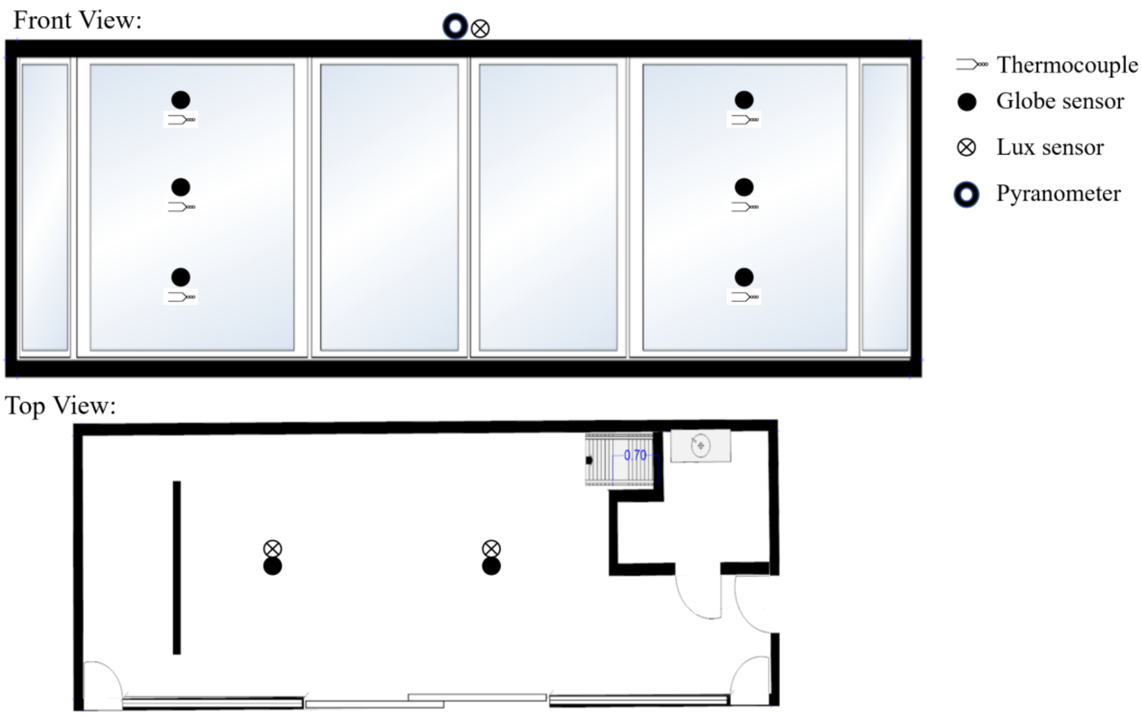

Figure 38:Positioning of the sensors in the conservatory

4.2.4.3 Internal Illuminance

Internal illuminance was measured using EKO lux meter sensors with the sensitivity of 0.191×10^{-6} v/lx, positioned horizontally at a 2 m height inside the conservatory.

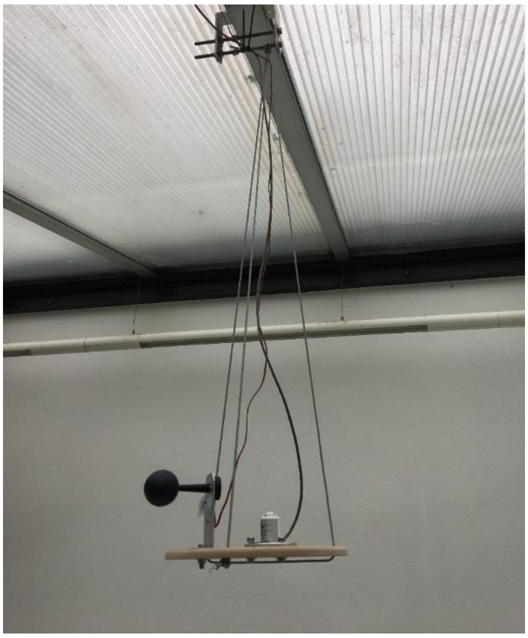

Figure 39: Internal globe and illuminance sensors

4.2.4.3.1 Illuminance Sensor Calibration

The external weather station data logger (DATAHOG2) and sensors including Relative Humidity and Air Temperature sensor (rht^{+} probe), CMP 3 pyranometer and SKL 310 pyranometer were calibrated by their manufacturer, Skye (sensor vendor) before starting the test. This was done to ensure the internal illuminance sensors and the data taker collect accurate and error-free data.

All EKO lux meters (for internal illuminance) connected to the data taker DT500 were calibrated against the calibrated SKL 310 Pyranometer for accuracy (Figure 40). This calibration was carried out at London South Bank University, before the test. By using natural daylight and artificial lighting, different conditions were created for various illuminance levels.

Figure 40: Illuminance sensor calibration at various lux levels

Required data were collected for two minutes with 10-second logging intervals at various lux levels. The output measurement unit of the internal sensors was in mV, but the external Skye sensor was measuring illuminance in Lux. So, by plotting the collected data in a scatter graph, a polynomial equation was obtained which was then used to calibrate sensors and change the mV unit to Lux for each sensor. Figure 41 shows the plotted graph and the polynomial equations for the sensors.

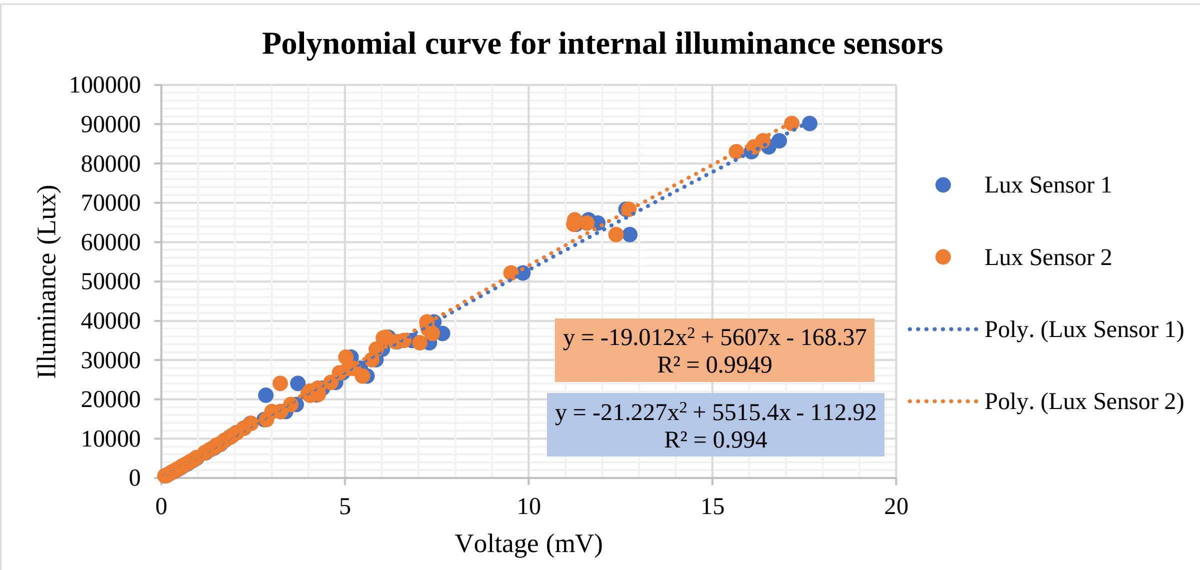

Figure 41: Polynomial Curve for internal illuminance sensors

To find the accuracy of the sensors, the calibrated Skye (external) lux sensor was again positioned next to the internal lux sensor in a similar condition to the calibration process. Then the data was collected for two minutes with 10-second logging intervals at various illuminance levels. After applying the polynomial equation to the relevant sensor results, the results were compared together, and it was found that internal sensors have an accuracy of ±40 lux. As the sensors were calibrated with the data loggers, the sensors were installed in the real-time test on similar channels to the calibration test.

4.2.4.4 Occupancy Monitoring

As an occupant was regularly present inside the conservatory, the internal area was monitored with occupancy sensors (24 hours a day). A XEVOX motion detector was used to monitor occupant presence inside the conservatory and one LED door switch was installed next to the right-hand-side hinged glass door to capture the door operation (Figure 42). This door was the main door that the occupant preferred to use to have access to the garden. These sensors were both connected to a Datataker DT500 data logger to store the data.

Figure 42: Occupancy sensors

4.2.4.5 External Weather Station

The external dry-bulb air temperature was measured using a Skye rht^{+} probe with the accuracy of $< \mp 0.2$ ˚C which was fitted inside a standard naturally ventilated radiation screen. This screen protects the sensor when it is outside also ensuring that the temperature is not affected by direct sunlight. This sensor was positioned on a stand, 50 cm away from the conservatory (Figure 43). External solar radiation was measured using a CMP 3 pyranometer with the sensitivity of 5-20 mV and external illuminance was measured by an SKL 310 pyranometer, with a sensitivity voltage of 10V/10 kLux and linearity error of <0.2%, both positioned on top of the conservatory's roof. All of the external sensors were connected to a battery-operated datalogger model DATAHOG2 to store the data. These sensors and the datalogger were all calibrated before the test.

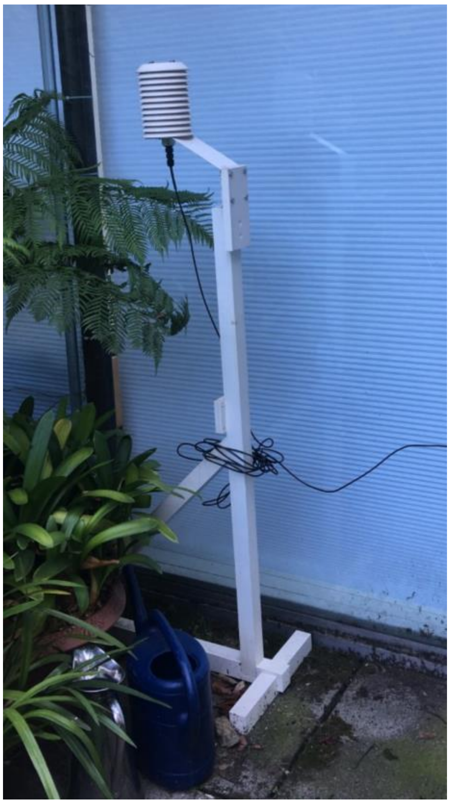

Figure 43: External dry-bulb air temperature sensor

4.2.5 Results and Discussion

As the external air temperature varies, the effect of blinds on internal operative temperature (with no heating system) from September 2019 to mid-March 2020 was analysed in relation to the external air temperature. Additionally, the effect of solar radiation and illuminance was considered in the analysis as solar irradiance during the day was the main reason for increasing the indoor operative temperature. According to the occupancy sensors data, during some days of data collection, the indoor environment was affected by the occupants' activities, i.e. the door was left open for several hours so those particular days were not considered in the data analysis.

The descriptive statistics of the results presented in Table 8 and Figure 44 show that having blinds increased the difference between internal operative temperature and external dry-bulb air temperature by 1.57 °C. Also, the inclusion of blinds has reduced the glass surface temperature by 0.29 °C which means blinds have reduced the thermal loss through the glass by 0.29 °C.

Table 8: The descriptive statistic of internal operative temperature and window glass surface temperature in relation to external dry-bulb air temperature, with and without blind

	Blind status	**Mean**	**Std. deviation**	**N**
External dry-bulb air temperature (°C)	Without Blind	8.83	2.53	12455
	With Blind	10.90	4.77	13259
Internal operative temperature (°C)	Without Blind	10.80	2.12	12455
	With Blind	14.43	4.99	13259
Glass internal surface temperature (°C)	Without Blind	9.87	2.12	12444
	With Blind	11.65	4.55	13259
External Illuminance (Lux)	Without Blind	1.53	2.83	12443
	With Blind	3.46	8.02	13259
External solar radiation (W/m^2)	Without Blind	14.74	28.55	12443
	With Blind	32.15	77.41	13259

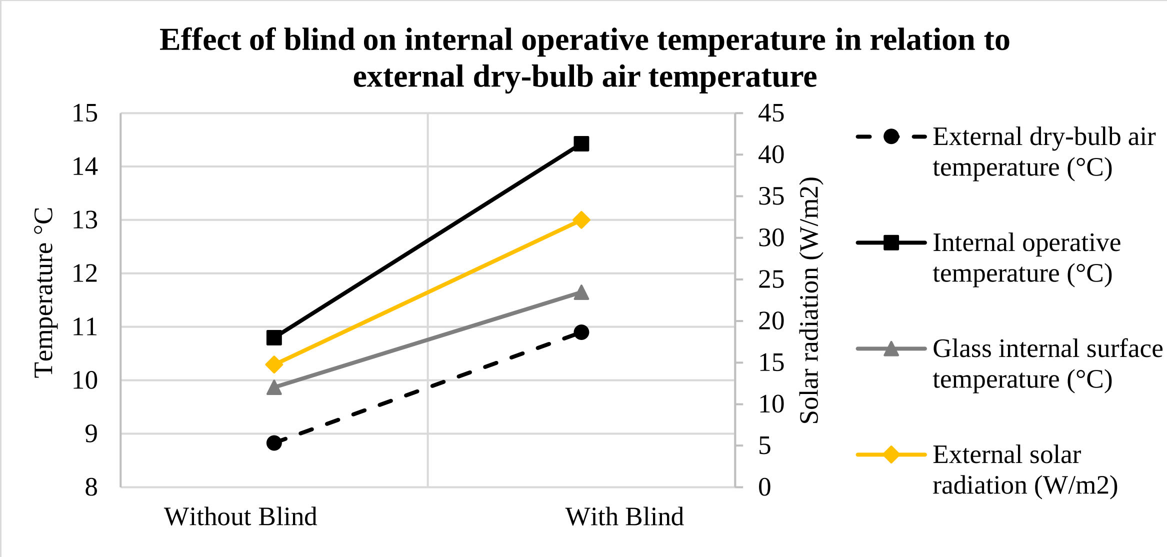

Figure 44: Effect of blind on the internal operative temperature and glass surface temperature considering the external dry-bulb air temperature

To be able to statistically analyse the results, Repeated Measured ANOVA analysis was performed which compares mean values across several variables that are based on repeated observations. The results showed that there was a statistically significant effect of blind presence on internal operative temperature and glass surface temperature where $F(1,4) = 369.7$, $p<0.001$. Although the effect of blind on the internal conditions was statistically significant, the researcher expected to observe a far better result. When referring to blind presence in this research, it is referring to the blind being drawn up or closed.

4.2.6 Limitations and Discussions

One of the reasons for conducting the non-sealed blind project was to illustrate the effect of cellular blinds on thermal retention during the cold season. Due to the orientation and construction of the conservatory, the direct solar irradiance was mainly received by the conservatory roof-light, not the windows, so adding blinds did not affect the direct solar heat gain during the day. Solar radiation is a combination of direct, diffuse, and reflected solar radiation. As the reflected radiation is considered negligible, the total solar radiation received from the sun is the sum of the diffuse and direct solar radiation which varies in different months due to the solar altitude (Sarbu & Sabarchievici, 2017). Additionally, the Thermoclear used for the roof light had an estimated 58% light transmittance which affected the amount of light and solar energy transmitted into the conservatory. As the used cellular blind was one of the most efficient blinds for thermal retention, higher results were expected. The main reasons which caused unexpected results were:

- Non-sealed blinds

To achieve the best thermal retention, it is important to use sealed blinds during the winter. According to the experimental hot box study conducted by Fang in 2001, on single glazed windows, using sealed curtains can improve the U-value and R-value by 19.26% (Table 9).

Table 9: Comparison of U-value and R-value (Fang, 2001)

	Loose curtain		Sealed curtain	
	R value (m^2K/w)	U value (W/m^2K)	R value (m^2K/w)	U value (W/m^2K)
Single Glazed	0.23	4.44	0.27	3.66
Double glazed	0.39	2.58	0.46	2.16

The blind used in the conservatory was sealed from the top and bottom but not from the sides. Also, the bottom of the blinds frequently moved back and forth which could be due to the size of the blind or the effect of the window air permeability. In normal situations where one blind is used for a window, the effect of a loose blind or curtain is only around the edges but in the conservatory, seven blinds were used to cover the glazing area which caused higher infiltration through the blinds.

- High air permeability and infiltration

The conservatory had a high infiltration rate as the window glass had no appropriate frame and there was a 3mm to 20mm gap between various parts of the glass. Furthermore, the suspended timber floor increased the infiltration as the timbers had a two mm distance from each other which caused infiltration through the air gap under the floor. Although the collected data where the occupant had opened the door through to the garden several times, was not considered in the analysis those days when the door was opened once, were indeed considered. Another potential reason for the higher infiltration was the presence of a 20mm diameter hole on each glass door instead of a handle. These holes were sealed with corks but sometimes they were pulled out which caused higher infiltration. As the purpose of this project was testing the blinds in natural settings with minimum changes and as the occupant was using the conservatory regularly, none of the gaps were sealed for the test.

- Impact of occupancy activities and unknown elements

A real-time data collection test requires a location with minimum human interaction. This sensitivity is much higher when the heat loss is investigated. In the majority of the similar research experiments including the overheating real-time test by Robert et al (Robert, et al., 2018), the thermal performance of the window covering by Fitton et al and the heat loss test through double glazing by Oleskowicz and Sobczak (Oleskowicz-Popeil & Sobczak, 2014), the building was not occupied during the test. Although the conservatory was monitored with occupancy sensors, the researcher could not prevent the occupant from going about their day-to-day activities. Furthermore, transparent elements (such as the window and roof light) were affected by heat gain/loss due to solar radiation so specific lab testing with Hot Box methodology is required to find out the thermal properties of these elements (Baldinelli & Asdrubali, 2011).

- Shading product challenges

The shading itself had some issues which were observed throughout the project partly due to the large size of each blind because they were heavy and were not static in their position. By the time they were in place and installed, the bottom of the blinds frequently moved back and forth which caused higher infiltration between the blinds. Another issue was with the beaded cord and braided ladder of the blind whereby the braided ladder (the strings that hold the blind together) would get tangled in the headrail of the blind which obstructed the blind operation. This occurred several times during the project which required frequent intervention by the technician to fix it. Furthermore, due to the string entanglement, the weight of the blind and the unsuitable cord system, manually operating the blind was difficult or sometimes impossible. So, the researcher had to spend about 30 minutes raising the blinds which caused delay and lost time. This highlights the importance of correctly specifying the shading device based on the application of use and how vital the ease of use and quality of a product can be in decreasing heat loss and ultimately energy consumption in buildings.

4.3 Case Study 2: Office Test Room

This section describes the location, geometry, construction, and any modification applied to the office test room. Also, the air leakage test which was conducted according to the requirements for ATAMA is described in this section.

4.3.1 Project Description

4.3.1.1 Site and Location

The test room is an office, located at London South Bank University, situated in central London, UK (51°29′56″ N, 0°6′01.4″ W). This east-southeast faced (110°) room is located on the 7th floor of the Tower Block (Figure 45).

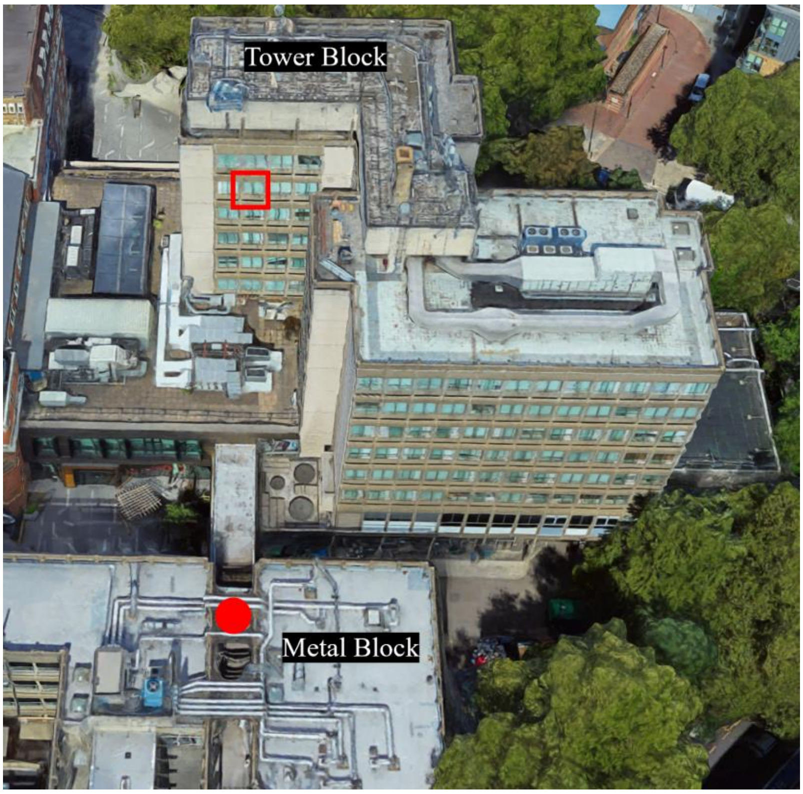

Figure 45: Aerial photograph of Tower Block and Metal Block, London South Bank University. The red square shows the location of the test room and the red circle shows the location of the external weather station. North is the top of the photo. Google Maps 2021.

4.3.1.2 Layout and Construction

Figure 46 and Figure 47 show the room and window geometry where the height of the room is 2.66 m (3.03 m including the extended ceiling).

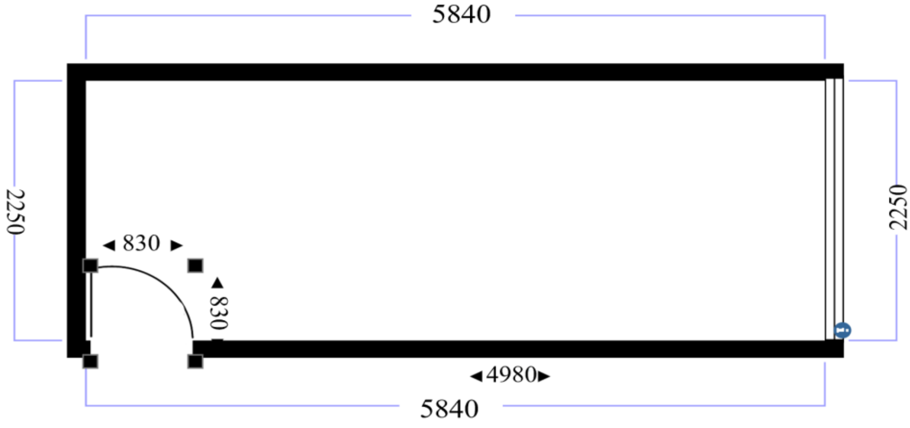

Figure 46: Floor plan of the test room (mm)

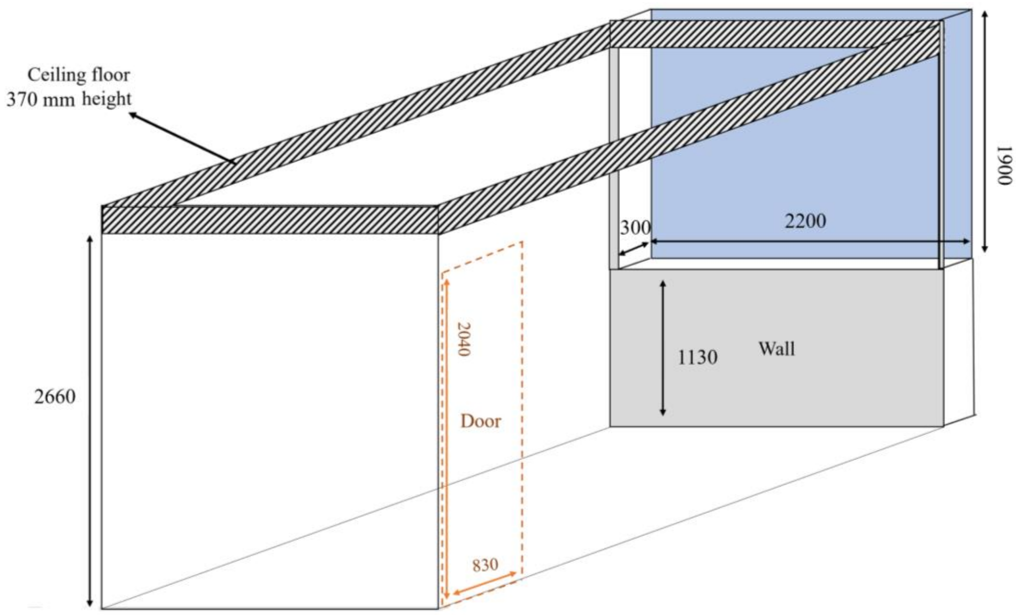

Figure 47: Room and window sizes (mm). The sizes in this picture are not to scale

The ceiling, room flooring and all internal party walls are all adiabatic and connected to other rooms/parts of the building with only one exposed external wall. The position of the window and being on the 7th floor mean that there are no elements vicinity that can cause shading on the window itself.

The Tower Block is mainly constructed from concrete and metal-based materials. The window itself is a sliding double-pane (20 cm distance from each other) with an aluminium frame during this test, the external sliding pane was consistently open, and therefore the window was considered as a single-pane sliding window and not a double-pane type. The suspended ceiling is 37 cm deep and was covered with ceiling tiles. Table 10 presents the construction elements of the test room. This building was owned by London South Bank University, however, the construction details were not available so the information provided here is all based on assumptions and observation.

The Tower Block was constructed in 1968 (LSBU Archive, 2021) and according to CIBSE TM53, it is assumed that the structural system of the Tower Block building is comprised of steel structure frames with bolted connections and cast concrete floor slabs. The concrete floor slabs used in buildings with a structural frame are more commonly cast in situ rather than precast and assembled on site. In the non-domestic construction type for the 1960s-1980s, the façade may consist of large-scale prefabricated wall panels and the cladding system is likely to be precast concrete panels with a wide variety of external finishes. The thermal insulation of 1960s public and commercial buildings was usually air cavity without insulation material and in table 3.1 CIBSE TM53 it is stated that in 1960s wall cavity more than 30mm was used as a typical application with a limiting U-value of 1.7 W/m^2K (CIBSE TM53, 2013).

Table 10: Construction elements of the test room.

Building Element	**Description**	**Area (m^2)**
Floor	Concrete floor	13.15
Ceiling	Suspended ceiling	13.15
Internal wall	Concrete wall without insulation	40.50
External wall	Concrete Block with precast concrete panels	2.64
Door	Plywood- 20 mm thickness	1.70
Window	Single glazed window with aluminium frame	4.18

4.3.1.2.1 Shading Specification

The shading device used in this test was an internal insulated cellular blind with a side-channel to reduce the air permeability of the blind through the perimeter gaps. The unique cell-in-cell structure with its three insulating air layers enabled this blind to be identified as an energy-efficient product (Luxaflex, 2018).

Table 11: Specifications of the internal cellular blind used in the test

Name	**Value**
Name Tag	Duette® Architella® 32 Elan RD 4.50 m
Colour	Swan -ColorSync
Visible Transmission	0
Visible Reflection	63

Solar Transmission	0
Solar Reflection	57
Solar Factor (g) with single glass, %	37.90
Heat Blocking Class	A++
Delta R	0.47
Openness Factor	0

The insulating air pocket included metallised mylar which is a polymer film coated with a thin layer of metal that provides a similar effect as a low-emissivity coating by reducing radiant heat transfer. The Duette® Architella® 32 Elan RD blind, as shown in Figure 48, is made with four layers of fabric which make up the three layers of air pockets. The incorporation of three insulating air pocket layers will increase the R-value of the blind which will result in a reduction in heat transfer through the blind. Due to the ability of the blind to block solar radiation (zero solar and visible transmission), this blind can consequently prevent solar heat gain if operated correctly. It should also be noted that as this blind is installed on the internal side of the window, it will not be as effective as being installed on the external side of the window (Littlefair, 2018). Furthermore, the side channels installed along with the blind helped to minimise the perimeter gaps of the blind and reduce the infiltration heat loss through the window.

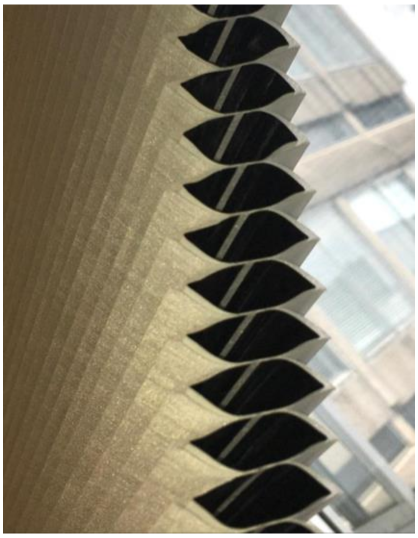

Figure 48: Luxaflex Duette® Architella® 32 Elan RD 4.50 m, cellular dimout duette blind for room darkening

4.3.1.3 Modifications

To reduce the infiltration rate of the room, the areas where the most possible infiltration occurs were sealed with masking tape and duct tape (Figure 49). These areas are mainly the ceiling diffusers, the edges around the ceiling tiles and under the main door.

Figure 49: Application of insulation of the ceiling diffusers and edges around the ceiling tiles.

Also, there were two pipes under the radiator that deliver hot water to the radiators located in the other rooms. The radiator itself was turned off but the pipes were still generating heat inside the room which was interfering with the experiment. To provide a better representation of the energy consumption measurement during the test, the pipes were insulated using the standard foam pipe insulation material as shown in Figure 50.

Figure 50: Insulation of the pipes under the radiator

4.3.1.4 Air Leakage Test

As air permeability has a direct effect on the heat loss process within a building, it's vital that the specific value of air permeability is known and understood. It should be noted that the guidelines set out by ATTMA regarding the measurement of the air permeability of buildings are based on BS EN 13829:2001 'Thermal Performance of Buildings -Determination of air permeability of buildings - Fan pressurisation method' with enhancements recommended by ATTMA. The testing of Non-Dwellings have been described in detail in Regulation 20B and Approved Document L2A of the Building Regulations for England and Wales in addition to the Technical Booklet Part F2 in Northern Ireland, and Section 6 of the Non-Domestic Handbook in Scotland.

In order to assess the room envelopes' air leakage parameters, the pressure differential across the envelope needs to be determined in addition to measuring the required airflow to reach the desired differential. To achieve this, variable flow portable fans are normally used which can be positioned in specific openings like doorways. The recorded fan flow (Q) and building pressure differential (Δp) data establish the correlation. This can be defined in terms of the power-law equation (Hutcheon & Handegord, 1995; ASHRAE, 2013):

$$Q_f = C\ (\Delta p)^n \qquad \textit{Eq 4-2}$$

Where C (flow coefficient in ($Pa^{1/n}.m^3$)/h) and n (flow exponent which is dimensionless typically 0.5 to 0.6) are constants related to the specific building under test and can be calculated by recording several measurements over a range of pressure differences (10, 30, 50 and 60 Pa). Q_f is airflow through an opening (m^3/h) and p is the pressure difference (Pa) between interior (reference pressure) and exterior (baseline pressure). So according to ATTMA and Approved Document L2A of the Building Regulations for England and Wales, air permeability is defined as “air leakage rate per hour per square meter of the envelope area at the test reference pressure differential of 50 Pascals” (HM Government (L2A), 2016).

The calculated airflow is then divided by the total building envelope area (A_E), which in this case it is the total room area, to provide the leakage rate in $m^3/(h.m^2)$ @ 50Pa. For calculating the room envelope area, the sum of the area of walls, floor and ceiling is calculated. The test was conducted via an experienced engineer through a third-party company. Figure 51 shows the blower door equipment used for the test which was installed in the door frame.

Figure 51: Full blower door equipment viewed from inside including blower door frame, fan and controller with pressure tubes. This equipment was connected to a laptop which is not in the photo.

Table 12 represents the results of the test. The official report for the air leakage test can be found in Appendix B.

Table 12: Results of the air leakage test

Parameter	**Value**
Air permeability (AP_{50})	17.89 $m^3.h^{-1}.m^2$ @50Pa
Air Leakage at 50 Pa (Q_{50})	1169 $m^3.h^{-1}$ @ 50Pa
ACH50	37.82
ACH	1.89

4.3.2 Methodology and Data Collection

The real-time data collection process was conducted in an office within a London South Bank University building for the duration of 22 nights. During this period, although the room was monitored fully during the day (24 hours) the main data collection occurred overnight (17:00 to 08:00). The real-time data collection was split into two scenarios, one being 11 nights with the blind closed and the other 11 nights without the blind present (blind drawn up and open) with the measurements of each ultimately being compared against each other.

To achieve the lowest temperature possible and to also avoid interference from direct solar radiation, this test (which was conducted in March 2021) occurred during the night. So, the main data collection took place from 17:00 to 08:00 every night where no individual was present in the room. According to CIBSE guide A, the recommended comfort criteria for offices in winter is 21-23 °C (CIBSE, 2019). As this test was conducted during March, the heating setpoint was set at 24 °C to increase the temperature difference between inside and outside.

4.3.3 Measuring Parameters and Equipment

The sensors and equipment used in this study are described in this section. All the indoor sensors were connected to a Datataker DT500 data logger to store the data.

4.3.3.1 Indoor Dry-bulb Air Temperature

The dry-bulb air temperature was measured using pre-calibrated TX-1/0.3 mm PFA insulated thermocouples, located in the middle of the room. Three sensors were used at three different heights to get the average air temperature of the room and prevent the effect of air stratification (Figure 52). The uncertainty of each sensor is calculated as ±0.18, ±0.33 and ±0.26 °C and the overall uncertainty for indoor air temperature is ±0.15 °C. The detailed calibration method and uncertainty analysis are presented in Sections 4.3.3.3.1.1 and 4.3.3.3.1.2.

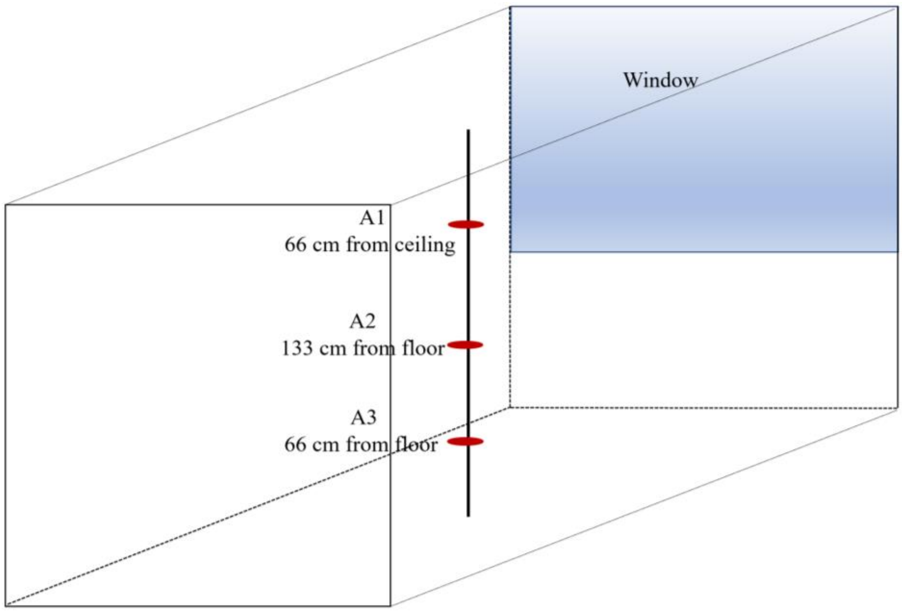

Figure 52: Location of the three thermocouples, which were located in the middle of the room at three different heights to measure the internal dry-bulb air temperature. The sizes in this picture are not to scale.

4.3.3.2 Window Surface Temperature (Blind and Glass)

In this case study and for the remainder of this chapter, window surface temperature covers both the blind and glass temperatures meaning when there is a blind present, window surface temperature refers to the blind surface temperature and when there is no blind, the window surface temperature is deemed as the glass surface temperature. The blind surface temperature was measured using type TX-1/0.3 mm PFA insulated thermocouples with an overall uncertainty of ±0.12 °C (refer to Section 4.3.3.3.1.2 for more details) attached to the internal surface of the blind with aluminium foil tape at four different locations to get an average temperature (refer to Figure 53 and Figure 54).

Figure 53: Location of four thermocouples attached to the internal surface of the blind to measure blind surface temperature

Internal window surface temperature was also measured using a similar type of thermocouples (TX-1/0.3 mm PFA insulated thermocouples) with an overall uncertainty of ±0.10 °C attached to the internal surface of the glass with aluminium foil tape at four different locations shown in Figure 54. Section 4.3.3.3.1 presents the calibration method and uncertainty analysis in detail.

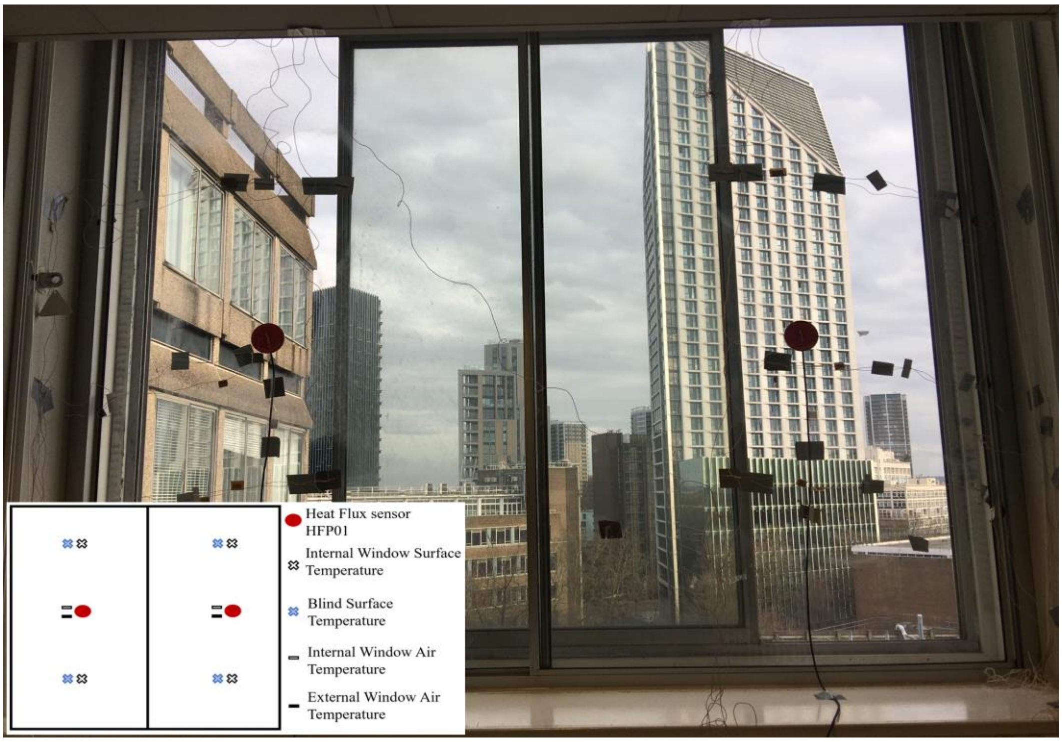

Figure 54: Location of the sensors for measuring internal parameters

4.3.3.3 Window Indoor and Outdoor Dry-Bulb Air Temperature

Pre-calibrated temperature sensors (type TX-1/0.3 mm PFA insulated thermocouples) were located inside and outside of the window with a 10 cm distance from the glass to measure the dry-bulb air temperature near the window. The location of the sensors is shown in Figure 54. The overall uncertainty for window external air temperature sensors is calculated as ±0.14°C and for the internal sensors ±0.15°C. The calibration method and uncertainty analysis are described in more detail in section 4.3.3.3.1.

4.3.3.3.1 Calibration of the Data Monitoring System

4.3.3.3.1.1 Sensor Calibration

The internal temperature sensors (type TX-1/0.3 mm PFA insulated thermocouples) are required to be calibrated before the test. These thermocouples were all connected to a Datataker DT500 data logger with an accuracy of 0.25% (Datataker, 2002). This data logger was then connected to a laptop with the data capture software to be able to save the data and form a data monitoring system (Figure

55). The data was recorded at 10-second intervals to be calibrated in a water bath before the data collection process.

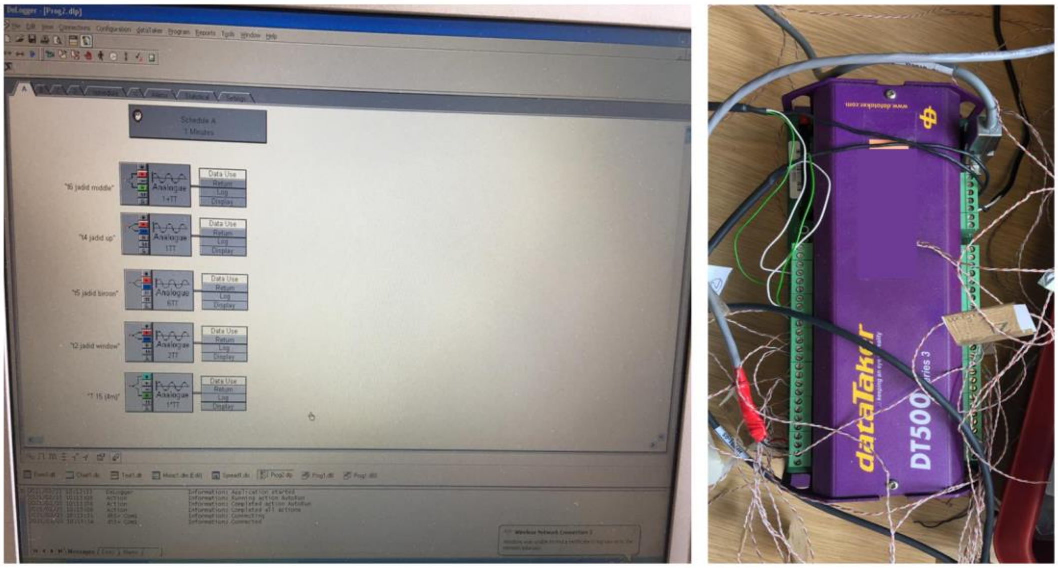

Figure 55: Data Tacker DT500 and the related software

The thermocouples connected to the whole data monitoring system were calibrated using a temperature-controlled Grant W28 stirred water bath with temperature stability of ± 0.004°C including a built-in temperature controller and electric heater. The calibration of sensors was done for a range of temperature between 2°C to 40°C.

Two pre-calibrated NPL mercury thermometers covering the range of temperatures between 0°C to 100°C with 0.1 scales, were located inside the water bath as a reference temperature. After adjusting the thermostat of the water bath to the desired temperature (ice cubes were added when required), it was left until it reached a steady-state temperature. Then to avoid local temperature variations, all of the sensors were inserted inside the calibration bath at the same reference temperature. As the sensors were all connected to the monitoring system, it meant the Data Taker and Laptop were calibrated as well.

Temperature sensors were calibrated for temperature ranges of 2°C, 5°C, 10°C, 15°C, 20°C, 25°C, 30°C, 35°C and 40°C with 10-second intervals for 10 minutes. During the following step, the temperature sensor readings were compared to the reference temperatures from the two mercury thermometers through a graph illustration. Then the best-fit equation and R-squared value for each sensor were generated. All the equations were rechecked before being applied to the readings. Figure 56 represents the calibration results of one sensor (WS-1) versus the NPL thermometer readings. The R-squared ($R^2 = 0.9995$) and the linear best-fit equation can be seen within the graph. The calibration results for the rest of the sensors used in the experimental test are available in Appendix C.

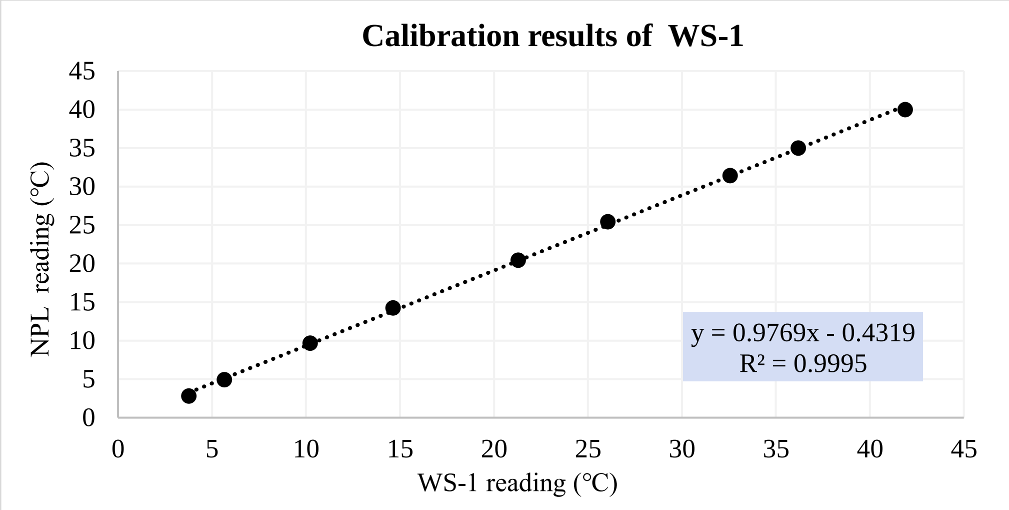

Figure 56: Calibration results and linear best-fit equation for T15 sensor

Table 13 presents the linear best-fit equation and R^2 value for all of the sensors (where $y=T_{actual}$ and $x=T_{reading}$).

Table 13: Calibration equation for each sensor used in the experiment

No.	**Name**	**Calibration Equation**	**R^2 value**	**Location**
1	WS-1	y = 0.9769x - 0.4319	0.9995	Window surface, upper left
2	WA-1	y = 0.9749x - 0.3116	0.9996	Window outside dry-bulb air, left
3	WS-2	y = 0.9745x - 0.2971	0.9996	Window surface, upper right
4	WA-2	y = 0.9745x - 0.2812	0.9996	Window outside dry-bulb air, right
5	A-1	y = 0.976x - 0.2058	0.9996	Internal dry-bulb air, Middle
6	BS-1	y = 0.9777x - 0.295	0.9993	Blind surface, lower left
7	BS-2	y = 0.9744x - 0.2817	0.9993	Blind surface, lower right

8	BS-3	y = 0.9757x - 0.2607	0.9994	Blind surface, upper right
9	BS-4	y = 0.9755x - 0.2941	0.9994	Blind surface, upper left
10	WA-3	y = 0.9802x - 0.434	0.9993	Window inside dry-bulb air, left
11	WA-4	y = 0.9779x - 0.2973	0.9994	Window inside dry-bulb air, right
12	A-2	y = 0.9766x - 0.1955	0.9994	Internal dry-bulb air, upper
13	WS-3	y = 0.9782x - 0.2341	0.9995	Window surface, lower left
14	WS-4	y = 0.9843x - 0.3247	0.9995	Window surface, lower right
15	A-3	y = 0.9745x - 0.035	0.9995	Internal dry-bulb air, Lower

4.3.3.3.1.2 Uncertainty Analysis

Uncertainty analysis can determine the accuracy of the experimental outcomes and is a prediction of uncertainty intervals from the experiment measurements (Geffray, et al., 2019). The total uncertainty (u_{tot}) of measurements includes the precision of random errors (u_{random}) and systemic errors (u_{sys}). A Random error is an error that differs from one data to the next one and by continuously averaging the repeat measurements, the more accurate results you would expect to get. Systemic error is the fixed errors associated with measurements that tend to change systematically and affect the mean value and the same influencing factor will impact the results no matter how many times the measurements are repeated. So, it shows the difference between the actual and mean value of the measurements (Moffat, 1982; Bell, 2001).

In order to calculate the total uncertainty, three main values should be known which includes: standard deviation of the mean ($\overline{\sigma s}$) of the set of N data which in this case are seven readings, the number of degrees of freedom (N-1) where N is the number of datum and systematic or bias error (u_{sys}).

The standard deviation of the mean ($\overline{\sigma s}$) was calculated with the equation below:

$$\overline{\sigma s} = \left[\frac{1}{N}\left(\frac{\sum_{i=1}^{N}(T_i - \bar{T})^2}{N-1}\right)\right]^{0.5} \quad \text{Eq 4-3}$$

Then, random error (u_{random}) was calculated based on the standard deviation of the mean with a 95% confidence level ($t_{N-1,0.95}$) from the equation below:

$$u_{random} = t_{N-1,0.95} * \overline{\sigma s} \quad \textit{Eq 4-4}$$

Total error (u_{tot}) was then calculated from the root-sum-square model:

$$u_{tot} = \sqrt{u_{sys}{}^2 + u_{random}{}^2} \quad \textit{Eq 4-5}$$

The uncertainty result for each sensor was calculated for the range of temperature between 2°C and 40°C. Table 14 shows an example of the uncertainty calculation method for the sensor A-1 at a temperature of 5°C.

Table 14: Uncertainty calculation for A-1 temperature sensor at 5°C

No.	**NPL reading**	**A-1 reading ($T_{reading}$)**	**T_{actual} =(0.9760*$T_{reading}$)-0.2058**	$(\mathbf{T}_{actual} - \overline{\boldsymbol{T}})^2$
1	5	5.34	5.00	0.0020
2	5	5.35	5.02	0.0010
3	5	5.35	5.02	0.0012
4	5	5.38	5.05	0.0000
5	5	5.39	5.05	0.0001
6	5	5.41	5.07	0.0007
7	5	5.46	5.12	0.0054
Mean temperature ($\overline{T}$)			5.05	$\sum(\mathrm{T}_{actual} - \overline{T})^2$ = 0.0103
Degree of freedom (N-1)				6
Standard deviation of T16 readings (σ_s)				0.0414
Standard deviation of the mean ($\overline{\sigma_s}$)				0.0157
Standard distribution coefficient for N-1 degree of freedom ($t_{N-1,0.95}$)				2.4469

Random	0.0383
Total	±0.0414

This

Table

No.	Name	Calculated
1	WS-	±0.22
2	WA-	±0.20
3	WS-	±0.21
4	WA-	±0.19
5	A-	±0.18
6	BS-	±0.31
7	BS-	±0.19
8	BS-	±0.20
9	BS-	±0.24
10	WA-	±0.24
11	WA-	±0.17
12	A-	±0.33
13	WS-	±0.18
14	WS-	±0.19
15	A-	±0.26

The

$$u(X) = \left(\frac{1}{n}\right)\left[\sqrt{\sum_{1}^{n}(u_T)^2}\right] \quad \textit{Eq 4-6}$$

Where u(X) is the uncertainty of the sensors for location X and u_T is the uncertainty of the individual sensor in location X. The calculated uncertainties of the measured data are listed in Table 16.

Table 16: Total uncertainty of measurements (°C)

Sensor	**Uncertainty of sensor (u_T)**	**Location**	**Total uncertainty of measurement $u(X)$ (°C)**
WS-1	±0.22	Window surface temperature	±0.10
WS-2	±0.21		
WS-3	±0.18		
WS-4	±0.19		
A-1	±0.18	Room dry-bulb air temperature	±0.15
A-2	±0.33		
A-3	±0.26		
BS-1	±0.31	Blind surface temperature	±0.12
BS-2	±0.19		
BS-3	±0.20		
BS-4	±0.24		
WA-1	±0.20	Window external air temperature	±0.14
WA-2	±0.19		
WA-3	±0.24	Window internal air temperature	±0.15
WA-4	±0.17		

4.3.3.3.2 Window Heat Flux

Heat flux through the window was measured using two HFP01 sensors mounted on the internal side of the glass (Figure 54). HFP01 shows a thermopile that measures the temperature difference across the ceramics-plastic composite body of the sensor. A 0.1×10^{-3} m air gap increases the effective thermal resistance of the sensor by 60% (Hukseflux, 2016). So, to avoid the presence of air gaps between the sensor and the surface, a double-sided removable TESA 4939 tape was used as recommended by the manufacturer (Figure 57). HFP01's factory calibration uncertainty under reference conditions is ±3% with a coverage factor k=2. The uncertainty caused by non-stability is <1 %/yr. As these sensors were brand new, this 1% uncertainty which should be added to the uncertainty for every year is not applied here.

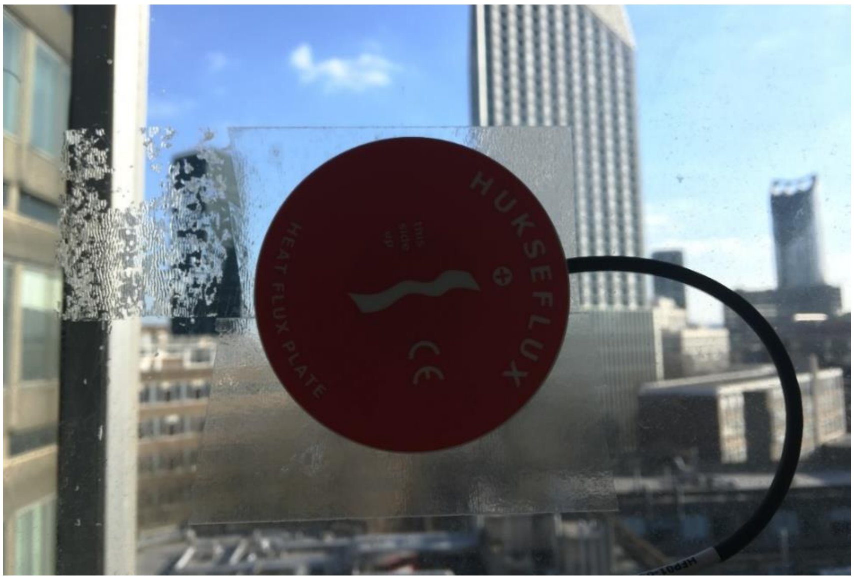

Figure 57: HFP01 Heat Flux sensors mounted on the internal central part of the glass with a double-sided TESA 4939 tape.

In order to calculate the heat flux (Φ) in $W.m^{-2}$, the HFP01 voltage output (U) should be divided by the sensitivity of the sensor (S). So, the measurement function of this sensor is:

$$\Phi = U/S \qquad \text{Eq 4-7}$$

The sensitivity of each sensor is provided by the manufacturer and can be found in the product certificate which for the sensors used in this study were 60.76×10^{-6} and 59.55×10^{-6} $V/(W.m^{-2})$. Under ideal conditions, measurements of heat flux in building physics may attain uncertainties in the ±6% range.

4.3.3.4 Heating System and Energy Meter

In order to maintain the temperature inside the room, an electric 3kW turbo convector heater with a timer was utilised. This thermostatically controlled heater located in the middle of the room was programmed to be on from 17:00 to 08:00 every night with a 24 °C setpoint. This heater was connected to an RS PRO power metering socket which could record the cumulative energy consumption value in kWh (Figure 58) with the resolution of ±0.01 kWh.

Figure 58: Electric turbo convector 3kW heater and RS PRO power metering socket

4.3.3.5 Outdoor Weather Station

The dry-bulb air temperature, solar radiation and illuminance sensors were positioned on the stand located outside the building (Figure 59). This weather station was located on the roof of the Metal block (block adjacent to the Tower block within London South Bank University) where it has the same orientation as the test room. The external sensors were connected to a battery-operated Skye data logger (DATAHOG2) to save the data. The sensors and datalogger used as a weather station were sent to the manufacturing company for calibration prior to the test so there was no need to calibrate them on-site.

Figure 59: External weather station including a CMP 3 pyranometer, a SKL 310 pyranometer and a rht+ probe fitted inside a radiation screen. All of the sensors are connected to DATAHOG2 to enable the saving of the captured data.

4.3.3.5.1 Dry-bulb Air Temperature

The external dry-bulb temperature sensor is a rht+ probe with an accuracy of $< \mp 0.2°C$ which was fitted inside a standard naturally ventilated radiation screen. This screen protects the sensor when it is outside whilst ensuring that temperature is not affected by direct sunlight.

4.3.3.5.2 Illuminance and Solar Radiation

Solar radiation was measured with a CMP 3 pyranometer with the sensitivity of 5-20 mV and the illuminance was measured by a SKL 310 pyranometer. Both sensors were located on the top of the weather station stand to avoid being overshadowed by the other sensors.

4.3.4 Results and Discussion

4.3.4.1 Thermal Images

In order to illustrate the effect of a cellular internal blind on heat transfer during the heating season, the thermal camera model FLIR ONE PRO LT was used to capture infrared photos. Figure 60 and Figure 61 show the effect of the blind on the inside surface temperature where it has increased from 13.6°C to 22.5°C. The heat loss through the window and, as a result, thermal comfort in the room will be heavily influenced by closing the blind. It should be noted that local discomfort can be prevalent when an individual is positioned next to cold glazing via thermal (long-wave) radiant heat exchange. This could have a significant impact on how someone feels in addition to the local air temperature.

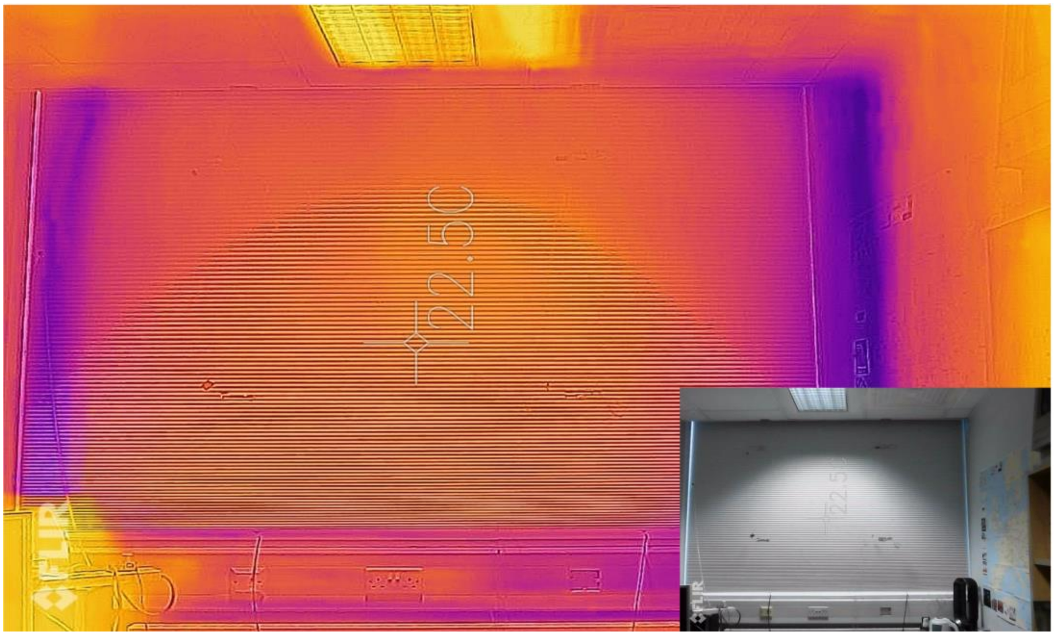

Figure 60: Thermal image captured with blind showing the blind area with a surface temperature of 22.50 ºC

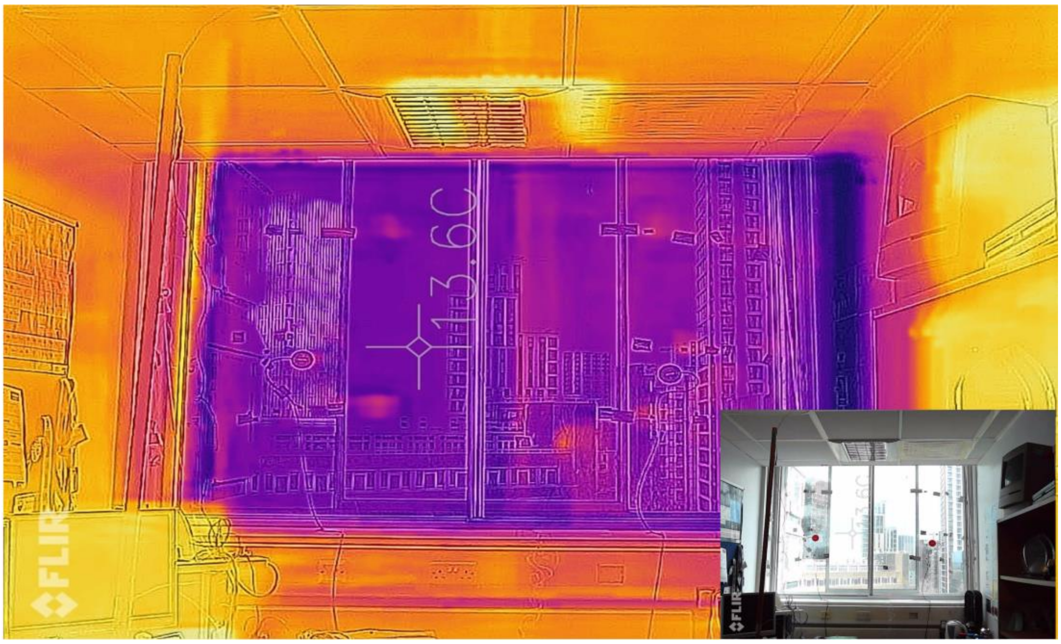

Figure 61: Thermal image captured without blind showing the glass area surface temperature of 13.60 °C

4.3.4.2 Real-time Results

Real-time data were collected for eleven nights with a blind installed and eleven nights without a blind during March 2021. To eliminate the effect of solar radiation on temperature and heat transfer mechanisms, the test was run during the night. However, solar irradiance in the room will still be absorbed during the day and re-radiated overnight. The amount of solar gain depends on the thermal mass of objects in the room and their materials. To minimise this effect, although the heater was on from 17:00, the data collection only started from18:00 to maintain the temperature at the desired setpoint.

In this section, the results and the effect of using an insulating blind on reducing heat loss are discussed. All of the parameters considered in this section were measured on-site, but wind speed data was sourced from the MET Office National Meteorological Archive. The nearest weather station was Kew Garden located 8.5 miles away from the test location.

4.3.4.2.1 Energy Consumption and Window Heat Flux

During the test, it was observed that energy consumption (to maintain internal air temperature at 24°C) and window heat flux were reduced considerably in the presence of the blind. The graphs in Figure 62 illustrate the hourly measured temperatures and window heat flux on two different nights during with and without blind scenarios in the heating season. These hourly values are the average values of 5-minute interval data and were collected with the purpose of increasing the accuracy of the results and being able to use the data for dynamic thermal modelling validation. The graphs show that while attempting to maintain internal air temperature at 24°C in both cases, the external dry-bulb air temperature differs between the two scenarios. The other variables which differed between the two scenarios were the window heat flux and window glass surface temperature values. Comparing the two graphs shows that the window glass surface temperature in the presence of a blind was measured at an average temperature of 8.61 °C whilst this measurement during the without blind scenario was 14.30 °C. The lower average glass surface temperature is seen when a blind was present meaning the blind has worked as a thermal barrier between the window glass surface and the internal environment which can also be interpreted as a factor in reducing heat loss through the window. Considering the heat loss through the window, heat flux sensors that were installed on the window glass surface to measure the flow of energy through the window, provided contrasting measurements in the graphs below. The graphs in Figure 62 show that the average heat flux value measured in the presence of a blind was 31.73 W/m^2 whilst the same value for the without blind scenario was 73.27 W/m^2. This clearly illustrates that when there is no blind, glass surface temperature and energy flow increase resulting in a higher proportion of heat loss through the window.

Another vital finding from Figure 62 is related to the direct impact of the blind / glass surface temperature on the occupants situated in the close vicinity of the window. In the presence of the blind, the average blind surface temperature was 21.11°C whilst without the blind, the average glass surface temperature was 14.30 °C. This can be linked to thermal comfort as it is clear that the with blind scenario should provide a more comfortable situation for the occupant than the without the blind case. Local discomfort can be prevalent when an individual is positioned next to cold glazing via thermal (long-wave) radiant heat exchange which in addition to the local air temperature could have a significant impact on how someone feels.

Furthermore, when comparing the blind surface temperature in the presence of a blind with the glass surface temperature when without a blind, it is observed that having a blind can increase the surface temperature by about 6-7°C which has a direct impact on thermal comfort.

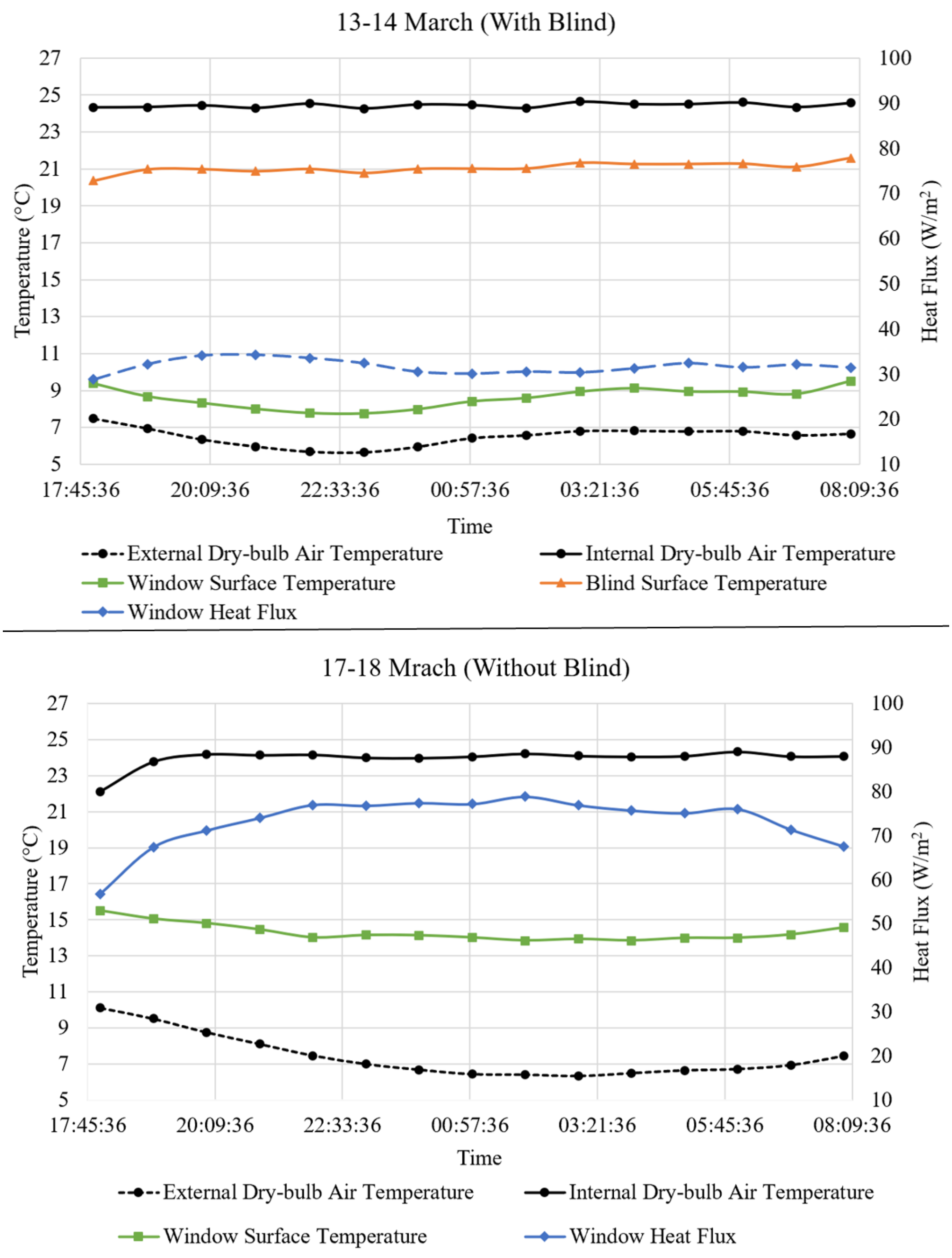

Figure 62: Graph showing Temperature and Heat Flux, With and Without Blind

The daily mean value of the hourly measured parameters with and without blind scenarios are presented in Table 17 and Table 18. For daily mean values, only the data from 17:00 to 08:00 the following day is considered.

Table 17: Real-time daily results with blind

ID	**Date (March)**	**Average External Dry-bulb Air Temperature (˚C)**	**Dry-bulb Air ΔT_{in-out} (˚C)**	**Blind Surface (˚C)**	**Window Surface (˚C)**	**Wind Velocity ($m.s^{-1}$)**	**Window Heat Flux ($W.m^{-2}$)**	**Energy Consumption (kWh)**
1	1-2	5.43	19.72	22.00	9.54	2.23	34.66	13.27
2	2-3	5.75	19.11	21.79	9.88	1.23	32.27	13.14
3	5-6	4.68	19.99	21.11	8.22	1.75	33.20	14.62
4	6-7	4.49	20.18	21.05	8.05	0.96	32.53	14.19
5	7-8	4.00	20.75	20.85	7.50	0.69	30.80	14.20
6	8-9	7.36	17.37	21.42	9.89	1.51	26.41	13.98
7	13-14	6.43	18.02	21.11	8.55	3.36	31.94	14.50
8	14-15	9.38	15.24	21.76	11.28	3.98	26.10	11.60
9	24-25	9.02	15.41	21.61	10.96	1.54	24.82	11.26
10	25-26	10.42	13.68	21.04	11.27	2.88	15.21	10.22
11	26-27	6.04	18.18	20.47	7.56	2.98	28.82	14.07

Table 18:Real-time daily results without blind

ID	Date (March)	Average External Dry-bulb Air Temperature (˚C)	Dry-bulb Air ΔT_{in-out} (˚C)	Blind Surface (˚C)	Window Surface (˚C)	Wind Velocity ($m.s^{-1}$)	Window Heat Flux ($W.m^{-2}$)	Energy Consumption (kWh)
1	3-4	6.21	18.52	23.30	14.58	1.44	79.88	30.79
2	4-5	4.98	19.77	23.05	13.09	1.92	91.47	32.08
3	9-10	8.47	15.40	22.63	13.73	2.78	81.59	29.08
4	10-11	11.14	12.32	19.56	14.60	5.49	70.77	23.06
5	11-12	7.07	17.01	21.81	12.38	3.46	89.00	28.02
6	12-13	7.75	16.21	21.31	12.68	4.18	86.72	26.12
7	15-16	9.67	14.49	22.62	15.70	1.58	62.74	23.13
8	16-17	7.21	16.88	22.35	14.21	1.99	74.45	24.08
9	17-18	8.44	15.70	22.31	14.61	2.47	69.29	25.53
10	18-19	8.94	15.19	22.87	15.64	0.96	67.25	26.70
11	22-23	7.59	16.65	22.58	14.30	1.17	78.77	24.97

The daily values show that $\Delta T_{in\text{-}out}$ fluctuated in both scenarios due to the external weather condition however, the window surface temperature was quite stable in the presence of blind. It should be noted that with the blind scenario, the window surface temperature was the temperature of the internal surface of the blind but in the without blind scenario, this temperature was captured from the internal side of the glass. The results in Figure 63 show that having a blind has increased the window surface temperature by 33.6%, whereby in the presence of a blind, the average blind surface temperature was 21.29 °C and when there was no blind, the average glass surface temperature was 14.14°C.

Due to the exchange of long-wave radiation between the occupant and the window, the higher surface temperature can have a positive effect on thermal comfort in cold weather (Lyons, et al., 2000).

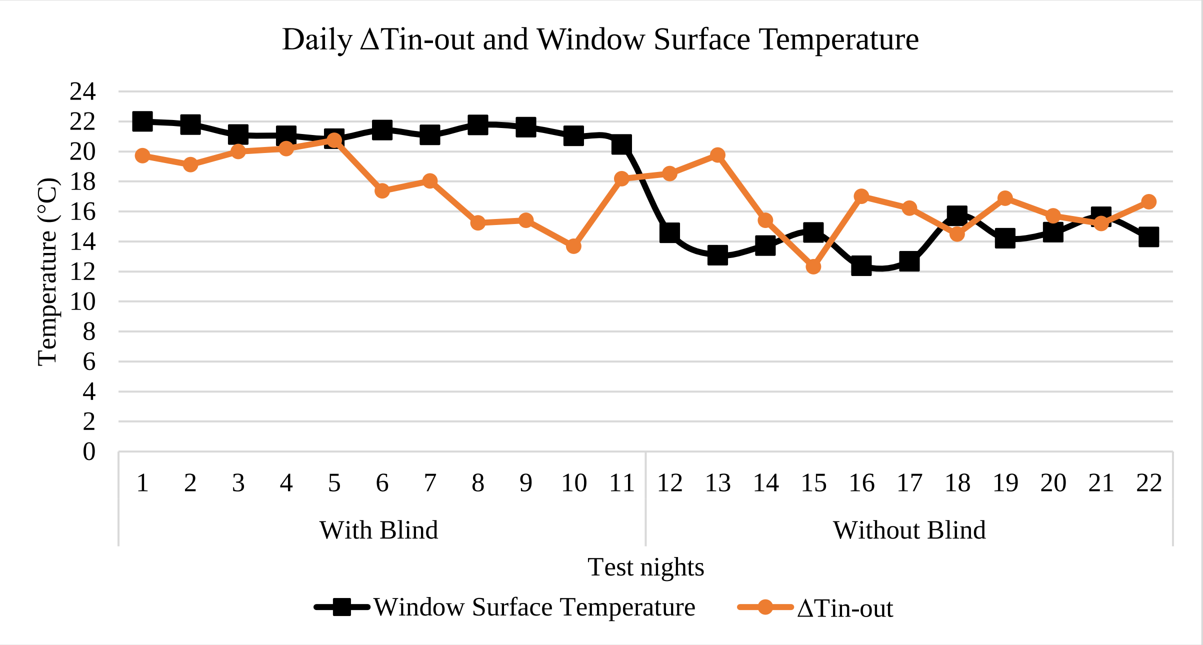

Figure 63: Daily ΔTin-out and Window Surface Temperature

Considering the daily energy consumption in the analysis, it is observed that the energy consumption to maintain internal air temperature at 24°C, in the presence of a blind was approximately half (50.59%) than without the blind scenario, whereby in the presence of the blind, the average energy consumption was 13.19 kWh and when there was no blind, the average energy consumption was 26.69 kWh. Additionally, the energy consumption values seen during the with blind scenario were more uniform than the without blind scenario. It is observed that in the presence of the blind, the average window heat flux value was 28.80 W/m^2 and in the without blind scenario, this average value was 77.45 W/m^2 (62.82% higher than with blind scenario) (Figure 64). Taking this into account, the window heat flux was considerably lower in the presence of a blind which means having a blind has acted as an extra layer of insulation for the window and prevented energy loss through the window.

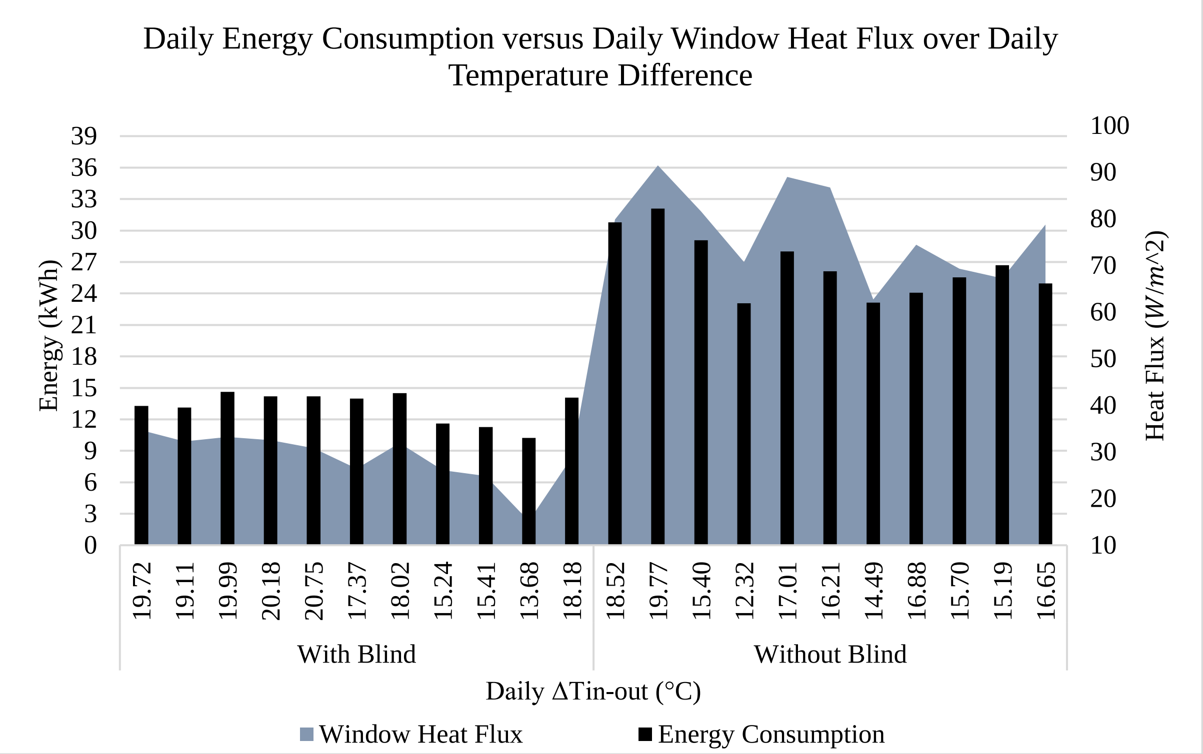

Figure 64: Daily Energy Consumption (over ΔTin-out) versus window heat flux

The descriptive results of the analysis are represented in Table 19.

Table 19: The descriptive analysis results

	Blind	**Mean**	**Std. Deviation**	**N**
$\Delta T_{in\text{-}out}$ (°C)	With Blind	17.97	2.32	11
	Without Blind	16.19	1.98	11
Wind (m.s^{-1})	With Blind	2.10	0.75	11
	Without Blind	2.49	2.41	11
WHF (W.m^{-2})	With Blind	28.80	5.54	11
	Without Blind	77.45	9.39	11

Energy (kWh)	With Blind	13.19	1.49	11
	Without Blind	26.69	3.01	11
Window Glass Surface Temperature (˚C)	With Blind	9.34	1.44	11
	Without Blind	14.14	1.09	11
Window Surface Temperature (˚C)	With Blind	21.29	0.46	11
	Without Blind	14.14	1.09	11

The results in Table 19 show the window surface temperature was 33.58% higher in the presence of a blind which could have an impact on thermal comfort. It was also observed that during the without blind scenario, the glass surface temperature was 14.14 ˚C and when there was a blind, the blind surface temperature was 21.29 ˚C whilst $\Delta T_{in\text{-}out}$ (˚C) was 10% higher and wind speed was 15.78% lower in the presence of a blind.

The average wind speed in this test was 2.49 $m.s^{-1}$ (4.8 knot) in the without blind scenario and 2.10 $m.s^{-1}$ (4.08 knot) in the with blind scenario which both are categorised as a light breeze (Met Office, 2016). It should be noted that this wind speed data was sourced from a weather station located in Kew Garden which was 8.5 miles far from the test location. So due to the urban area effect, the actual wind speed in the test location should be slightly less than what it is captured by Met Office (CIBSE, 2019). So, the wind force in the two scenarios was not considerably different and by considering the urban area effect, it can be seen that the impact of wind speed is negligible and even if it was to be considered, the energy consumption and window heat flux in the with blind scenario was much lower than without a blind.

4.4 Conclusion

The results of case study 1 showed that the presence and addition of blinds have the potential to alter internal operative and window glass surface temperatures by 1.57°C and 0.29°C, respectively.

Additionally, the results of repeated measured ANOVA analysis indicated that there was a statistically sizeable effect of blind presence on internal operative and glass surface temperatures where $F(1,4) = 369.7$, $p<0.001$. Although the effect of blind on the internal conditions was statistically significant, it fell short of the expectations and values predicted at the start of the study.

The main reason found for not achieving the highest potential impact of the blind presence on the internal temperature in the first case study, conducted in a conservatory, was utilising non-sealed blinds which were not successful in reducing infiltration through the window. This is despite the blinds being specified and installed by professional shading specifiers and technicians who are part of the UK shading association. This limitation in the research study highlighted the importance of correct selection, specification and installation of blinds on the effectiveness of the shading devices, as an incorrectly specified or installed blind can reduce efficiency considerably. Furthermore, based on the challenges seen during this test, for future real-world research studies, it is recommended to conduct the test in a more controlled environment and to have the possibility of applying modifications in the test room if required.

In the first case study, the achieved temperature was less than what was expected, another case study was run to investigate the effect of sealed blinds on thermal retention. The results showed that using an internal sealed cellular blind has the potential to reduce the energy consumption required to maintain the internal dry-bulb air temperature at 24 °C from 17:00 to 08:00, by 50.59% whereby in the presence of a blind, the average energy consumption was 13.19 kWh whereas when there was no blind, the average energy consumption was 26.69 kWh. Furthermore, it was observed that in the presence of the blind, the average window heat flux value was 28.80 W/m^2 and in the without blind scenario, this average value was 77.45 W/m^2 which is 62.82% higher than the with blind scenario. This means that the blind has acted as an insulating layer and prevented energy from escaping through the window. Additionally, having the blind has increased the window surface temperature by 33.60%, whereby in the presence of the blind, the average blind surface temperature was 21.29 °C and when there was no blind, the average glass surface temperature fell to 14.14°C. This has a positive impact on thermal comfort as due to the exchange of long-wave radiation between the occupant and the window, the higher surface temperature can aid thermal comfort in cold weather.

Further studies are required to identify various elements affecting the thermal retention capabilities of shading devices. This includes utilising different types of shading devices and at different durations i.e. during the day where solar radiation is taken into account. Also, comparison of the results is essential between the measured real-time data and the predicted results of the thermal dynamic models to test the ability of software packages in modelling the shading devices concerning thermal retention.

4.5 Summary

The real-time data collection process conducted in the two case studies for thermal retention purposes were outlined in this chapter. The detailed description of the instruments, calibration, calculation of uncertainty of sensors, sensor positions and the results were presented in this chapter. The main conclusions and findings from the real-time data collection study are:

- Adding a non-sealed blind in a conservatory (Case Study 1) could increase internal operative temperature by 1.57 °C and window glass surface temperature by 0.29°C which according to the Repeated Measured ANOVA analysis, blinds had a statistically significant impact on temperature. However, these results were much lower than expected.
- In Case Study 2, in the presence of a sealed blind, the energy consumption in the office whilst maintaining the temperature at 24 ˚C from 17:00 to 08:00, was 50.59% lower compared to the without blind scenario. Having a blind had reduced window heat flux by 62.82% compared to the without blind scenario. Additionally, having a blind had an impact on the thermal comfort of the occupant sitting near the window as in the presence of a blind, the window surface temperature was 33.58% higher than without a blind scenario.

CHAPTER 5

Building Energy Modelling and Simulation Software Packages within the UK Building Industry

5.1 Introduction

Dynamic thermal models generated by building energy modelling and simulation software tools are one of the key methods of evaluating and predicting the energy efficiency of a building especially in the early stages of the design. The dynamic thermal simulation results can influence the building professional and specifiers' decision regarding the use of different elements in the buildings such as utilising shading devices. Nevertheless, there are instances where discrepancies have been found between real-world data and the dynamic simulation results or between the results of different software tools themselves. This can be due to various elements such as weather data, energy systems used in the building, indoor environment, maintenance of the building and occupant behaviour. In order to identify the reasons behind these uncertainties and gaps, some research studies have investigated this discrepancy with different software tools (Petrou, et al., 2019). When it comes to modelling shading devices, some of the software tools do not truly and visibly incorporate the full parameters of the shading device within the software and the required shading inputs that do exist in the software do not cover the whole spectrum of shading specifications (Venturi, et al., 2018).

To investigate this issue in more depth, it is essential to initially identify the most commonly used Building Energy Modelling and Simulation (BEMS) software tools for dynamic thermal modelling within the UK. To achieve this, a survey was distributed to the building energy modellers within the UK who were involved directly or indirectly with shading devices in their projects. This survey also evaluated the advantages and disadvantages of each software package in relation to the modelling of shading devices. This chapter describes the results from the survey on BEMS software tools within the UK building industry. In Section 5.2, the distribution and Ethics Approval Letter of the survey are included and in Section 5.3, the qualitative results are analysed and discussed. The last section presents a summary of the chapter.

5.2 Data collection method and survey distribution

The survey, which can be found in Appendix D, initially went through the London South Bank University Ethical Approval process whereby the form in Appendix B had been approved, before being distributed to the external parties. For confidentiality and ethical reasons, the survey responses were collected anonymously. In the online survey, the participants were provided with the Information Sheet (Appendix E) and Consent Form (Appendix) before starting the questions and the Debriefing Form (Appendix F) appeared once the survey was completed at the end.

Before the distribution of the survey, a list of the relevant organisations and individuals were compiled through web-based searches and through contacts obtained via previously attended events and conferences. The survey was then presented as an online version using the Qualtrics survey tool to enable distribution to participants around the UK. The key aim of this study which was executed between July and November 2020 was to obtain a better understanding of the various stakeholders' feedback within the wider construction industry related to building energy modelling software packages. Within this survey, these stakeholders are considered to be *Building Services Engineering, Facade Engineering, Sustainability Engineering, Architectural Practice*, *Academia and Research*. Although there are many organisations and communities for each of the mentioned groups of stakeholders across the UK, due to the focus of the survey being around participants who work directly with shading products in some shape or form, the number of participants who were approached was limited to 400. The final number of participants that were contacted for this survey are not considered to cover absolutely all relevant stakeholders but this is the number reached through extensive engagement, networking and recommendations of various groups. It must be noted that despite the focus of the survey being direct links and exposure to shading products and the reasons outlined in the literature review stating relatively low levels of engagement and knowledge of these stakeholder groups with the shading industry, a total of 98 responses (24% response rate) were received.

There have been only a handful of studies focusing on building energy performance software tools use via surveying specialist groups in the industry. One of these studies conducted in Holland (2012) focused on the barriers that prevent more frequent use of these software tools for greener building designs whereby 149 participants (mainly architects) were involved in the survey (Erbas & Van Dijk, 2012). In addition to this study, there have been a few studies globally (Singapore, Austria and Belgium) focusing on the use of building energy software tools (Lam, et al., 1999; Mahdavi, et al., 2003; Weytjens & Verbeeck, 2010), but not many recent studies focusing on the UK landscape. The main recent UK based studies of note were conducted by Alsaadani et al (2012) where the focus was on the non-technical challenges faced by architects and users in the UK with 175 participants. A second recent study conducted by Mahmoud et al (2020) assessed the use of building energy performance software tools in the early stages of the design through responses received from 300 (15% response rate) architects in the UK (Mahmoud, et al., 2020; Alsaadani & De Souza, 2012). All of the studies mentioned have had a very generic and overall view on the use of these software tools with the main focus group being architects whereas the survey conducted in this chapter covers more stakeholder groups but with a specific relation to shading products and their exposure to them in their area of expertise. Table 20 represents the field of work and years of experience of the participating modellers. To better group and categorise some of the fields together, a reference category is shown below specifying the reference names used throughout this chapter.

Table 20: Participants' field of work and years of experience

Field of work	Reference Name	**Frequency**	**Years of experience**	
Building Services Engineering, Facade Engineering and Sustainability Engineering	Building Services	66	Fewer than 5 years	20
			5-10 years	25
			11-20 years	16

			More than 20 years	5
Architectural Practice	Architects	11	Fewer than 5 years	4
			5-10 years	3
			11-20 years	3
			More than 20 years	1
Academia and Research	Academia	21	Fewer than 5 years	8
			5-10 years	8
			11-20 years	2
			More than 20 years	3
Total		98	Fewer than 5 years	32
			5-10 years	36
			11-20 years	21
			More than 20 years	9

The majority of participants work in the building services sectors while 22% of participants work in academia and the rest of them are working in the architectural field (Figure 65).

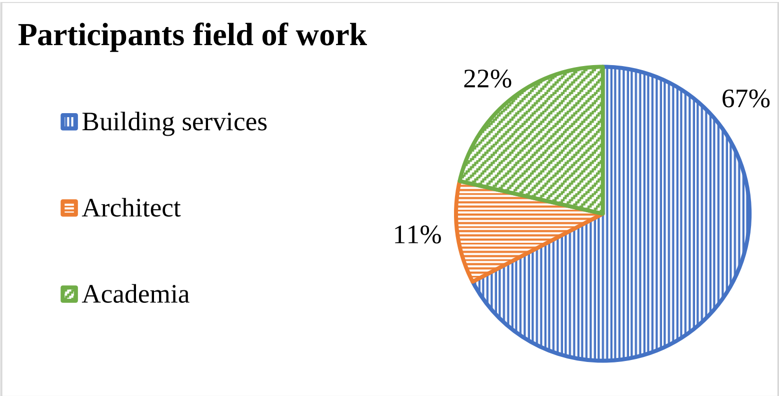

Figure 65: Participants' field of work

Figure 66, shows that the participants' experience in all three groups of expertise is quite similar when comparing the groups together. The figure illustrates between 30% to 38% of participants in each group have fewer than five years of experience, while 27% to 38% of participants have five to ten years of experience. As the years of experience increase, the percentage predictably decreases whereby 10% to 24% of participants in each group have 11 to 20 years of experience and fewer than 14% of each group have more than 20 years of experience.

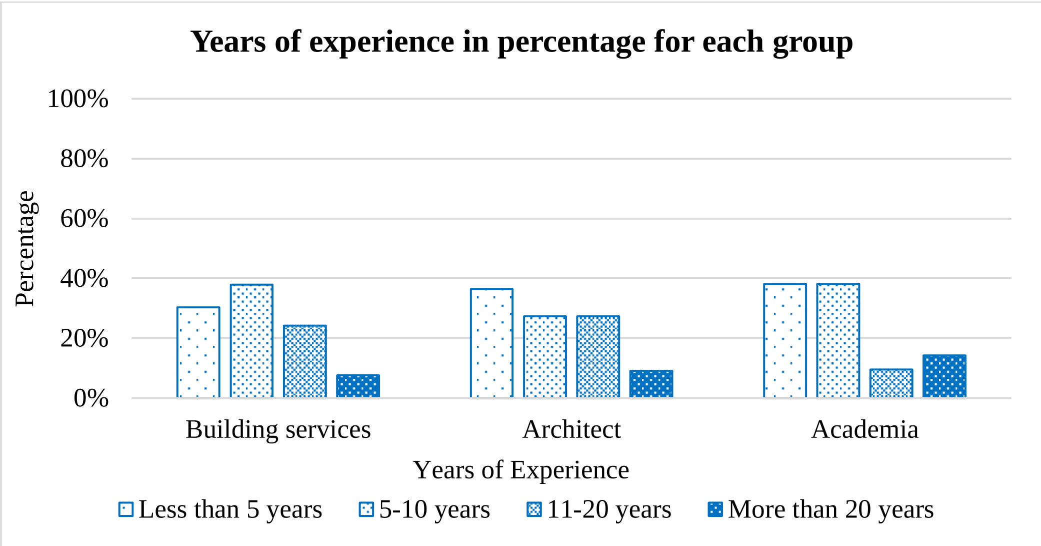

Figure 66: Years of experience in percentage for each group

5.3 Results and Discussion

This section outlines the discussions and results from each investigated topic. It should be noted that reference to total participants (98) relates to the total number of participants who started completing the survey and as further questions are asked the total number of participants for each specific question may fluctuate whilst the analysis will be based on the total responses for that question and not the total number of participants who started the survey (98). This is due to the fact that participants are asked to choose one of the options in some of the questions and the following questions can only be responded to by participants who chose a particular option hence the total number for some of the questions may differ.

5.3.1 The Frequency of Considering Different Types of Shading Devices During the Modelling Phase of the Projects

Use of external shading is more prevalent than internal shading in all three groups (Figure 67). For example, based on the selections that architects made in the survey, external shading is frequently used on at least half of the projects they contribute to whereas 54% stated they've experienced instances whereby internal shading has been used in less than half of their projects or been completely absent. Building services engineers considered external shading used in all their projects 10% more than the application of internal shading in all their projects whilst the responses from academia showed that 24% more of their group stated the complete lack of internal shading in the projects they were exposed to. One of the reasons for the consensus among the groups especially within academia can be related to the fact that elements such as planning approval challenges and the financial aspects are not necessarily a key factor considered at the modelling phase of the projects (Mahmoud, et al., 2020).

Interstitial shading is the least considered type of shading in modelling projects amongst all three groups. This is most likely in line with the reasons explained in CHAPTER 3 Section 3.3.1 which outlines how this type of shading is a lot less widely used due to the high cost of maintenance and lack of an established position and knowledge within the industry (Dardalis, 2017), and this is reflected in the software modelling packages as well.

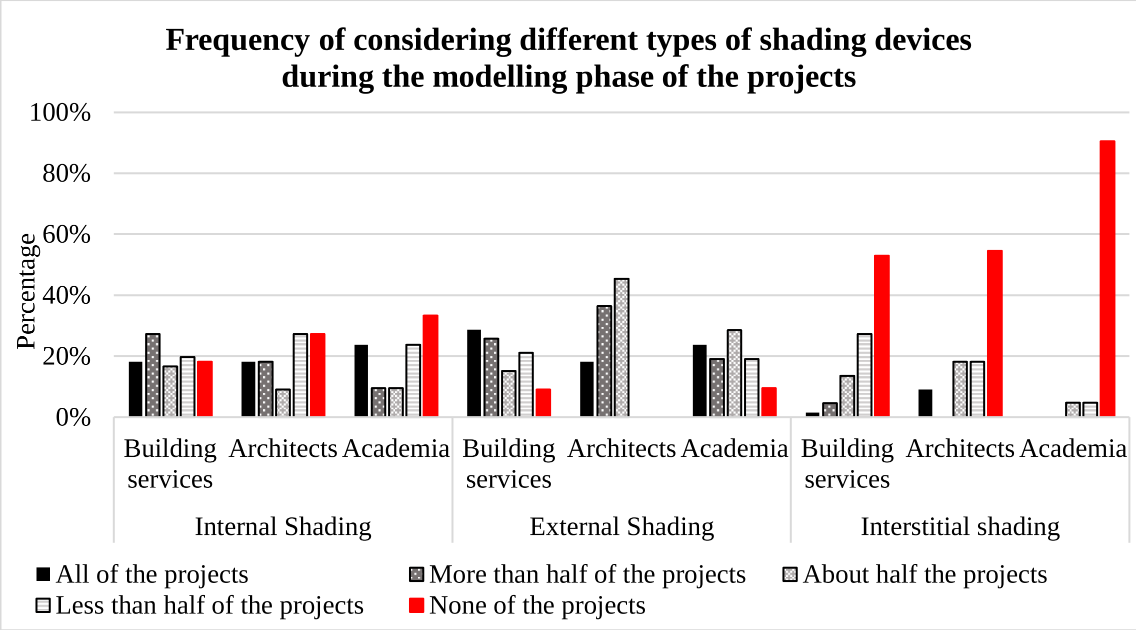

Figure 67: Frequency of considering different types of shading devices during the modelling phase of the projects

5.3.2 Main Reasons for Considering Shading Devices in Modelling Projects

The two options *thermal comfort benefits* along with *Energy efficiency benefits* are the most popular reasons for use of shading products amongst the three groups as more than 68% of participants in each group have selected these two benefits. This is consistent with the findings in Chapter 3 and shows the awareness within the groups regarding the benefits of shading specifically in relation to thermal management and energy-saving applications. The recent drive and focus from building regulations and environmental labels such as Part L Building Regulation, WELL and BREEAM, to discuss topics such as energy conservation and thermal comfort has had a part to play in influencing and increasing the knowledge and interest regarding these two factors (HM Government (L2A), 2016; HM Government (L1B), 2018; International WELL Building Institute, 2020; BRE, 2018).

Regulatory and compliance obligations are more important for building services compared to other groups of expertise as 41% of them have selected this option while only 10% of academia chose this option. This can be expected as building services professionals directly deal with regulatory bodies to ensure sanctioning and compliance of their projects whereas academics will not necessarily have this exposure.

The option *shading devices are key components of the building* was chosen by just under 30% of architects and building services professionals whilst approximately 16% of academia have chosen this option; These are quite low percentages for all three groups. This highlights a distinct gap in knowledge and interest that has a negative impact on the consideration of shading devices in buildings especially in the early stages of the design. Furthermore, it illustrates that there is a perception and approach within the UK building industry that shading devices are more thought of as add-ons, when and if required, depending on thermal comfort and climate conditions after the building has been constructed (Seguro & Palmer, 2016). The *Client requirements* option is the least popular reason to consider shading devices in buildings amongst all three groups which shows that clients are not necessarily interested in using shading devices or are not aware of its benefits. As mentioned in CHAPTER 3 Section 3.3.4.1, clients' desire to use shading devices is an important factor that can increase the use of these products in buildings as projects are modelled around compliance to clients' needs and guidelines so if more and more clients request this as a core requirement in their specifications then the aforementioned groups will adapt and include shading devices more often in their respective scopes (Seguro & Palmer, 2016).

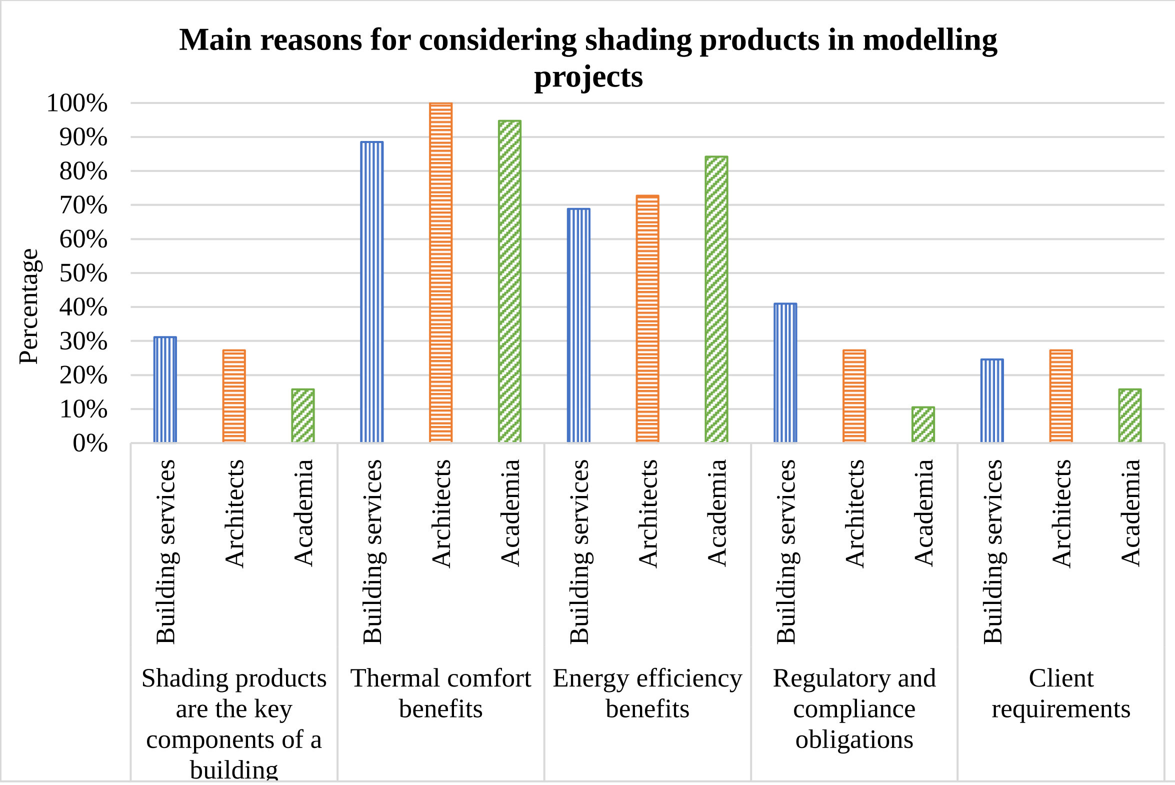

Figure 68: Main reasons for considering shading products in modelling projects

5.3.3 Current Trending Building Energy Modelling and Simulation Software Packages in the UK

In this analysis, to highlight and illustrate the most commonly used software packages in the UK, the percentages of participants in each group of expertise are calculated based on 84 participants who have responded to this question. Based on the responses, IES VE is the most popular software used amongst building services engineers (58%). This may be in line with the fact that companies' training programs and university teaching are more tailored towards IES VE which may be a result of the software companies' better reach and sales strategy in the UK. The remaining software packages selected by the participants are EnergyPlus (17%), DesignBuider (12%) and EDSL Tas (11%) for building energy modelling purposes. Within participants who work in academia, EnergyPlus is the most popular software (61%) which can be partly due to the fact that the software is code-based meaning academics might believe that it is more accurate compared to the others as they can modify the code itself to suit their needs (Castell & Solé, 2015). Additionally, as obtaining software licenses can be a significant financial burden for academic institutions, using a free software package like EnergyPlus is more beneficial for academia which encourages more frequent use. As DesignBuilder utilises the same user interface as EnergyPlus and uses EnergyPlus as its simulation engine, fewer than 10% of academia have selected this software based on the responses from the survey.

Architects use other / less common software tools more frequently in comparison with academia and building services which can be due to the different purposes/applications they use the software for in their work. In most cases, architects are not involved in the energy modelling phase of the project and they mainly focus on the design aspects and decision making rather than energy modelling (AIA, 2012). As discussed in CHAPTER 3, this can affect the use of shading devices in a building as it can result in not being considered in the early stages of the design. The first graph below (Figure 69) is analysed and illustrated based on dividing the responses by the total number of participants for each group which can be slightly misleading in representing the overall view of the most commonly used software packages in the UK. To better visually demonstrate and represent the overall analysis based on the total number of participants Figure 70 has been put together which shows the percentages of use by dividing the responses by the total number of participants (96).

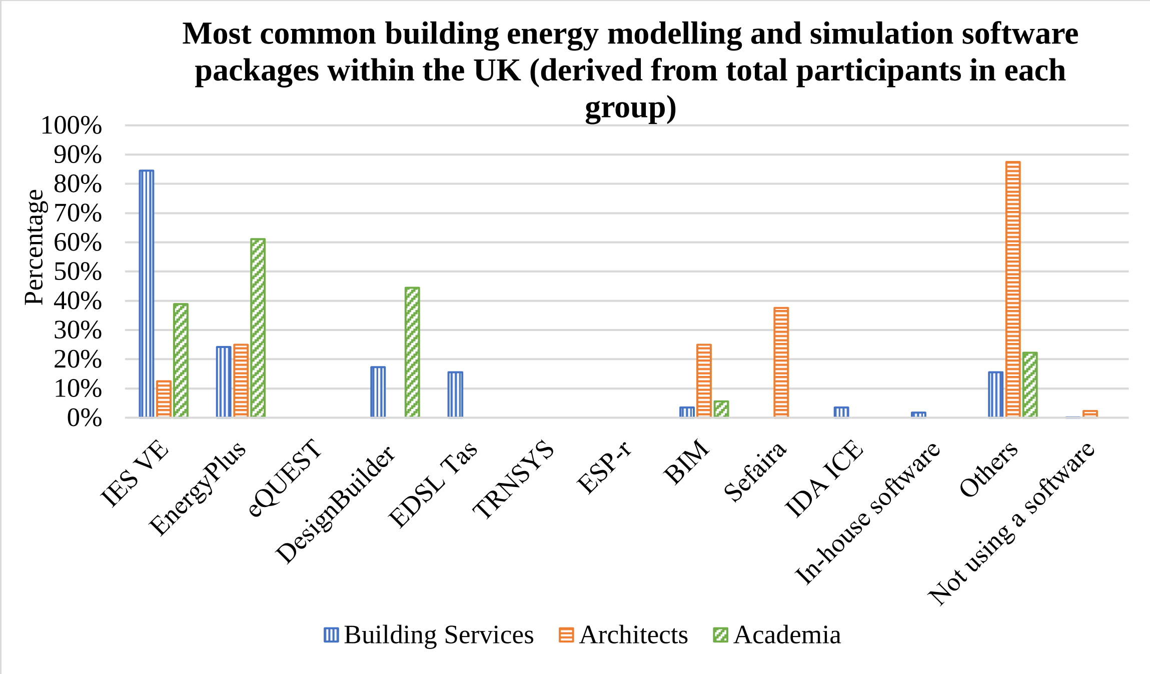

Figure 69: Most common building energy modelling and simulation software packages within the UK (Derived from total participants in each group)

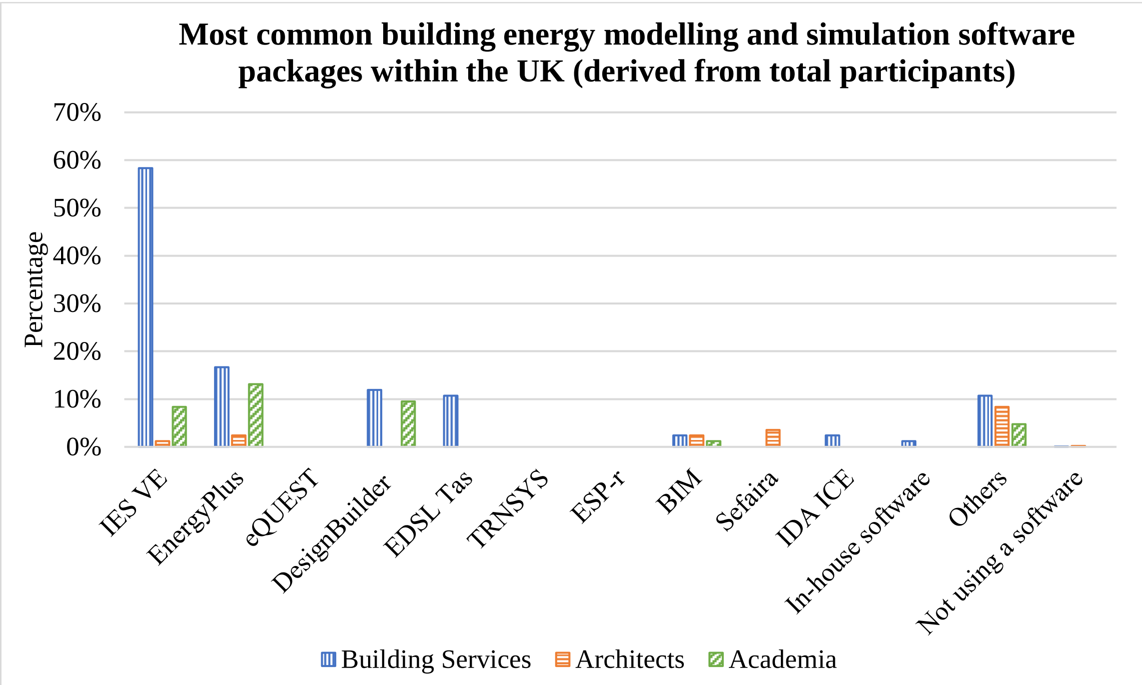

Figure 70: Most common building energy modelling and simulation software packages within the UK

Table 21 presents the *other* software tools that participants use for their building energy modelling projects.

Table 21: "Other" software tools that participants are currently using

Field of expertise	Software
Building Services Engineering / Facade Engineering /Sustainability Engineering	Rhino + plugins
Building Services Engineering / Facade Engineering /Sustainability Engineering	Honeybee (EnergyPlus)
Building Services Engineering / Facade Engineering /Sustainability Engineering	Ladybug Honeybee
Building Services Engineering / Facade Engineering /Sustainability Engineering	PHPP, DesignPH, PSI-Therm, Stroma FSAP, RHINO with Ladybug/Honeybee
Building Services Engineering / Facade Engineering /Sustainability Engineering	Radiance
Building Services Engineering / Facade Engineering /Sustainability Engineering	PHPP
Building Services Engineering / Facade Engineering /Sustainability Engineering	NHER Plan Assessor
Building Services Engineering / Facade Engineering /Sustainability Engineering	Rhino
Architectural Practice	PHPP
Architectural Practice	Rhino, Grasshopper
Architectural Practice	Cove Tool
Architectural Practice	Honeybee
Architectural Practice	Rhino
Architectural Practice	Grasshopper / Honeybee / Ladybug
Architectural Practice	Ladybug/Honeybee
Academia and Research	PHPP
Academia and Research	Rhino/Grasshopper/Diva/Ladybug/Honeybee
Academia and Research	ENVI-met
Academia and Research	CONTAM

A review of the varying *other* software tools showed that some of them can be grouped based on their similarities or the main software packages they're linked to like EnergyPlus plugins and Rhino which encapsulate many of the *other* software tools. By categorising the similar software packages in one group, it is concluded that packages related to EnergyPlus and Rhino (including Ladybug, Honeybee, Rhino and Grasshopper) by more than 30% each and Passivhaus Planning Package (PHPP) by approximately 20%, are the most popular software packages which are defined as other software packages.

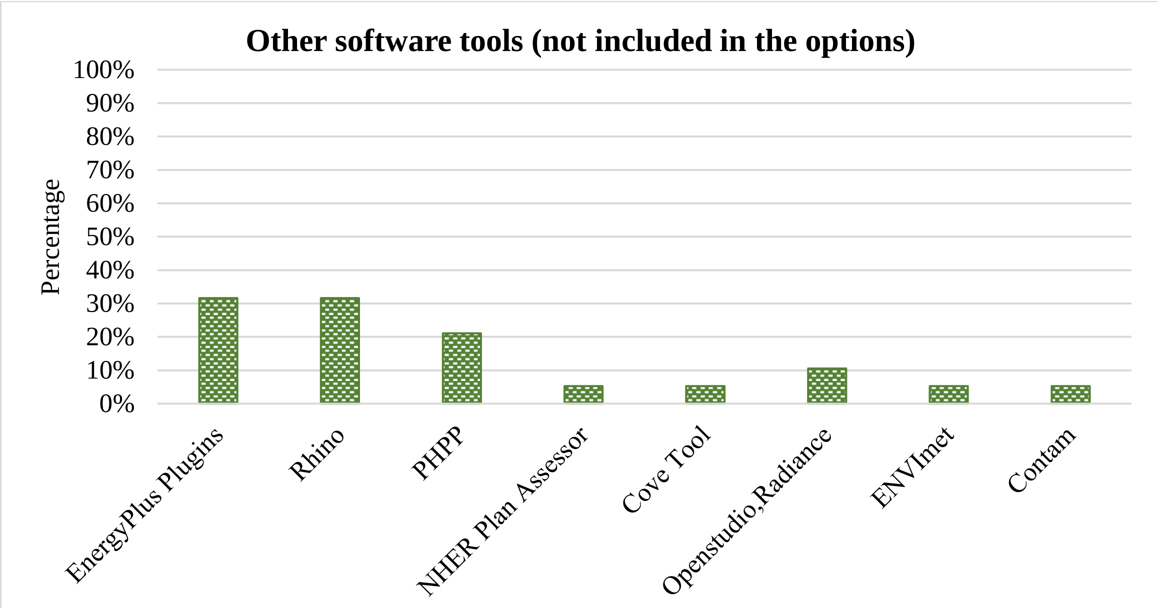

Figure 71: Other software packages

5.3.4 Most common application/purpose of energy modelling software when used for simulating shading products

It is important to note that for this question, participants had the opportunity to choose as many options as they desired (Design, Compliance and Research) which means the total response percentage for each group may exceed 100%. Also, the responses received were divided by the total participants (49) as opposed to the total number of each group which better illustrates the number of participants who responded to this question (Building Services being the most in this case). From the 30 participants who form part of the building services group, nearly half (49%) chose dynamic thermal modelling software tools for *design purposes*, 39% for *compliance* and 22% for *research* purposes. Participants working in academia mostly use these tools for *research* (18%) and *design* (14%) purposes whilst architects have chosen *design* (12%) as the main driver for using the energy modelling software tools when simulating shading devices. Based on the findings, it is clear that building services mainly use the software tools when simulating shading devices for design and compliance purposes due to their direct involvement with the engineering phase of the project in addition to the early stages of the building development which involves complying with certain building regulations in order to be able to get the approval for the design and work. Conversely, academia understandably chose research purposes and then design as the main application of the tools and compliance the least. This response can be attributed to the potential involvement of academia in general research and studies which ultimately have some input to the design and less on compliance which is most common among the project execution phase groups such as building services. Architects have also chosen design more than the other two options which is based on the contribution to the design phase and working closely with the building services at the early stages of the projects i.e., concept and design. To summarise, all three groups have highlighted the importance of assessing shading devices and their application at the early stages i.e. the design phase which amplifies the vital relationship between the software tool being used and the shading device input data to ensure a high level of accuracy when simulating the shading devices and where and how they're fitted in the design of the building (Mahmoud, et al., 2020).

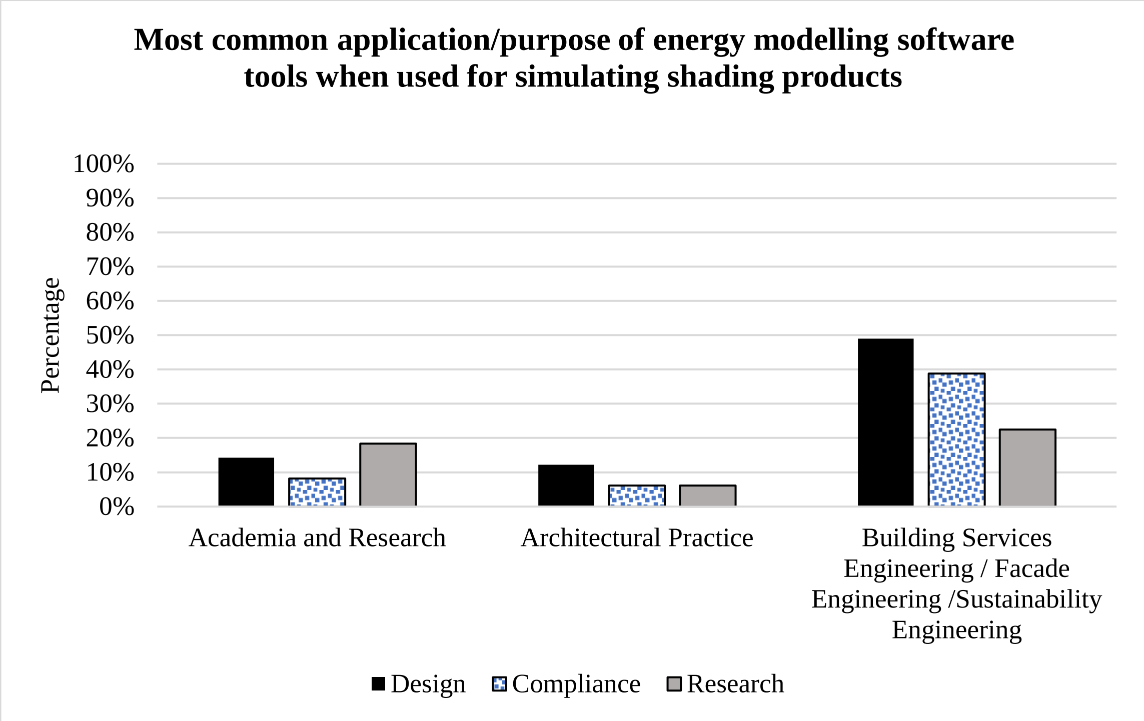

Figure 72: Most common application/purpose of energy modelling software tools when used for simulating shading products

In addition to the selections made by the participants, they were given the opportunity to add comments to provide some insight and context to their decision making. The comments which are presented in Table 22, highlight that many participants across the groups agree that all three options can be applicable based on the situation they find themselves in and one single option is not necessarily the sole driver to the application of use for these software tools when simulating shading devices.

Table 22: Participants comments

ID	Field of Expertise	Comment
1	Academia and Research	*It is a mixture of design and compliance on the basis that we want to make sure the buildings we are involved will meet best practices in energy efficiency and carbon emissions, will actually be comfortable to live in, and it is also necessary to demonstrate compliance with regulations.*

2	Academia and Research	*I think it depends on the context. It can be all three of the reasons depending on the context of the project and the reasons you are modelling. For example, in building services engineering it is probably mostly for design - i.e. so we obtain the correct solar gains to size our systems accurately. As facade design becomes more complex, software needs to be available, accessible and user friendly to be able to model this accurately and timely. In terms of compliance - yes, sometimes it is needed, but I would think it is more for a binary answer, i.e. PASS/ FAIL (for example in overheating criteria).*
3	Building Services Engineering / Facade Engineering /Sustainability Engineering	*Design: We use modelling software to understand the benefits of the shading products in reducing the overall load in the building but on a limited scale. Compliance: We use the modelling software for compliance.*
4	Building Services Engineering / Facade Engineering /Sustainability Engineering	*Probably over the last few years, the main reason for assessing shading within software would be for Design & Compliance. That said, I have over the last year or so, had input on the development of a new volumetric modular platform for our European regions and it would probably be fair to say that entailed an element of research/design development, but with the express intention of ensuring that our new product can achieve compliance in those regions. So, I guess I could probably tick all the boxes there, which is probably not entirely unusual for a building physicist that would work on a variety of workstreams.*

5.3.4.1 IES VE

5.3.4.1.1 Years of Experience

Figure 73 represents the years of experience that participants have been using IES VE based on their field of expertise. Approximately 80% of participants (calculated based on 64 participants) in this question were part of the building services group, 16% were academia and only 3% (only two participants) were architects. As only two architects responded to the questions in this section (Section 5.3.4.1) related to the use of IES VE, it is not possible to draw a conclusion from their responses, so their responses have been omitted from the analysis. The majority of participants who work in academia, have 1-5 years of experience using IES VE, 40% of participants in building services have 1-5 years and 30% of them have 6-10 years of experience.

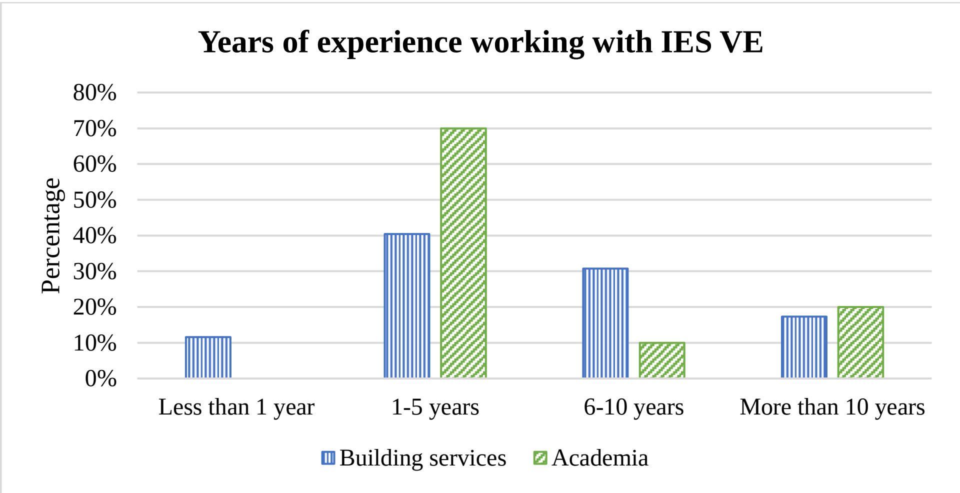

Figure 73: Years of experience working with IES VE

5.3.4.1.2 Satisfaction

More than 50% of both groups of expertise (building services and academia) are mostly satisfied with the user-friendliness, compatibility, reliability and accuracy of the software. This reiterates how having a simplified software tool interface can be more user friendly whilst the other options' chosen will need to be put to the test to ensure the level of satisfaction is replicated in normal circumstances (Figure 74).

Regarding the shading portfolio or database, only approximately 20% of building services and 40% of academia are satisfied. Additionally, more than 50% of all participants are neither satisfied nor dissatisfied with the shading portfolio in IES VE. This shows a clear gap in the shading database this software has and the expectation of the direct/indirect end-users which needs to be strengthened and will ultimately dictate how accurately and frequently shading products will be used in buildings.

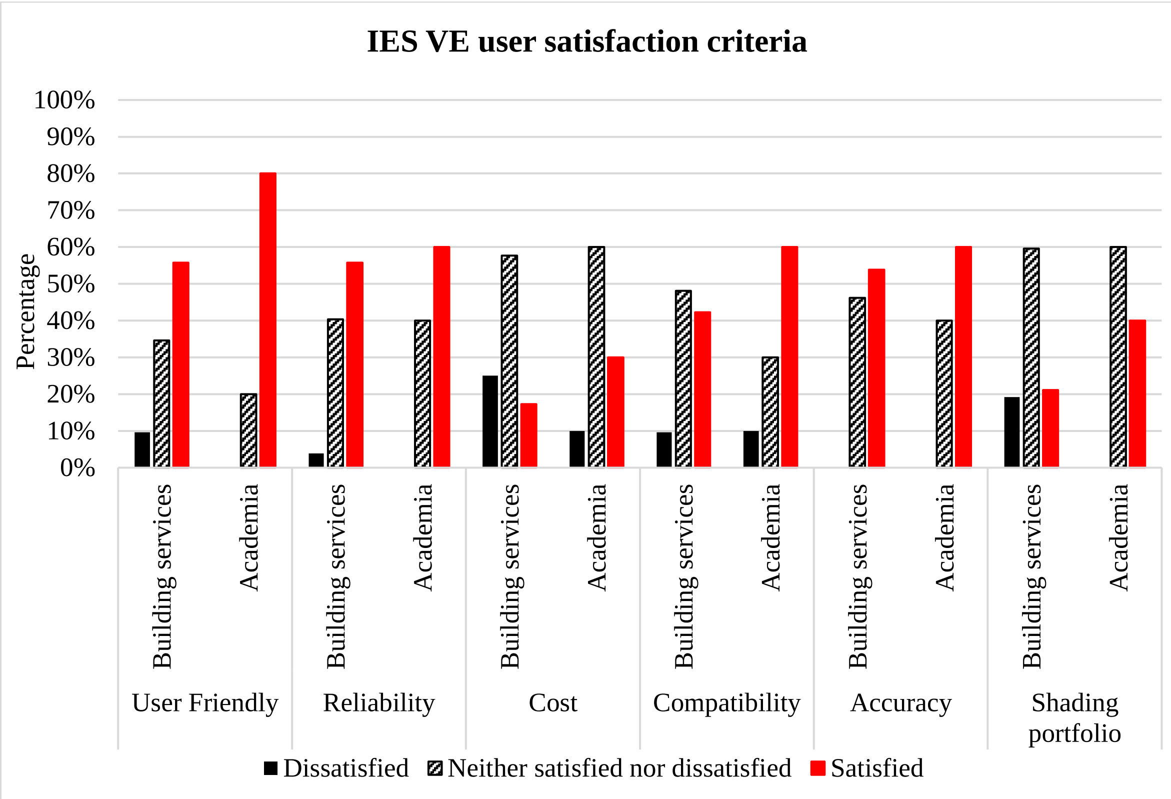

Figure 74: IES VE User Satisfaction Criteria

5.3.4.1.3 Modelling Shading Devices using IES VE

The majority of participants who responded to this question (approximately 90%) use IES VE to model shading devices. From this group, more than half of the participants who work in building services (69%) need to draw shading devices by themselves and only 33% of them believe that various types of shading products are available in the software database. As fewer than 33% of participants believe that various shading types are available in the software database, the participants may need to use their own input for modelling shading devices which means (in the absence of default values set for each shading type in the software database) users will have to manually enter values either taken from manufacturers or other general online resources. This may decrease the level of accuracy when modelling shading due to the possibility of using incorrect input data and assumptions which can ultimately lead to incorrectly specified shading for buildings and inefficient energy. The importance of the input data is highlighted in a recent research study where one of the technical barriers related to the use of BEMS software tools is connected to the data input and output interpretation (Mahmoud, et al., 2020).

Assessing the 69% statistic of building service engineers who draw shading devices themselves, can show that most independent drawing relates to external shading which then means the main focus will be on external shading devices and their ability to reduce overheating and less so on internal shading and their capabilities in reducing heat loss. This is in line with the results presented in Section 5.3.1which shows that external shading devices are more prevalent amongst building modellers. Also, as building services engineers (outlined in Section 5.3.4) mostly use software tools to model shading devices for design and compliance purposes, using external shading has a positive impact on reducing the risk of overheating and consequently the cooling load (Littlefair, 2018). Additionally, it illustrates the lack of interest or knowledge of the modellers regarding the use of internal shading devices for thermal retention purposes which was highlighted in CHAPTER 3.

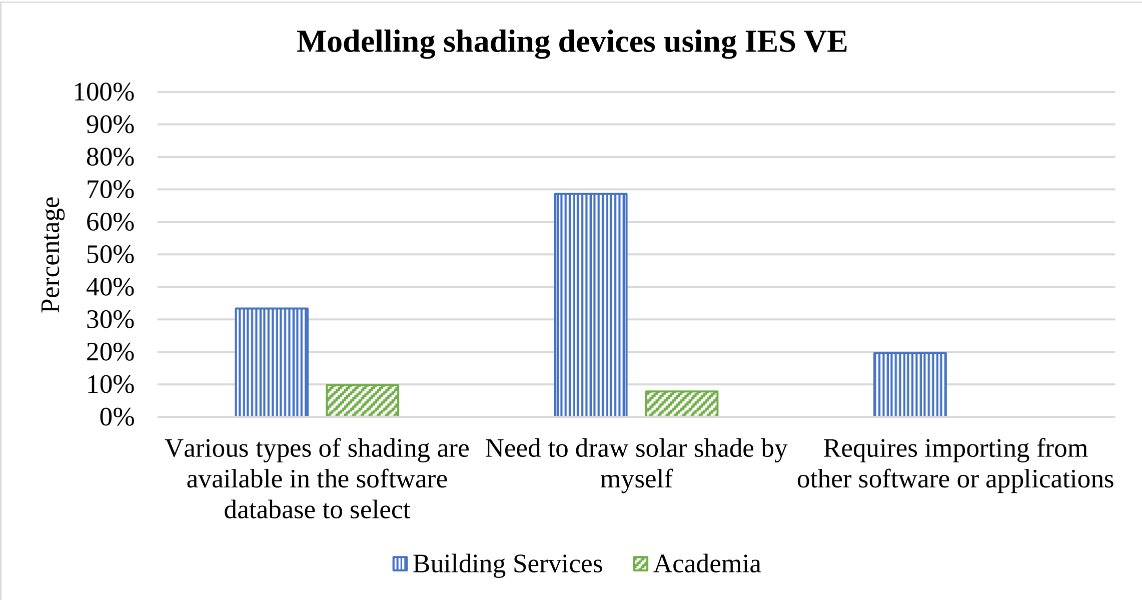

Figure 75: Modelling Shading Devices using IES VE

Fewer than 20% of participants who work as building service engineers, need to import the shading model from other software or applications. The main software tools that participants use to import shading device models are SketchUp, Rhino, Window, Optics, Therm, IGDB (International Glazing Database), CGDB (Complex Glazing Database) and Solidworks. In most cases, these software tools provide a more detailed model and calculation for shading devices compared to solely relying on shading device models in IES VE. As fewer than 20% of building services and none of the academia use alternative software tools for their shading device models, it shows that, from this survey, all of academia and more than 80% of building services rely on IES VE itself to model shading devices. In this case, if the software shading database is not sufficient or fails to model the shading devices and their thermal calculation correctly, there will be a significant impact on the decisions made by the modeller regarding the application and use of shading devices in buildings. This highlights the need for extensive testing of the software against the available shading database to ensure the accuracy levels are high and consequently less chance of inaccurate decisions being made by modellers.

5.3.4.1.4 Impact of IES VE Shading Models on Energy Consumption and Thermal Comfort in Modelling Projects

The majority of participants in building services and academia (more than 87%) acknowledge and appreciate the positive effect of shading devices in reducing overheating which can ultimately improve thermal comfort and energy efficiency in buildings. Furthermore, more than 68% of both groups have seen a positive effect of shading devices on glare reduction. However, in terms of heat loss reduction for thermal comfort and energy efficiency, only 30% of building services have seen a positive effect, while none of the academia has experienced it. Additionally, fewer than 10% of participants in building services have seen a negative effect by adding shading on reducing heat loss for energy and thermal comfort purposes (Figure 76). Participants in academia have seen either no effect or have never checked the effect of shading in reducing heat loss. All these statistics and responses show that participants are not very interested, or necessarily aware, of the beneficial impact of shading devices in reducing heat loss and improving thermal comfort and energy efficiency, so they have not normally checked it in the software. This was discussed in CHAPTER 3 where the results of the survey showed that the effect of shading devices on reducing heat loss is not well recognised by the participants compared to overheating. This was potentially down to the perception that shading devices were being predominantly and historically used in the warmer climates to tackle the overheating issues in buildings (Dwyer, 2018; MakeMyBlinds, 2018). It is possible that those participants who have seen a negative effect of shading devices, have not utilised and applied the shading device in its correct application because reducing heat loss depends on the design and operation of the shading device (Littlefair, 2018). For instance, to reduce heat loss in a building during the heating season, the best approach is use of an internal sealed blind overnight and not closing the device during a sunny day so the room can receive as much solar radiation as possible and reduce the need for lighting and heating. However, when shading is closed throughout the day, it blocks solar irradiance, more heating and lighting energy is required (Littlefair, 2018). The participants who have seen any difference in thermal retention by adding shading devices, may have modelled an unsuitable shading type, for example, external shading is not effective in thermal retention (Littlefair, 2018) or the software was not capable of altering the results by adding the shading device. This requires more investigation into the effect of considering a correctly specified shading device for thermal retention purposes in IES VE. This software was previously tested for reducing overheating by adding a shading device which illustrated that the software results and values do not represent the real effect of shading devices (Venturi, et al., 2018).

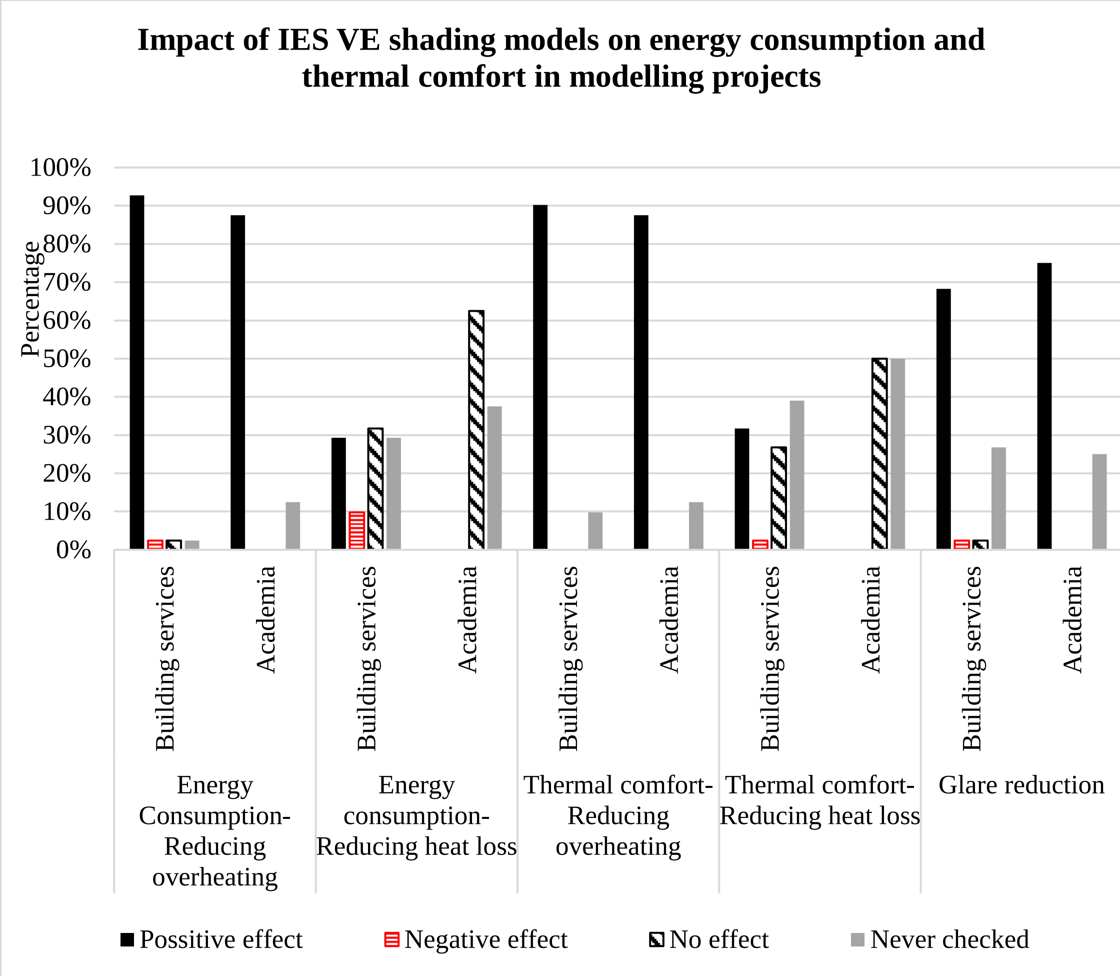

Figure 76: Impact of IES VE shading models on energy consumption and thermal comfort in modelling projects

5.3.4.2 EnergyPlus

5.3.4.2.1 Years of Experience

The total number of participants who responded to this question was 37 with 18 participants working in building services, 16 participants in academia and 3 participants in architecture. As only three architects responded to the questions in this section (Section 5.3.4.2) related to the use of EnergyPlus, it is not possible to draw a conclusion from their responses, so their responses have been omitted from the analysis. The majority of participants (more than half) in all groups have one to five years of experience in using EnergyPlus.

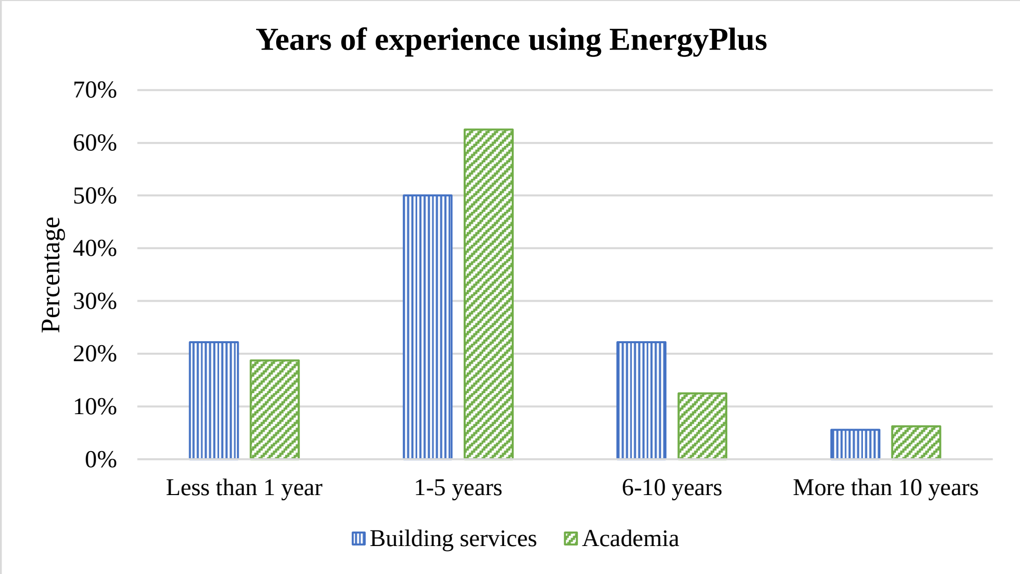

Figure 77: Years of experience using EnergyPlus

5.3.4.2.2 Satisfaction

More than 50% of participants in all groups are satisfied with the “reliability”, “compatibility”, “cost” and “accuracy” of the software. This highlights a general level of satisfaction similar to IES VE which needs to be verified in practice. It also shows whilst EnergyPlus being an open-source software has helped with free access to users and potentially more global reach, being code-based and having a more complex interface does not necessarily make it more user friendly. The shading portfolio and being user friendly are the two main elements that users are not satisfied with. This again highlights the gap in the shading database of EnergyPlus and how the code-based system has impacted the user-friendliness of the software.

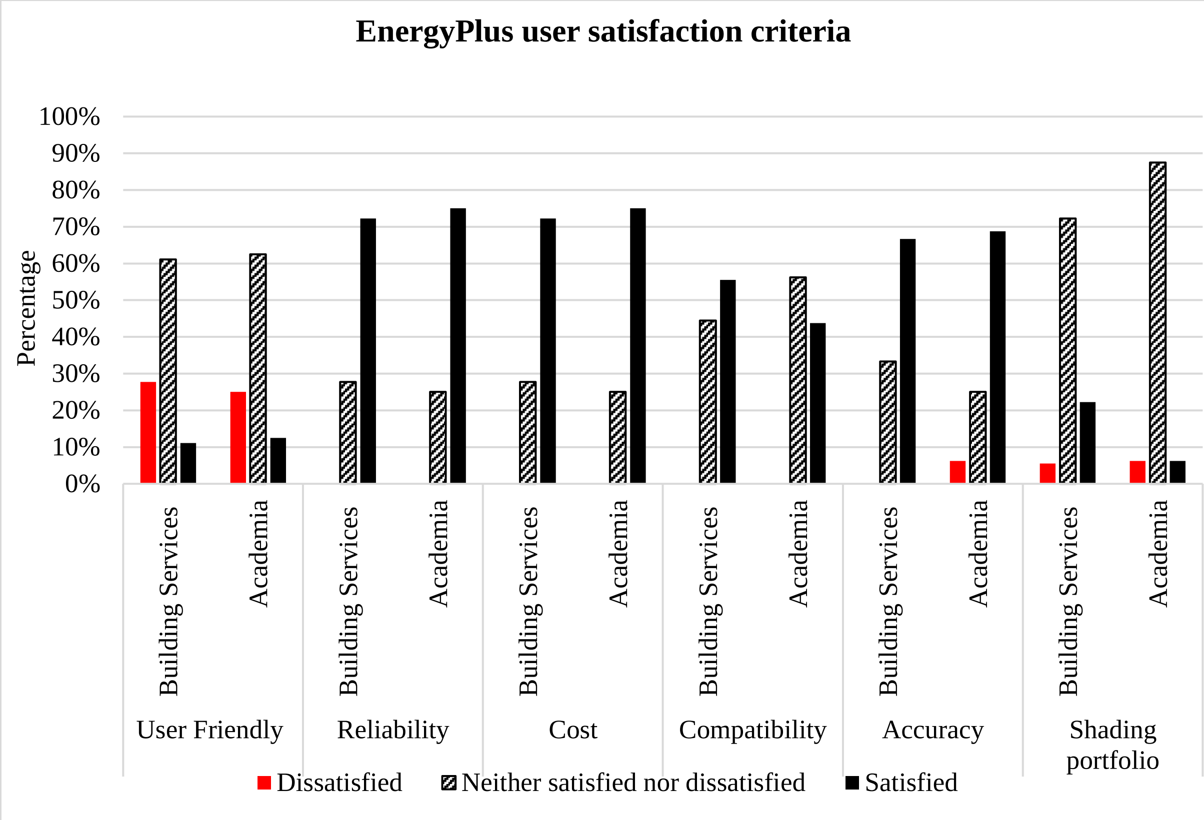

Figure 78: EnergyPlus User Satisfaction Criteria

5.3.4.2.3 Modelling Shading Devices using EnergyPlus

More than half of the participants using EnergyPlus (54%) use this software to model shading products and approximately 53% of building services and approximately 16% of academia need to draw shading devices by themselves. Fewer than 20% of both groups believe that various types of shading are available in the software database. This reinforces what was seen in Section 5.3.4.1.3 where there seems to be a clear gap in the software regarding shading modelling as most of the participants in both groups believe that the shading database within the software is not sufficient. Furthermore, more than half of building services draw their shading themselves which usually refers to external shading types i.e. overhang shading. As discussed in Section 5.3.4.1.3, this highlights that participants are potentially using external shading more often than internal shading as external shading is more beneficial in reducing cooling loads and the risk of overheating (Littlefair, 2018).

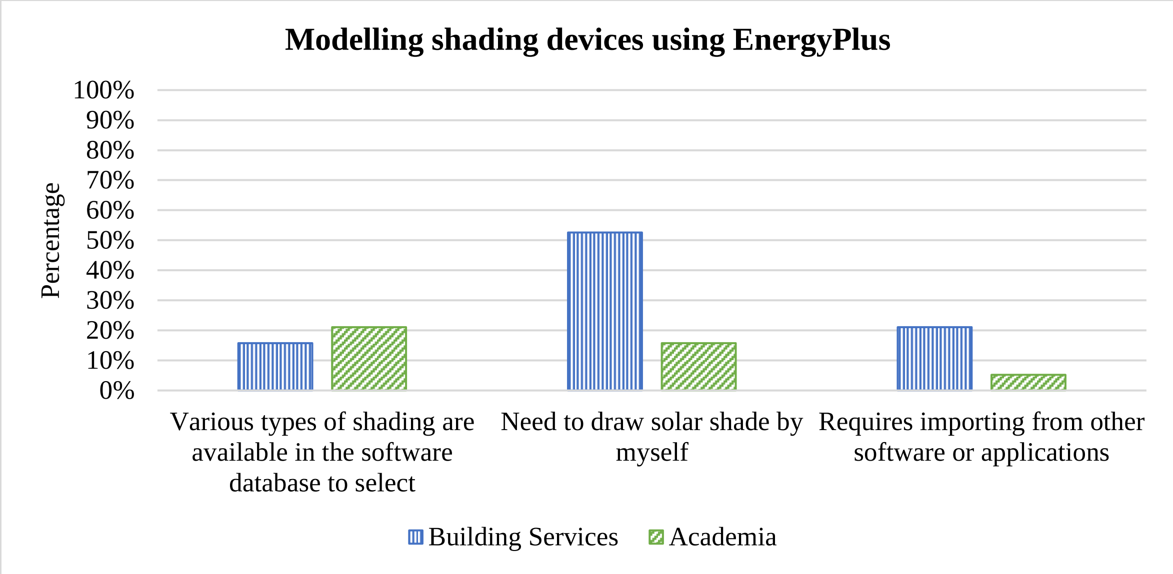

Figure 79: Modelling Shading Devices using EnergyPlus

Table 23 shows that fewer than 20% of participants would use software tools if they were required to import shading models. Those participants who use specific software tools which are designed to model windows such as *LBNL window* and *Therm* achieve a more detailed calculation of window thermal properties (including both internal and external shading devices) but use of software tools such as *Solidworks* or *Rhino* are more useful for drawing external shading devices.

Table 23: Software Tools used to Import Shading Product Models

Field of expertise	Software
Building Services Engineering / Facade Engineering /Sustainability Engineering	SketchUp, Rhino, LBNL window
Building Services Engineering / Facade Engineering /Sustainability Engineering	Rhino
Building Services Engineering / Facade Engineering /Sustainability Engineering	Window, Optics, Therm, IGDB, CGBD
Academia and Research	Solidworks

5.3.4.2.4 Impact of EnergyPlus Shading Models on Energy Consumption and Thermal Comfort in Modelling Projects

All the building services and more than 70% of academia have seen the positive effect of adding shading devices to their EnergyPlus models because it reduces overheating which consequently improves energy efficiency and thermal comfort. Furthermore, 70% of building services and 28% of academia have seen a positive effect on glare reduction. This means that they are aware of the benefits of using shading in reducing overheating and glare, and the software has been able to illustrate this effect in their models. However, regarding reduction in heat loss for thermal comfort and energy consumption, fewer than 40% of building services and even fewer than 15% of academia have seen a positive effect in this matter. More than 20% of building services and more than 57% of academia have never checked the effect of shading on reducing heat loss. As discussed in Section 5.3.4.1.4 and CHAPTER 3 Section 3.3.3, this is in line with the point that participants who are a sample of building professionals in the UK, were not fully aware of the benefits of adding shading devices to their software models regarding thermal retention in buildings, although they acknowledged the benefits of shading devices in preventing overheating. As in Section 5.3.4.1.4, 10% of building services that have experienced a negative effect by including shading devices in their models, may have not modelled or operated the shading device correctly. This again highlights the lack of knowledge regarding shading devices and how to operate them correctly (Littlefair, 2018). Between 20% and 40% of building services and academia have seen no effect of adding shading devices to thermal retention in building models. Again similar to Section 5.3.4.1.4, this can be either due to incorrectly specifying shading devices for heat loss as only internal sealed blinds can be effective in this situation, or it can be due to the inability of software tools to alter temperature and energy consumption values by adding a shading device. This requires further investigation further to check the ability of software tools that represent the effect of shading devices in much more detail and in line with real-world scenarios.

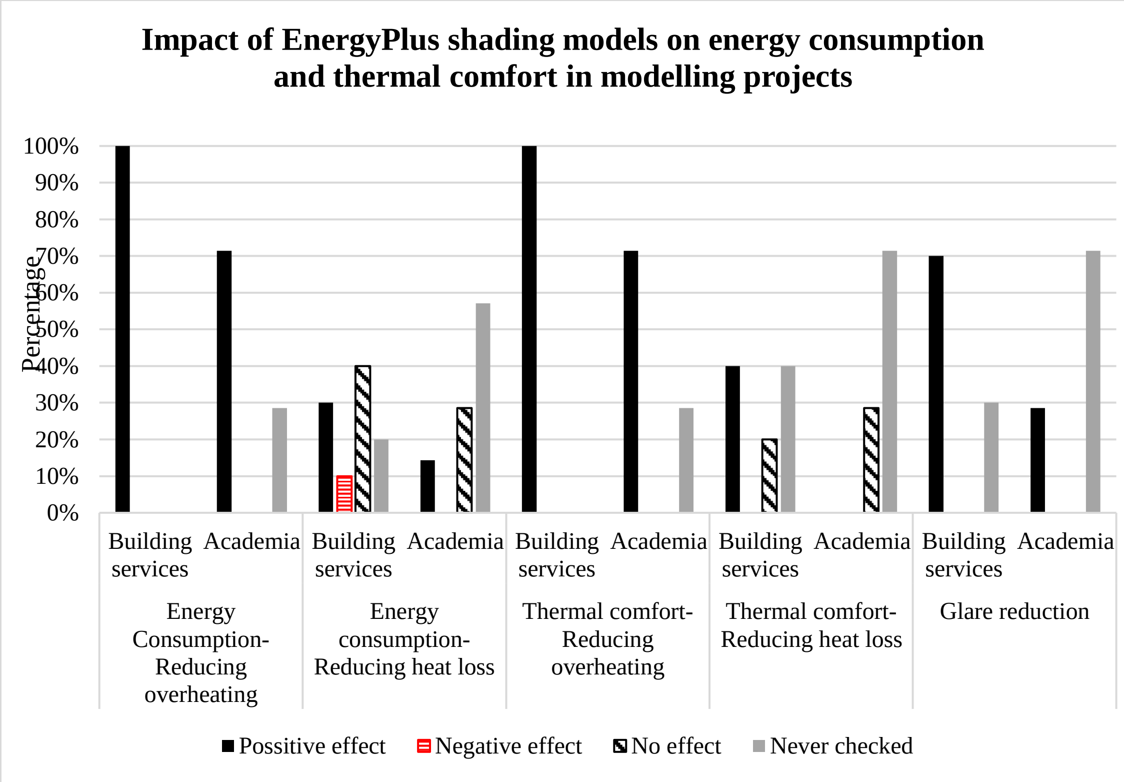

Figure 80: Impact of EnergyPlus Shading Models on Energy Consumption and Thermal Comfort in Modelling Projects

5.3.4.3 EDSL Tas

5.3.4.3.1 Years of Experience

All of the participants who are using this software (14 participants) work in the building services sector which shows its application is quite tailored to building services and building regulations. Regarding the years of experience, 36% of them have one to five years and 29% have fewer than one year of experience.

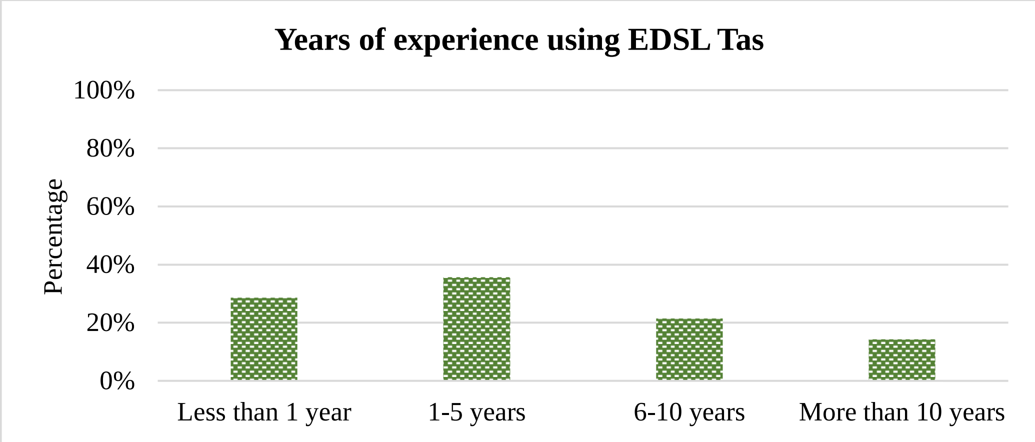

Figure 81: Years of experience with EDSL Tas

5.3.4.3.2 Satisfaction

Participants are generally satisfied with all of the criteria apart from the shading portfolio. As the responses are solely from one group, it shows that general satisfaction is based on the application of use of this software in their respective sector. Fewer than 10% of participants are satisfied and more than 90% are neither satisfied nor dissatisfied with the shading portfolio in EDSL Tas. It is a common theme amongst most software packages that shading databases need more focus and strengthening.

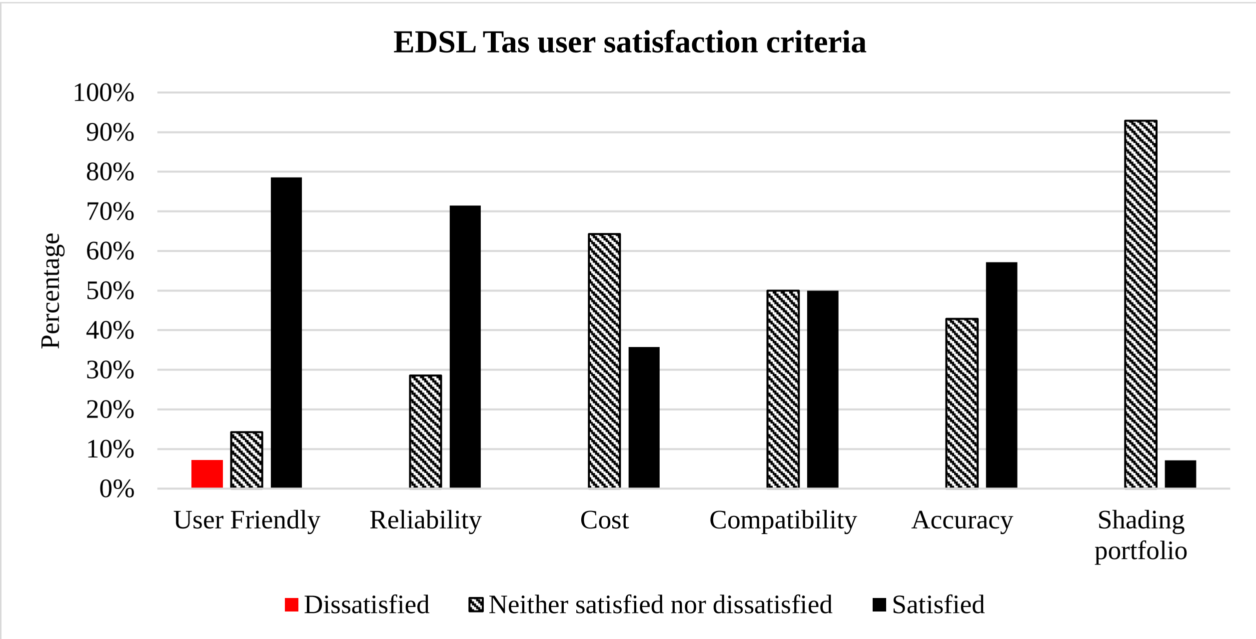

Figure 82:EDSL Tas User Satisfaction Criteria

5.3.4.3.3 Modelling Shading Devices Using EDSL Tas

More than half of the participants (57%) who use EDSL Tas, use this software for modelling shading devices. Half of the participants believe that various types of shading devices are available within the software database and a vast majority (88%) draw shading by themselves. As previously mentioned, when a modeller draws a solar shade in the software, it usually refers to external shading devices (i.e., overhang and awnings) which highlight the point that external shading is more common amongst modellers compared to internal shading devices. This is in line with what was found in Section 5.3.4.1.3 and CHAPTER 3.

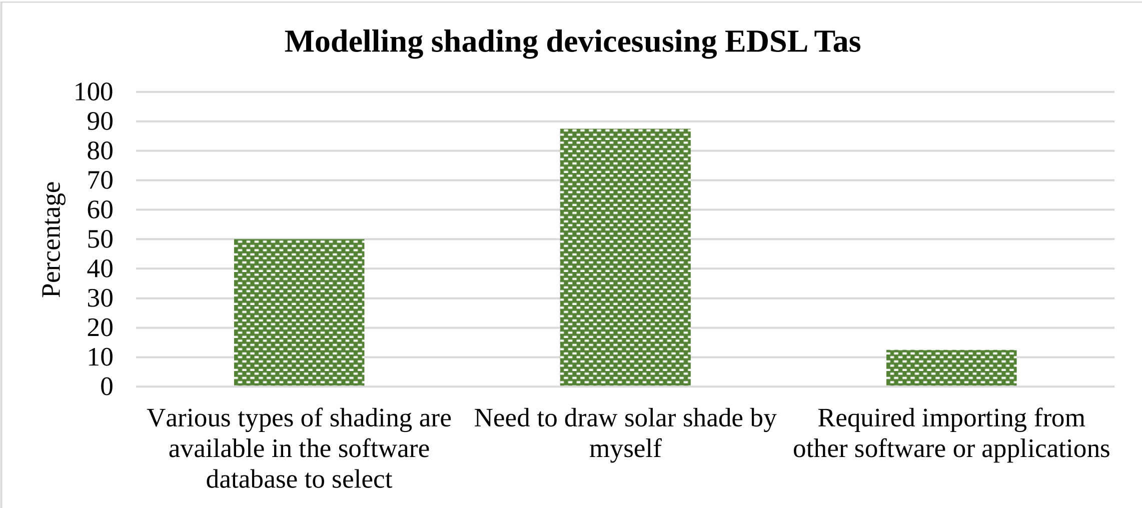

Figure 83: Modelling Shading Devices Using EDSL Tas

The only participant who needed to import shading device models from other software tools or applications used *Revit* for this purpose.

5.3.4.3.4 Impact of EDSL Tas Shading Models on Energy Consumption and Thermal Comfort in Modelling Projects

The results highlight that the participants are aware of the effect of shading devices in reducing overheating and glare and this software is capable of illustrating its positive effects. However, regarding the thermal retention benefits of shading, the participants have either never checked or if they have checked, they have seen no effect on the results or have seen negative impacts of adding shading devices on energy consumption. As discussed in previous sections, the negative effect may be due to the incorrect use of shading devices. For instance, if a shading device is closed during the day in a heating season, it can block solar radiation and will consequently increase the need for lighting and heating during the day (Littlefair, 2018). This again illustrates the lack of knowledge and interest in using shading devices to reduce heat loss which was discussed in previous sections.

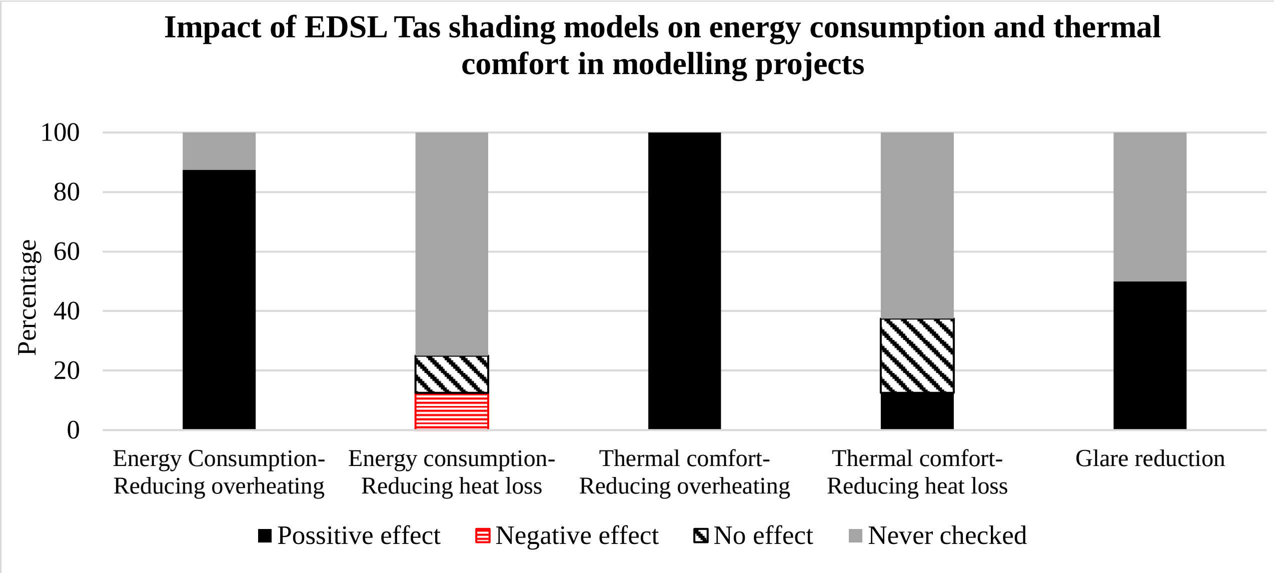

Figure 84: Impact of EDSL Tas Shading Models on Energy Consumption and Thermal Comfort in Modelling Projects

5.3.4.4 DesignBuilder

5.3.4.4.1 Years of Experience

The total number of participants who use this software is 24 where 63% (15 individuals) of them work in building services and 33% (eight participants) are academics. Only one participant belongs to the architects' group, based on this, it is not possible to factor in their response, therefore, their response has been omitted from the analysis so the architect group is not considered in this section. All of the participants have a similar number of years of experience.

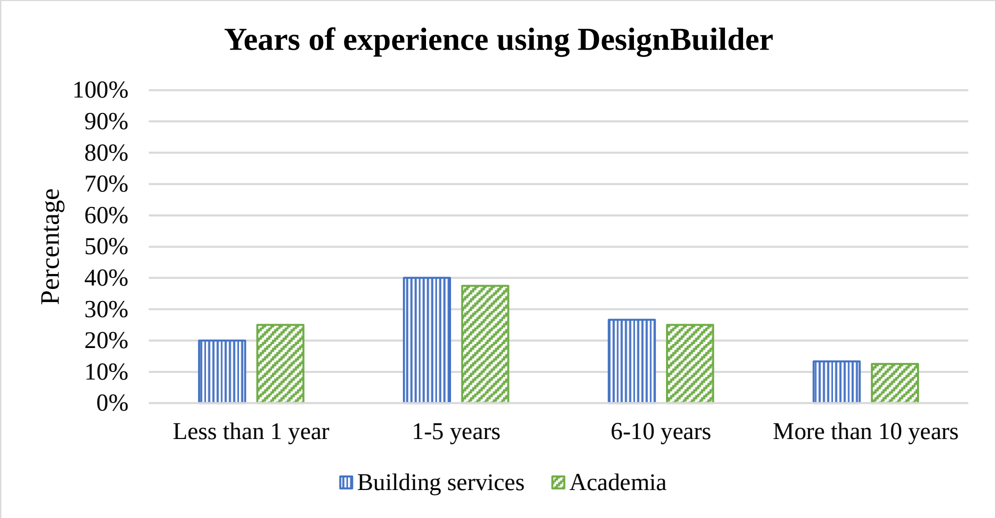

Figure 85: Years of Experience using DesignBuilder Satisfaction

5.3.4.4.2 Satisfaction

Results presented in Figure 86 show that participants have the least satisfaction with *shading portfolio* but *user-friendly, reliability and accuracy* have the most. For the shading portfolio option, although none of the participants chose the dissatisfied option, most of the participants (more than 60%) are *neither satisfied nor dissatisfied*. This highlights the point that the shading database of DesignBuilder was either not able to satisfy the users, or the users do not value shading devices in the model so they may have never checked the shading database to see if they are satisfied or dissatisfied. This can be in line with the point discussed in Section 5.3.1 that the participants mostly draw external shading devices in their models, so they're less likely to pay attention to the shading database in their models. This was illustrated and discussed in Sections 5.3.4.1.4, 5.3.4.2.4 and 5.3.4.3.4 where participants mostly draw their shading devices in their models which can refer to overhang or side fins which are sometimes specified in the model as a local or external shading device.

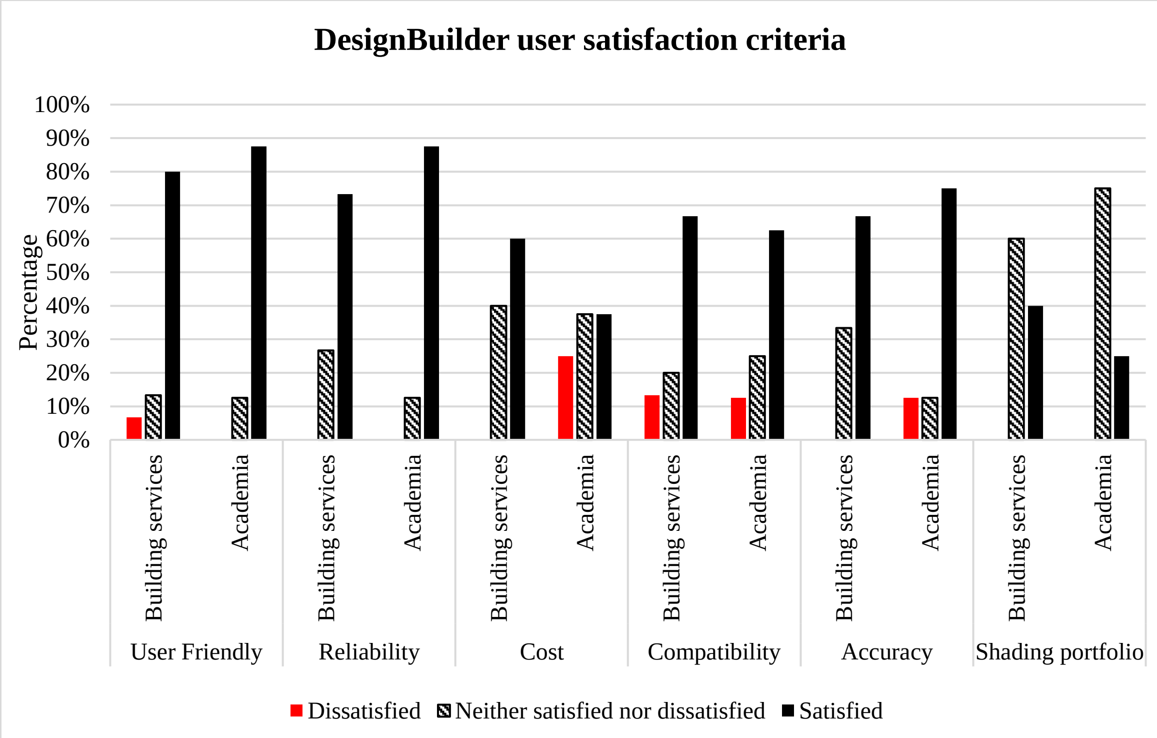

Figure 86: DesignBuilder User Satisfaction Criteria

5.3.4.4.3 Modelling Shading Devices Using DesignBuilder

About a third (38%) of building services and 15% of academia are satisfied with the software shading database and they use it for modelling shading devices. The majority of participants in both groups (approximately 60% of building services and 30% of academia) draw shading devices in the model by themselves. When they draw a shading device, it usually refers to the external shading. This is in line with the results of Section 5.3.1 which states external shading is more frequently used by the participants.

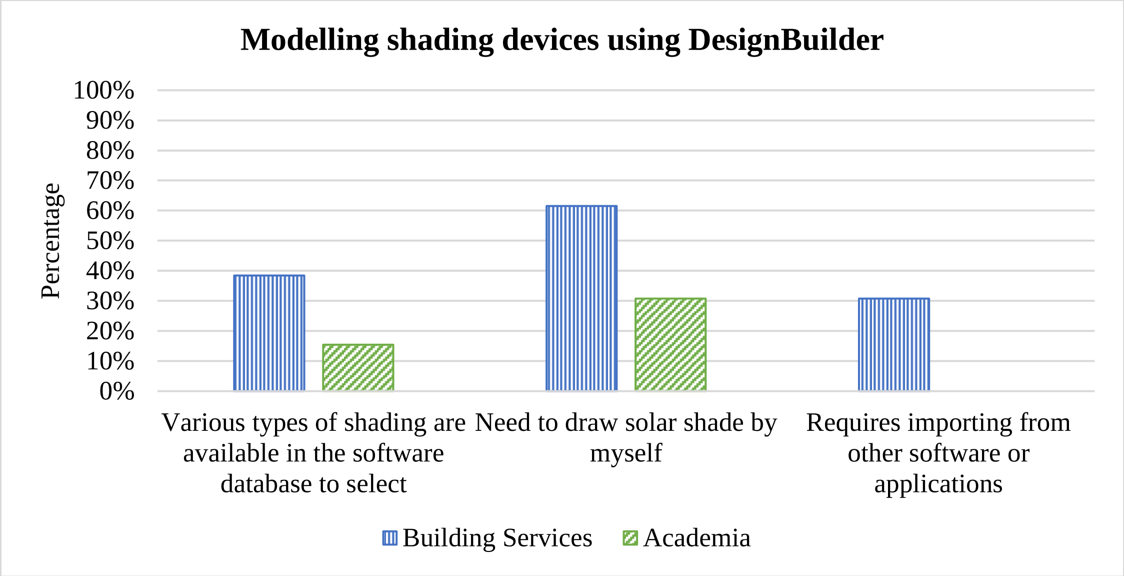

Figure 87: Modelling Shading Devices Using DesignBuilder

A third (30%) of building services import shading models from other software tools or applications including *Rhino*, *SketchUp*, *Window*, *Trimble SketchUp* and *Revit*. As discussed in previous sections, software tools such as Rhino and Revit are mostly used for modelling external shading devices.

5.3.4.4.4 Impact of DesignBuilder Shading Models on Energy Consumption and Thermal Comfort in Modelling Projects

All of the participants in academia and more than 88% of building services are aware and have seen the positive effect of adding shading devices to reduce overheating which can improve thermal comfort and increase energy savings. More than half of the participants in both groups have seen a positive result in reducing glare. Regarding the reduction of heat loss, more than 55% of participants who work in building services have seen a positive effect of adding shading devices in reducing heat loss in terms of energy consumption and thermal comfort while only 25% of academia have seen this effect on energy consumption and neither of the groups have seen the positive effect on heat loss to assist with thermal comfort. This is because more than 50% of academia and about 30% of building services have never checked the effect of shading on thermal retention or if they have checked, they have not seen any effect on the results. This is a similar pattern to other software tools (Sections 5.3.4.1.4, 5.3.4.2.4 and 5.3.4.3.4) where modellers were not aware of the beneficial effect of shading devices on heat loss reduction, or in cases where they intend to consider shading, due to the wrong operation method or use of an incorrectly specified device, they have either seen a negative effect or no effect at all (Littlefair, 2018). Furthermore, the software package may not be capable of illustrating this effect which highlights the importance of checking and testing the software tools in relation to the impact of shading devices on heat loss.

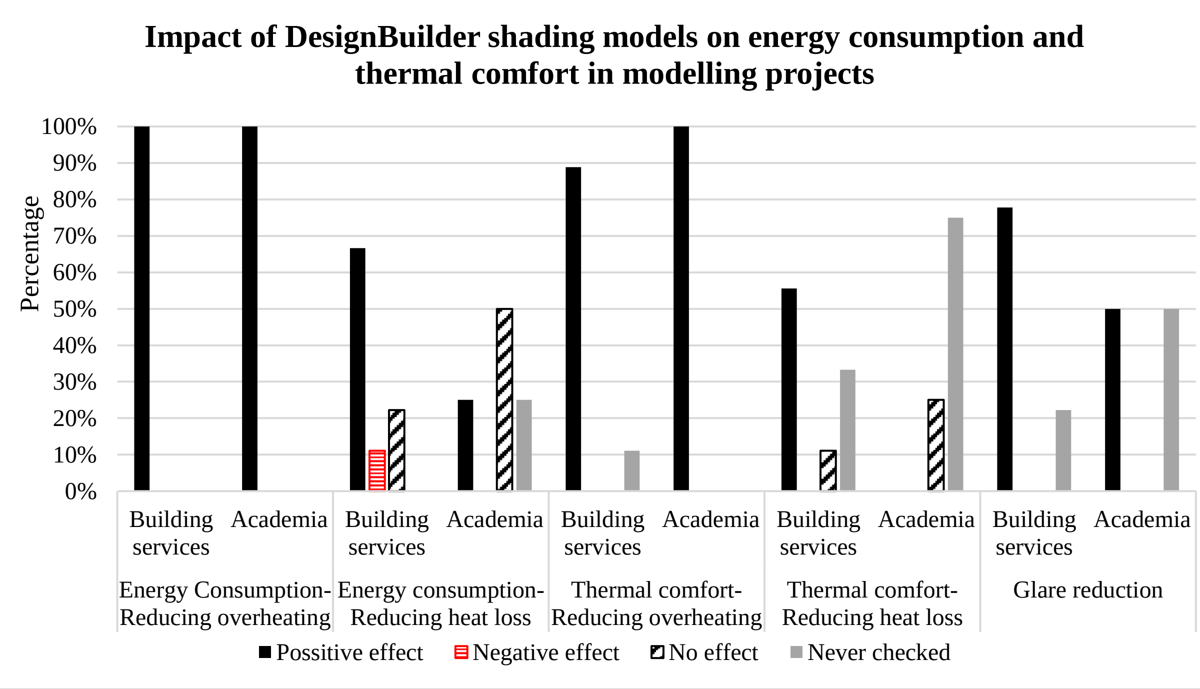

Figure 88: Impact of DesignBuilder Shading Models on Energy Consumption and Thermal Comfort in Modelling Projects

5.3.5 Additional Participant Feedback regarding Modelling Software Packages within the Shading Industry

In the final stage of the survey, the participants were asked to provide their feedback for the shading industry with regard to the BEMS software tools (Table 24). Reviewing the feedback and comments highlighted the importance of the architect's role and decision making in relation to how frequently and correctly shading devices are used in buildings. This is mentioned by participants number 5, 9 and 10 and relates to what was discussed in CHAPTER 3 and even further highlighted by the fact that most of the architects who participated in this survey did not fully complete the survey as they do not consider shading devices in their projects. In this case, as participants numbers 5, 9 and 10 have stated, even if architects intend to use shading devices in their projects, they do not have sufficient knowledge in this matter and building services engineers are more prone to reactive methods rather than proactive ones which tend to result in short term retrofit options as opposed to utilising solutions at early concept stages of the project.

Another point mentioned by the participants is the requirement of having a dedicated free technical support function on how to model shading devices in buildings in addition to continuous training programmes. In addition to that, having a complete datasheet of various types of shading devices within the software can make the modelling process easier and more accurate so providing a datasheet or guideline readily available to modellers would go a long way in closing the knowledge gap and avoiding mistakes in specifying shading devices or even completely omitting them from the design. Regarding this topic, the CIBSE Good Practice Guide to Dynamic Thermal Modelling of Basic Blinds is expected to be published in 2022. In addition, European Solar Shading Organisation (ES-SO) has developed a database of solar shading materials which includes independently validated performance data of blind fabrics, materials and complete products to European standards. However, the datasheet is not complete and lacks most of the shading types. It was found to be quite complex and difficult for modellers to extract the data they need from it. This feedback was noted by the researcher during multiple meetings with modellers at various events and conferences.

Furthermore, similar to what was investigated and identified in CHAPTER 3, participants are aware of the benefits of external shading devices on reducing the risk of overheating, but this is not the case when it comes to the benefits of internal shading devices in respect to thermal retention.

Table 24: Additional Participant Feedback regarding Modelling Software Packages within the Shading Industry

ID	**Field of Expertise**	**Feedback/Comment**
1	Academia	*More **free technical support on how to model shading** is required*

2	Building Services	*It would be more useful* ***to have a large set of families to choose from for a variety of shading options****. These would save time and be useful due to the reliability and adaptability they could have with the projects we do.*
3	Architectural Practice	*We* ***prefer to use external shading on buildings to internal shading as it is more effective -*** *but really we should be reducing the fenestration/ glass ratio of buildings.*
4	Building Services	*Please make modelling* ***input parameters****, particularly solar reflection/transmittance properties of products* ***more commonly available on datasheets****.*
5	Architectural Practice	*Shading needs to be integrated into the* ***architectural approach from the outset of projects****. As someone who comments on planning applications, I frequently raise concerns about overheating during pre-application discussions and see many projects where no consideration is given to the need for* ***external shading*** *to help mitigate the risk of* ***overheating****.*
6	Building Services	*I think a* ***universal standard*** *for the solar properties should be provided in all shading product literature. Often there is a discrepancy between American & EU terminology of shading coefficient and Solar factor - it can easily get misconstrued*
7	Building Services	*Data monitoring would help a better understanding and modelling of shading products*
8	Building Services	*Would be great if software packages accounted for reduced airflow when drawing in external shading such as brise-soleil.*

9	Building Services	*For* ***external shading*** *devices - in my experience this is mainly* ***architecturally driven****, so we would model (and sometimes have input on) what form these would take. I have not seen many "off the shelf" external shading devices used on projects I have worked on.* *For mid-pane blinds I have seen glazing specifications where these come as a product with a g-value quoted. I would model this as a g-value in IES (without necessarily modelling the glass structure with the mid-pane blind, as I understand the correct g-value should give the same or very similar results as actually using a glazing build up with a mid-pane blind in IES).* *For internal blinds - I would use the standard options in IES for what the architect intends to use.* *I have seen internal film used before to reduce the g-value of existing glazing. In this instance - I would speak to the manufacturer and ask the resultant g-value and model this as a piece of glass in IES with that g-value.* *In general - as mechanical engineers, from what I have seen, the external shading is architecturally driven - and from what I've mostly seen, with some exceptions - given little thought. In cases where architects do think about external shading and understand its benefits - it makes the modelling process much better and rewarding for the project - and the benefits of the shade are reflected in the finished design (and finished building).*
10	Building Services	*I think it is really an* ***architectural decision*** *and Building Services are not involved but really should be to help drive the benefits. I*

		think Building Services are very reactive rather than proactive on this subject.
11	Building Services	*Actually just getting hold of* ***reliable data from manufacturers*** *in terms of performance, reflectance's,* ***isn't always straightforward****.*
12	Building Services	*IES VE's ability to model shading systems is certainly open for improvement. This was illustrated in the Bayham Street case. Modelling of internal blinds appears to be inaccurate. It appears that the heat gain between an internal blind and glazing is not modelled in an accurate fashion. Further, internal blinds do not influence natural ventilation behaviour when dropped, nor the calculated daylight lux levels, so the user needs to be well aware of what is and is not accounted for when simulating. If internal blinds are present, I tend to introduce these into the software as a modified glazing g-value, as I do not trust the software's modelling of internal blinds. I use IES because it is what I have become accustomed to. The performance varies as the software is updated. I do find the software to be quite buggy at times. IES does not seem to have a robust software testing program in place before releasing updates. This exposes users to the pain of trying to find workarounds until the next update. This is my primary complaint about the software, but overall, I am sufficiently satisfied to keep using it.*
13	Architectural Practice	*PHPP is a purely Excel-based calculation, yet very advanced, but no fancy interface. Shading products or objects, including trees and neighbouring buildings are entered manually by specifying their height and depth in relation to the windows.*

5.4 Discussion and Conclusion

The results from the BEMS Software Packages survey show that external shading devices are more prevalent than internal and interstitial shading types specifically at the design phase of buildings which may be due to the fact that elements such as planning approval challenges and the financial aspects are not necessarily a key factor considered at the modelling/design phase of the projects (Mahmoud, et al., 2020). However, when it comes to the actual building phase (not the modelling phase of the project), internal shading is more prevalent as discussed in CHAPTER 3. This conclusion highlights the gap between the design and modelling phase where various elements may be considered in theory but when it comes to the practical phase i.e. the execution phase of the project, other factors such as commercial and planning obstacles play a role in what is actually considered in the building.

As discussed and highlighted in CHAPTER 3, architects have a pivotal role in the shading industry as they are considered one of the key professionals who can consider shading devices within a building at the early stages of the design and before planning permissions. However, this survey showed that architects either fail to consider themselves directly linked to the shading industry, or there is a clear lack of shading device input in their projects which can be a contributing factor to the evident challenges seen related to the use of internal shading devices. This was emphasised by the fact that most of the architects who were approached to complete this survey with the criteria of having some kind of exposure to shading devices in their projects, failed to complete the full survey. This again highlights the need for further training, knowledge sharing tailored specifically to the architects in this matter regarding the benefits of shading devices and to ensure the correct use of these devices in buildings.

The most common software packages in the UK for dynamic thermal models are IESVE, DesignBuilder, Energy Plus and EDSL Tas. Investigating the level of satisfaction of participants regarding the shading portfolio within the software highlighted that the shading database requires improvement and must include various types of shading and materials by the software vendors to enable more accurate and wider use of shading devices. In the instances where the software packages have included these databases, additional and tailored training for the modellers is a necessity to ensure full understanding and application of the database. This issue was also highlighted and repeated in the comments and feedback provided with participants in Section 5.3.5 where the participants mentioned the lack of a comprehensive shading database within the software and also access to databases provided by manufacturers is challenging and needs improvement.

Furthermore, the building energy modellers within the UK are generally aware of the impact of shading devices in reducing overheating and glare; however, there is a clear gap in awareness and understanding regarding the benefits of shading devices with regards to reducing heat loss in buildings. Considering the overwhelmingly cold weather in the UK and the addition of extremes of colder and warmer weather as a result of climate change, it is imperative to insulate windows as well as the other parts of the buildings. Therefore, educating the construction professionals and building specifiers regarding this topic can be the initial step to enhance the energy efficiency level of buildings especially during the heating season.

Further analysis on the effect of internal shading devices on reducing heat loss in buildings in the four software packages, investigated in this survey, is required in order to assess the accuracy of the results and to identify the most suitable software with the least error and discrepancy with real-world data.

5.5 Summary

This chapter outlined the data collection method to investigate the BEMS software packages within the UK building industry. The survey was completed by 98 individuals including building energy modellers. The results of the survey were discussed in this chapter and the main findings are listed below:

- External shading devices are the most commonly used type of shading by the building energy modellers within the UK

- There is a clear gap in awareness and knowledge of the benefits of internal shading devices in terms of thermal retention between the individuals who directly or indirectly deal with building energy software modelling packages
- There is relative dissatisfaction from all groups across all software packages related to shading device databases used in the software tools and the lack of readily available datasheets that provide guidance to modellers
- There is a missing link between the architects and the application of shading devices due to their low participation in this survey (not fully completing the survey) despite being one of the key groups of professionals who need to understand the importance of including shading devices at the concept design phase of projects because the decisions that they make have a significant impact on building performance, thermal comfort and energy

CHAPTER 6

Dynamic Thermal Modelling

6.1 Introduction

Dynamic thermal models have a prominent place in the building industry as their results can influence the building professionals' decisions when considering shading devices in buildings. However, if the BEM software packages are not capable of generating accurate results regarding the inclusion of shading devices, this can significantly affect the use of these devices in the building projects specifically during the early design phase. A representative and corrected simulated model with the least discrepancy compared to real-world data can ensure that more consideration is given to the use of shading devices in the early stages of the building design. However, very few research projects have illustrated the discrepancy between the simulated results generated with various software tools and the discrepancy between the simulated results and the measured data collected in real-world case studies (Venturi, et al., 2018; Petrou, et al., 2019). Additionally, none of these studies has specifically investigated the effect of using shading devices overnight during the heating season.

Within this chapter, the results of the real-world Case study 2 presented in CHAPTER 4 are compared with the simulated results generated with the four most common software packages in the UK (EnergyPlus, DesignBuilder, EDSL Tas and IES VE). These software packages have been selected according to the results of the conducted survey presented in CHAPTER 5 of this thesis. The simulated results of the software packages used are also compared against each other to find the most suitable software package for modelling shading devices with a specific focus on heat loss.

In this chapter, the details of the case study models generated by the four software packages are explained in Section 6.2. Within this section, building geometry, construction material, shading specification, internal gain, infiltration, heating system and weather files are all defined in detail. Whilst in Section 6.5, the simulated results are compared with the measured values and a sensitivity analysis is performed to evaluate the software packages' performance in modelling shading devices.

The conclusion and summary of this chapter are presented in Section 6.7 and Section 6.8, respectively.

6.2 Modelling the Case Study Envelope

In this section, the modelling inputs and the construction details of the dynamic thermal model of Case Study 2, generated by four software tools are described including factors such as geometry, construction material, shading specification, internal gains and the heating system schedule.

6.2.1 Building Geometry

To simulate the closest condition to the Case Study 2 test room especially replicating how high up the test room was from the ground, an 8-floor building was modelled whereby the test room was located on the 7th floor (Figure 89). This allows consideration of the influence of adjacent rooms and floors on the thermal behaviour of the test room. The geometry and orientation of the room are similar to the real-world Case Study 2.

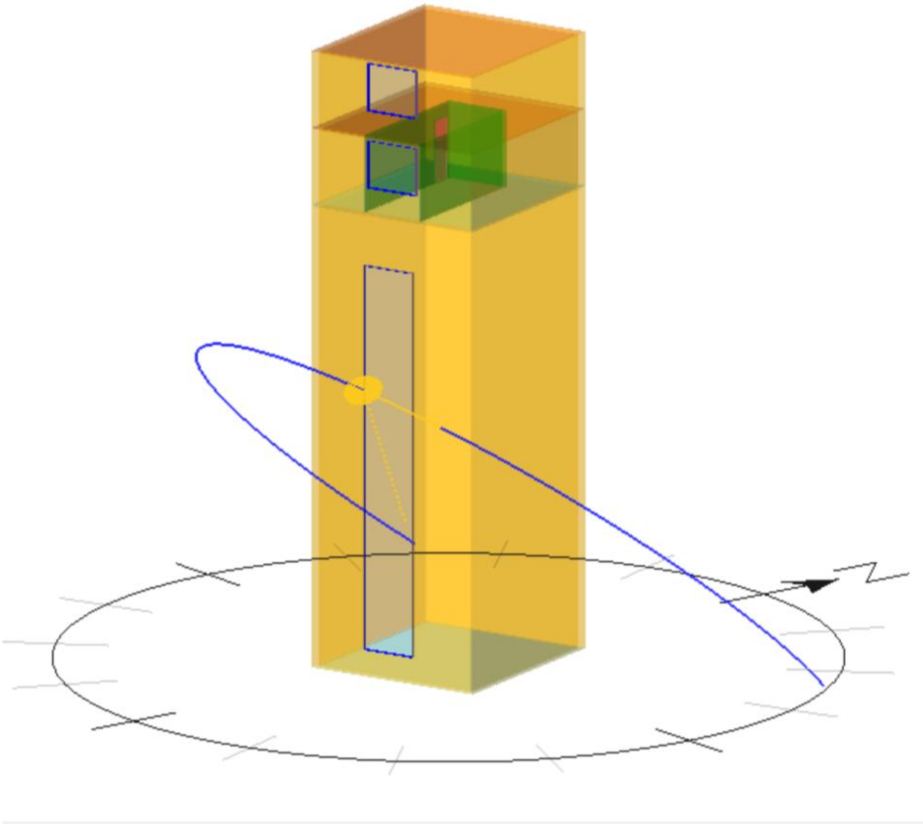

Figure 89:3D model of the test room located on the seventh floor of Tower Block modelled in EDSL Tas

6.2.2 Construction Material and Properties

The construction properties and materials of the test room were estimated according to the CIBSE TM 53, CIBSE Guide A and through observation as stated in Section 4.3. Table 25 shows the thermal transmittance values of the building elements used in the dynamic models, for a more detailed breakdown of the construction elements of the test room, the thickness, density and conductivity of the materials used in the models based on each software tools' library please refer to Appendix G. To reduce possible discrepancies and to ensure a more unified comparison, the models were generated in the four software packages with similar U-values and construction layers as shown in the table below. In an attempt to ensure the overall U-value is quite consistent across the board, they were kept quite similar for all the software packages but no modifications were made to the construction data and their sub-components such as density and conductivity in order to truly represent the content of each software packages library used by the modellers.

Table 25:Thermal transmittance of the building elements used in dynamic thermal models

Building Element	U-value (W/m². K)			
	EDSL Tas	**EnergyPlus**	**DesignBuilder**	**IES VE**
Internal floor/ceiling	1.11	1.11	1.11	1.11
External wall	0.60	0.63	0.61	0.61
Internal wall	0.59	0.66	0.614	0.66
Windowpane (without blind)	5.81	5.78	5.77	5.70
Door	1.82	1.80	1.84	1.84

6.2.3 Shading Specification

Input parameters for modelling shading devices vary for each software package. Table 26 presents the required input each software package needs to enable modelling of the shading devices in terms of solar gain and thermal performance. The reference to “input” data means it's either directly sourced from the manufacturer (EnergyPlus, DesignBuilder and EDSL Tas) or provided by the modeller via calculations (IES VE) and when referring to “calculated” it means the value is calculated by the software itself. EnergyPlus, DesignBuilder and EDSL Tas follow the same approach for modelling shading devices by being quite reliant on the manufacturers' raw data whereas IES VE utilises more calculated values provided by modellers as their input data.

Table 26: Software input requirements for modelling shading devices

Input parameter		EDSL Tas	DesignBuilder	EnergyPlus	IES VE
Solar gain properties	**Transmittance**	Input	Input	Input	No
	Reflectance	Input	Input	Input	No
	Shading coefficient (SC)	Calculated	No (SHGC is used instead)	No (SHGC is used instead)	Input

	Short-wave radiant fraction	Calculated	Calculated	Calculated	Input
Thermal performance properties	**Thickness**	Input	Input	Input	No
	Conductivity	Input	Input	Input	No
	Emissivity	Input	Input	Input	No
	Thermal transmittance (U-value)	No	No	No	Calculated based on R_{sh} input
	Fabric thermal resistance (R_{sh})	Calculated based on conductivity and thickness	Calculated based on conductivity and thickness	Calculated based on conductivity and thickness	No
	Additional thermal resistance (ΔR)	No	Calculated	Calculated	Input
	Shade to glass distance	No	Input	Input	No
	Perimeter gap (top, bottom and sides)	No	Input	Input	No

Now that the input requirements for each software package are known, Table 27 shows the actual input values used (either from manufacturers or calculated by the modeller) which are similar to the values used in the real-world case study.

Table 27: Software input values for modelling shading devices

Input parameter		**Unit**	**EDSL Tas**	**Design Builder**	**Energy Plus**	**IES VE**
Solar gain properties	**Solar transmittance**	-	0	0	0	N/A

	Solar reflectance	-	External: 0.57 Internal: 0.57	0.57	0.57	N/A
	Light transmittance	-	0	0	0	N/A
	Light reflectance	-	External: 0.63 Internal: 0.63	0	0	N/A
	Shading coefficient	-	N/A	N/A	N/A	0.37
	Short-wave radiant fraction	-	N/A	N/A	N/A	0
Thermal performance properties	**Thickness**	mm	20	20	20	N/A
	Conductivity	W/m.°C	0.04	0.04	0.04	N/A
	Emissivity	-	External: 0.1 Internal: 0.1	0.1	0.1	N/A
	Nighttime resistance	m^2K/W	N/A	N/A	N/A	0.47
	Daytime resistance	m^2K/W	N/A	N/A	N/A	0.47
	Shade to glass distance	mm	N/A	100	100	N/A
	Top opening multiplier	-	N/A	0	0	N/A
	Bottom opening multiplier	-	N/A	0	0	N/A
	Left-side opening multiplier	-	N/A	0	0	N/A
	Right-side opening multiplier	-	N/A	0	0	N/A
	Airflow permeability	-	N/A	0	0	N/A

Thermal conductivity and emissivity of the blind used in the test were not provided by the manufacturer. The emissivity of the cellular blind, which is a ratio between 0 to 1, was estimated as 0.1 which represents a low emissivity surface and high thermal resistance (LBNL, 2013). According to ES-SO, the default value for the conductivity of an internal roller blind is 0.1 W/mK, as most materials are thin and of a similar thickness (less than one mm (ES-SO, 2014)). However, as the blind used in this study was a thermal insulating cellular blind, the thermal conductivity was assumed as the low value of 0.04 W/mK. When using EDSL Tas, the blind is considered as a transparent layer within the window construction and the distance between the blind and the window glass was specified as a layer of air with a thickness of 100 mm.

Shade opening multipliers or perimeter gaps of the shading is the effective area for airflow at the top/bottom of the shade divided by the horizontal area between glass and shade whereas when considering the airflow at the sides, the effective area is divided by the vertical area between glass and shade (DesignBuilder, 2018). According to ASHRAE Fundamental 2013, shade airflow permeability or openness factor of the blind is the ratio of the open area between the fibres to the total area of the fabric (ASHRAE, 2013) and as this blind was a blackout thermal blind, its openness factor was considered zero.

The required inputs for shading devices in IES VE (presented in Table 27) are different from the other software packages discussed in this chapter. According to the description provided in the IES VE website help section, nighttime and daytime resistance is explained as "*The additional thermal resistance (if any) associated with the device when it is in operation at night (taken to be when the sun is below the horizon) and day (taken to be when the sun is above the horizon). A value of zero is appropriate in most cases. Net curtains and most types of blinds have minimal insulation effect on the glazing. They can therefore be ignored for most applications. However, the effect of heavyweight curtains and blinds should be included*". The blind manufacturer has provided the resistance of the blind as 0.47 m^2K/W but it is not clear if the method of calculation to reach this value is similar to the IES VE calculation method. In this model, this value is considered for both daytime and night-time resistance. Shading coefficient (SC) is another required input for shading in IES VE which is explained as "*A proportion of the absorbed heat (sometimes called re-transmitted heat) is transferred into the room by convection and long-wave radiation*" and it is calculated using the equation below:

$$SC = T + 0.87 * A \qquad \text{Eq 6-1}$$

Where T is solar transmittance and A is solar absorptance. The short-wave radiant fraction (SWRF) is calculated by dividing solar transmittance by the shading coefficient (SWRF= T/SC) (IES VE, 2016). For this case study, according to the manufacturer, solar transmittance and absorptance were zero and 0.57, respectively. By substituting these values in the equation, shading coefficient (SC) is calculated as 0.37 and short-wave radiant fraction (SWRF) is equal to zero.

6.3 Internal Gains, Infiltration and Heating System

Prior to the real-world test, the air permeability of the room was assessed through a blower door test which provided the value of infiltration to be 1.89 ACH. As the window and door were closed during the test, the ventilation was considered as zero in the simulation. During the test, no occupant was present in the room and all lighting was turned off. The monitoring system including a laptop and a data taker were on 24 hours a day to store the captured data from the sensors. Consequently, the emitted heat and thermal gain from the equipment was assumed as 5 W/m^2 in all models (CIBSE, 2019).

The heating system used in the test room was an electric heater which was working from 17:00 to 08:00 the following day to maintain the temperature at 24°C. The heating system schedule and setpoint considered in all four models were similar to the real-world case study.

6.4 Weather File

When comparing the simulation results with real-world data collected during the test, the simulation weather file needed to represent the real weather condition during the test period to reduce the discrepancies between the real and simulated measurements and also between the simulations themselves. Elements version 1.0.6 was used to enable editing of the custom weather files for the building energy modelling and simulation which is an open-source cross-platform software tool created by Bigladder software. This edited weather file was then used in all four models generated by the four different software packages.

Some of the weather parameters such as dry-bulb air temperature, solar radiation and illuminance were measured on-site but some others such as wind speed were derived from the nearest weather station measured by the Met Office. The remaining parameters were not modified and were maintained as the original weather file. Table 28 presents the elements of the weather parameters which were modified in the weather file.

Table 28: Modified Weather Parameters

Parameter	**Unit**	**Source / Location**
Dry bulb temperature	°C	Measured on-site, from the roof of Metal Block building at London South Bank University
Global solar radiation	W/m^2	Measured on-site, from the roof of Metal Block building at London South Bank University
Global illuminance	Lux	Measured on-site, from the roof of Metal Block building at London South Bank University
Dewpoint temperature	°C	St James's Park weather station
Relative humidity	%	St James's Park weather station
Mean wind direction	Degree	Kew Gardens weather station
Mean wind speed	kn	Kew Gardens weather station
Snow depth	cm	Heathrow weather station
Visibility	m	Heathrow weather station
Rainfall	mm	St James's Park weather station

Cloud cover	Oktas	Heathrow weather station

The wet-bulb temperature was automatically calculated by the software, Elements, by inserting dry bulb temperature and relative humidity. Cloud cover (Oktas) and mean wind speed (kn) were converted to Tenths and m/s, respectively. To convert the mean wind speed to m/s, the value in kn was multiplied by 0.514 and to convert the cloud cover in Oktas to tenths, the criteria stated in Table 29 were used (WMO, 2020).

Table 29:Conversion factor for cloud cover from Oktas to Tenths

Value in Oktas	0	1	2	3	4	5	6	7	8
Equivalent value in tenths	0	2	3	4	5	6	8	9	10

6.5 Results and Discussion

The dynamic simulation results generated by each software package are presented in this section. To investigate the results of each software package, the hourly simulated results derived from the models are compared with the real-world data from the case study presented in CHAPTER 4 Section 4.3. It is important to note that these values are analysed from 18:00 to 08:00 the following day to allow overnight values to be considered. Although the heating was on from 17:00, the results are considered from 18:00 in both the simulations and the real-world study in order to slightly overcome the effect of thermal mass. The main three parameters investigated in this chapter are the window internal surface temperature (°C), window heat loss (W/m^2) and room energy consumption (kWh) to maintain the internal air temperature at 24°C in with and without blind scenarios.

6.5.1 Window Internal Surface Temperature

One of the investigated parameters in this section was the internal surface temperature of the window (°C), with and without a blind. In this section, as the blind is considered as an inclusion in the whole window system, the internal surface of a window in the presence of a blind, is the internal surface of the blind and when there is no blind, the internal surface of the window is the glass surface. Figure 90 presents the simulated internal window surface temperature results of each software package and the real-world measured values. To better illustrate and comprehend the results of the modelling in comparison with the measured data, it should be stated that the uncertainty of real-world surface temperature measurement was calculated as ±0.10 (°C) for the glass surface (without blind) and ±0.12 (°C) for blind surface temperature (with blind) in Section 4.3.3.3.1.2. As it is observed from Figure 90, all of the software packages have predicted the window internal surface temperature in a similar pattern to the measured values where the temperature in the presence of the blind was higher than when there was no blind.

Comparisons were made by using parameters against time plots and by considering mean error ($\bar{E}$) to measure the errors (differences) between software prediction and real-time measurements results as below:

$$\bar{E} = \sum_{t=1}^{n}(E_t)/n \qquad \textit{Eq 6-2}$$

In this analysis Error is calculated as below:

$$E_t = P_t - M_t \qquad \textit{Eq 6-3}$$

Where P_t is the predicted value at hour t (°C), M_t is the measured value at hour t (°C) and n is the total number of hours in the comparison period (Robert, et al., 2019).

Observing the mean differences (errors) between the daily measured and daily simulated values (from 18:00 to 08:00 following day) presented in Figure 91, show that in the presence of the blind, simulated results generated with EDSL Tas have the lowest error count whereas the other three software tools have similar error values. Assessing the without blind scenario in Figure 91 shows that EnergyPlus and DesignBuilder have the lowest error values compared to the measured temperatures.

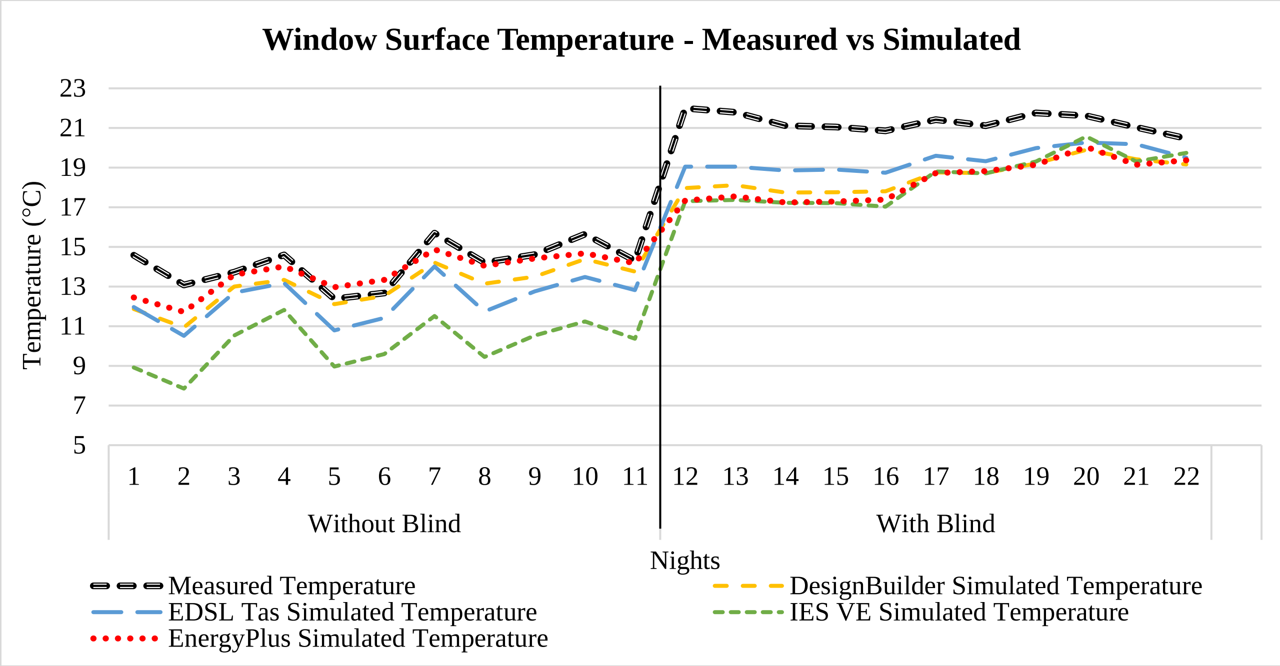

Figure 90: Window Internal Surface Temperature- Measured vs Simulated

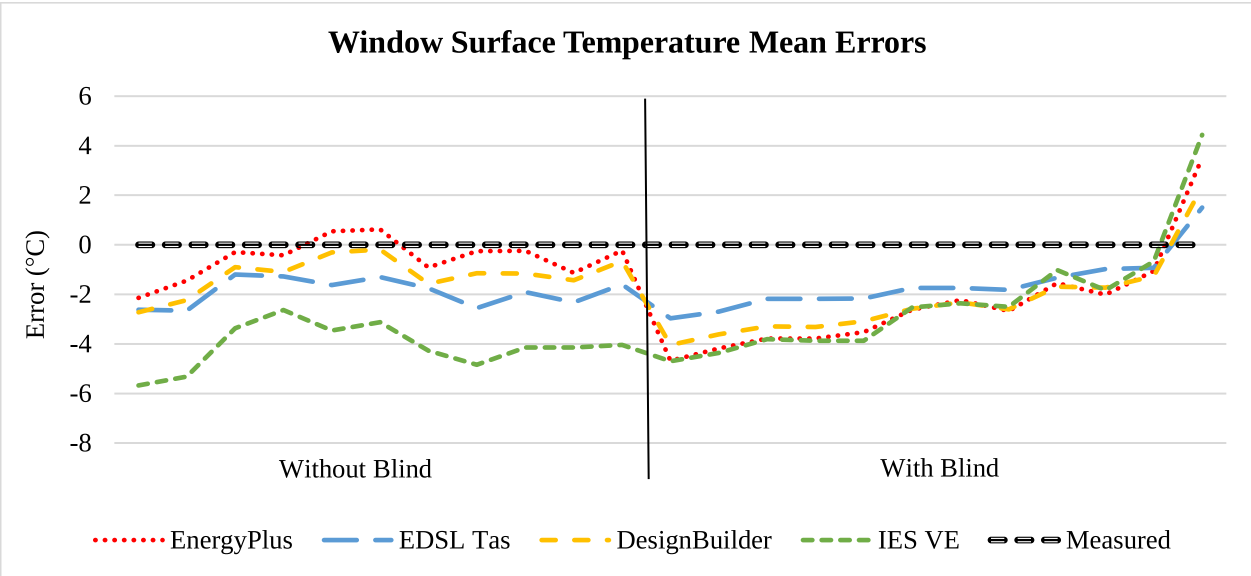

Figure 91: Window Surface Temperature Mean Errors

The total average difference between the measured and simulated values which are presented in Figure 92 shows that IES VE has the highest error in both with and without blind scenarios with 3.85 °C when a blind is present and 4.14 °C without a blind. After IES VE, DesignBuilder and EnergyPlus have the highest total errors during the with blind scenario (2.92 °C and 3.59 °C, respectively) and the lowest errors in without blind scenario (1.23 °C and 0.84 °C, respectively). EDSL Tas has a similar relatively low error count in with and without blind scenarios with 1.98 °C and 1.89 °C, respectively.

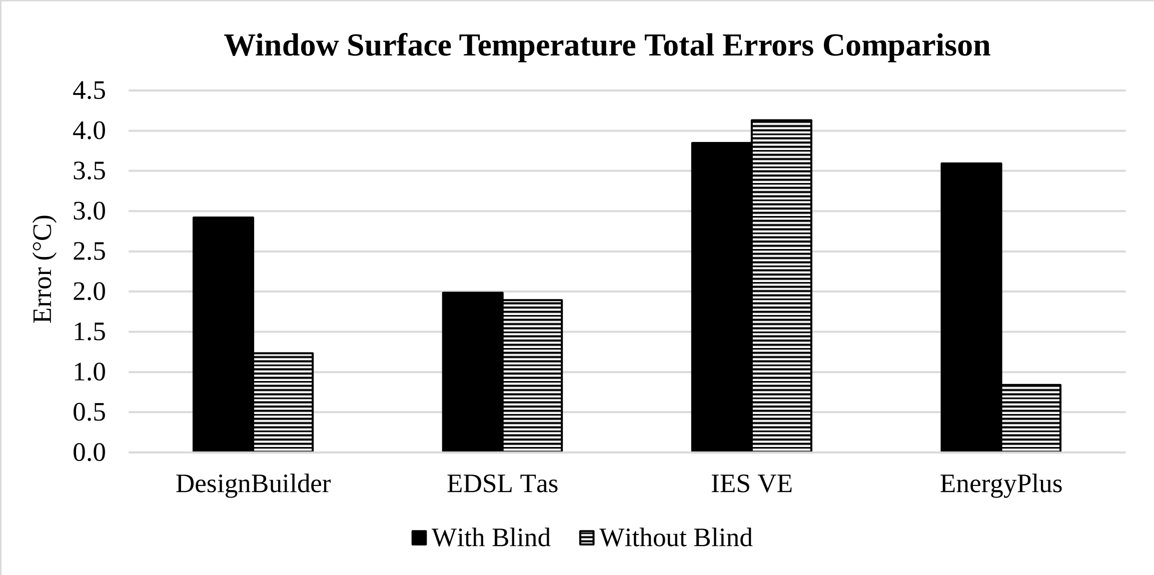

Figure 92: Window Internal Surface Temperature Total Errors Comparison

6.5.2 Window Heat Loss Energy (W/m^2)

The average daily values (from 18:00 to 08:00 following day) presented in Figure 93 shows that the simulated results related to window heat loss generated with EnergyPlus and DesignBuilder are fairly similar as DesignBuilder is using EnergyPlus as its engine for simulation. All software packages have simulated the results with a similar pattern to the measured values for both with and without blind scenarios meaning that without the blind, the window heat loss is higher than when the blind is present. The sensitivity of the sensors used for window heat loss (heat flux) measurement was stated as 60.76×10^{-6} and 59.55×10^{-6} $V/(W.m^{-2})$. The possible uncertainty for this measurement was in the ±6% range. Looking at the differences between simulated and measured values for each software tool presented in Figure 94, EDSL Tas has the lowest error in the without blind scenario and its error rate in the with blind scenario is similar to EnergyPlus and DesignBuilder.

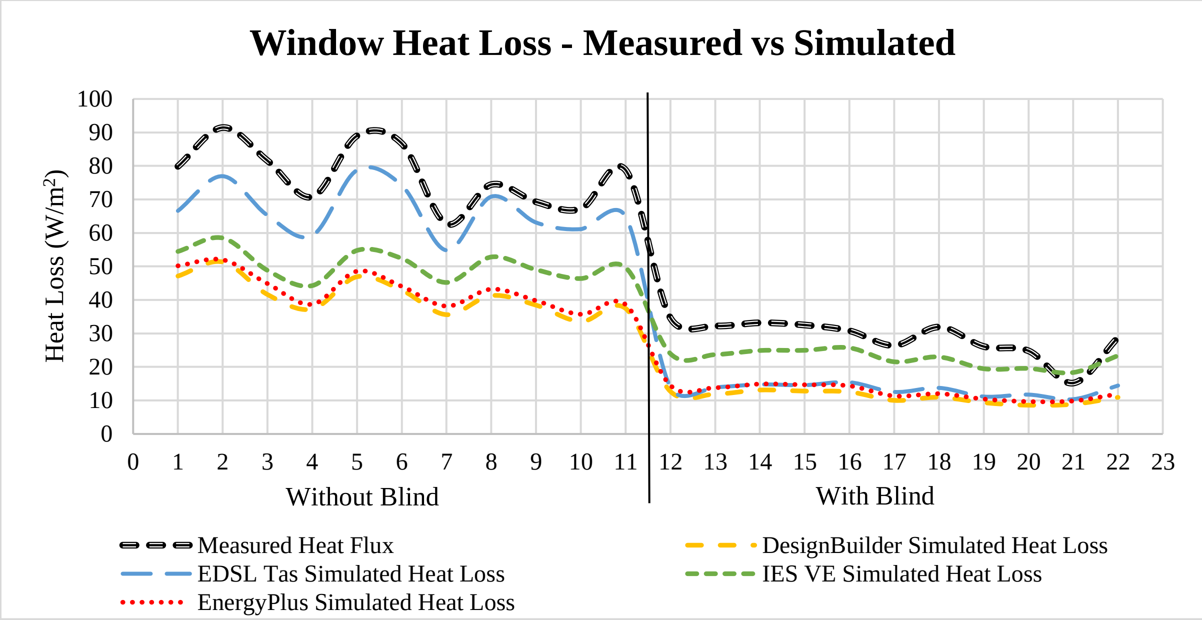

Figure 93: Window Heat Loss - Measured vs Simulated

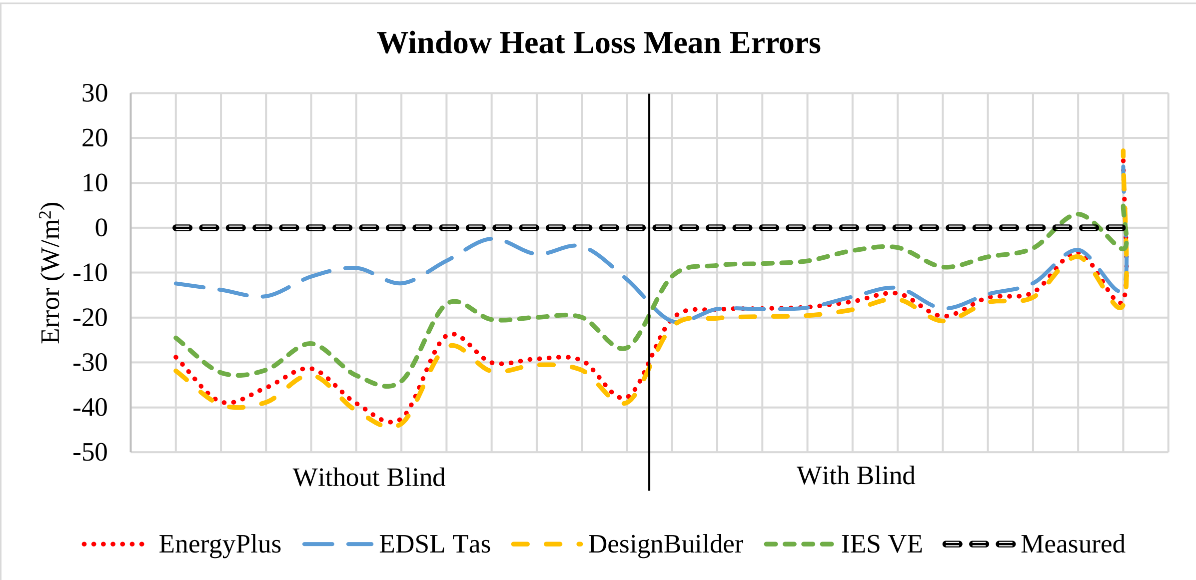

Figure 94: Window Heat Loss Mean Errors

Figure 95 presents the total average error/difference between the simulated and measured values for window heat loss. Apart from EDSL Tas, all the other software packages have more errors when a blind is absent compared to when a blind is present whereby the values are 25.85 W/m^2 for IES VE, 33.35 W/m^2 for EnergyPlus and 35.19 W/m^2 for DesignBuilder. IES VE has the lowest error of 6.54 W/m^2 when a blind is used while this error for the other software tools is between 15.21 W/m^2 and 17.47 W/m^2.

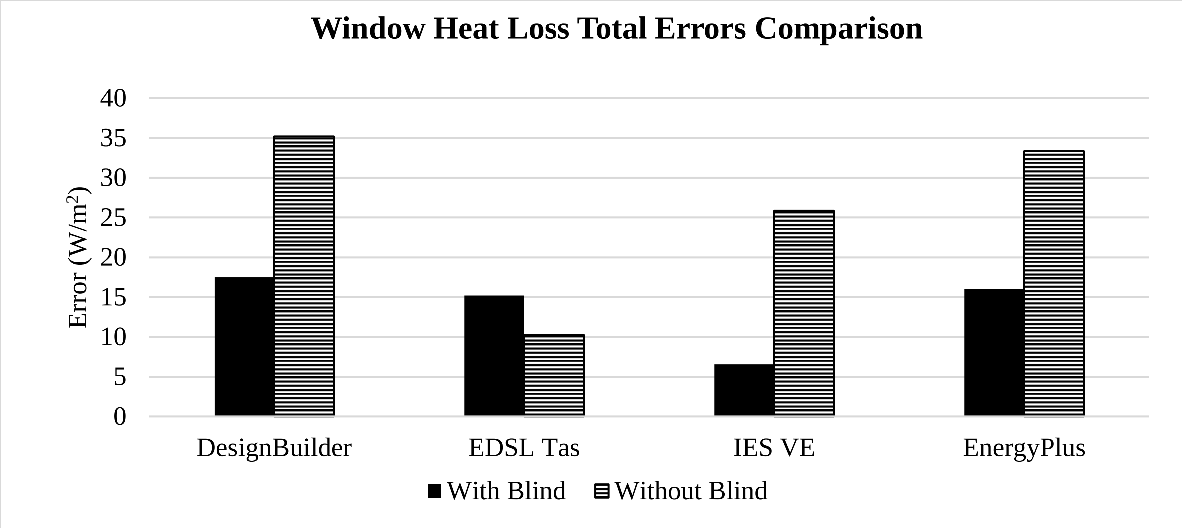

Figure 95: Window Heat Loss Total Errors Comparison

6.5.3 Energy Consumption

The energy consumption required to maintain the temperature at 24 °C during the test period is simulated using the four models generated by the different software packages. The cumulative energy consumption was measured in the real-world setting with the resolution of ±0.01 kWh. As it is illustrated in Figure 96, the simulated energy consumption does not follow the same pattern as the measured values. In other words, considering a blind in the model does not affect the energy consumption values predicted in all four of the models. Overall, the simulated energy consumption in DesignBuilder and Energy Plus is higher than in IES VE and EDSL Tas. The differences between the simulated and measured values which are presented in Figure 97 shows that in the presence of the blind, IES VE and EDSL Tas have simulated this value as being closest to the measured value but when the blind is absent the other two software tools DesignBuilder and EnergyPlus are closer to the measured values.

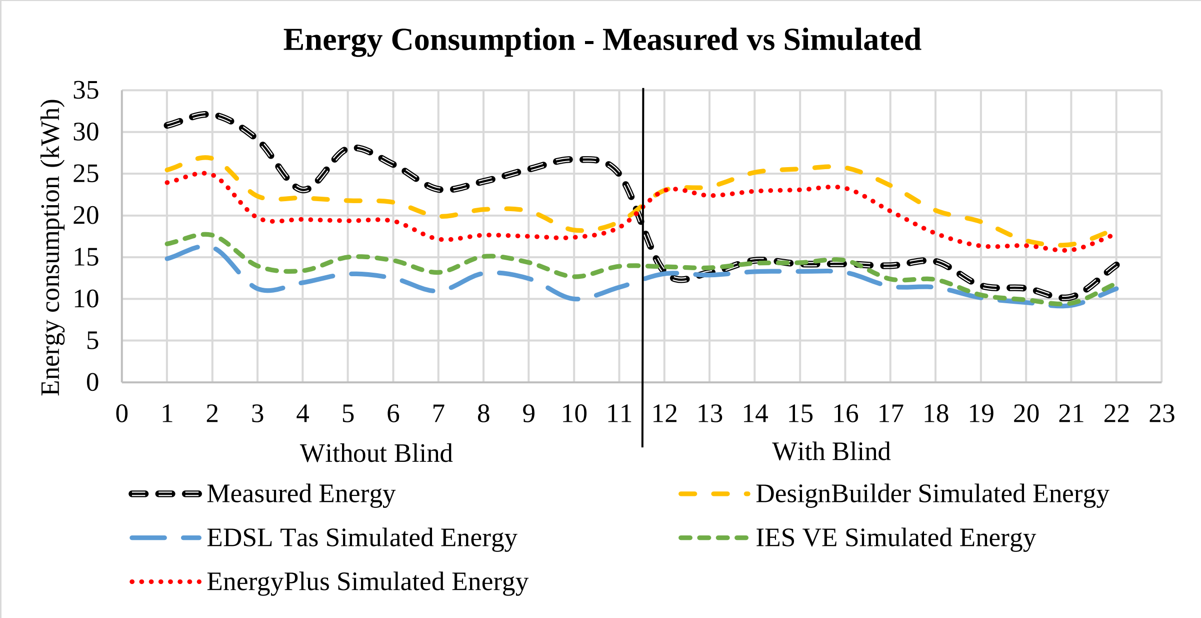

Figure 96: Energy Consumption - Measured vs Simulated

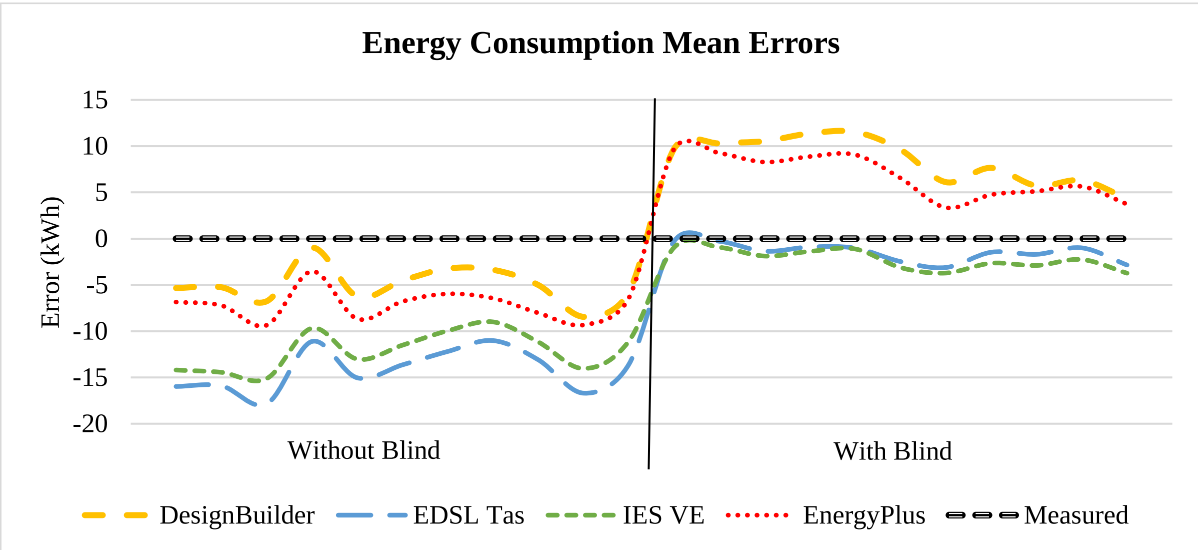

Figure 97: Energy Consumption Mean Errors

The total absolute errors calculated for with and without blind scenarios are presented in Figure 98, as the figure shows, there is quite a bit of discrepancy for all the software tools in the absence of the blind whereby the error values start from 4.99 kWh (DesignBuilder) and reach 14.19 kWh (EDSL Tas). When the blind is present, IES VE and EDSL Tas do perform better than the other two software tools with error values of 1.49 kWh and 2.24 kWh respectively.

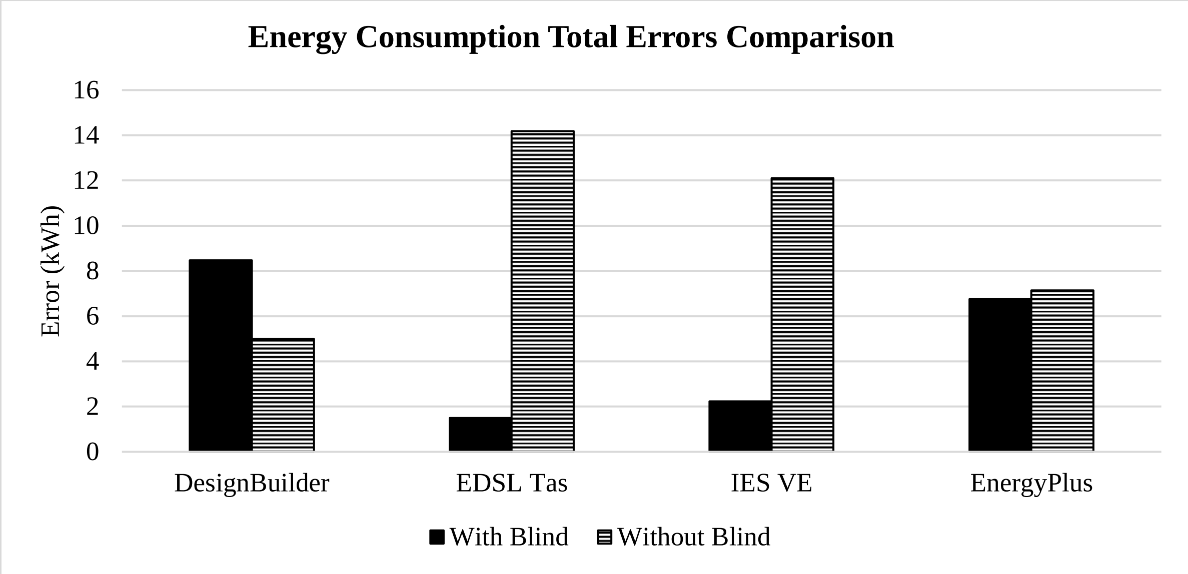

Figure 98: Energy Consumption Total Errors Comparison

6.6 Discussion

Simulated and measured values related to three main parameters including internal window surface temperature, window heat loss and energy consumption were compared. The common weather data used throughout all the four software models were modified to match the real-world conditions. Although an attempt was made to generate the models as close as possible to the real-world case study, discrepancies were observed between the simulated results and the measured values and between the simulated results themselves (between the four software tools) which were persistent throughout the test period.

The heating thermostat setpoint in both the model and the real-world case study was set at 24°C. However, in the case of the real-world study as the heating thermostat was attached to the heater and the internal dry-bulb temperature sensors were positioned about a meter far from the heater, the internal dry-bulb air temperature in the case study was recorded between 23°C to 24°C so some fluctuation was seen whereas the temperature was fixed at 24°C in the models. This could be due to the heat loss in the room via infiltration and the room fabric loss or the uncertainties of the heating system and the sensors.

Additionally, the dynamic behaviour of radiators and the heating system can cause a time delay as the internal air temperature reaches the desired setpoint but this delay or lag is not observed in the model and a much more rapid increase in air temperature is seen in the models compared to the real-world setting (Zhai & Chen, 2005). Furthermore, differences between the wind speed taken from the weather stations (Met Office) and the actual site could increase the possibility of discrepancies. It should also be noted that the modified weather file used in all four software packages was based on hourly weather data meaning it may have averaged some values and not fully covered all variations in reality. For example, when simulating the energy consumption, there is a possibility that some of the software tools considered the weather parameters in more detail and some in less detail which could cause some slight discrepancy. The use of each of the software packages' libraries for the construction elements of the test room, the thickness, density and conductivity of the materials can also play a part in the variations seen in the simulated models between themselves and the real-world measure data. A sensitivity analysis was performed for each software package focusing on the blind input parameters to evaluate the capability of each software in modelling internal blinds.

As DesignBuilder is using EnergyPlus for its calculation engine, the results of these software packages were quite similar to each other. The software packages using EnergyPlus as their main calculation engine have different interfaces that allow different functionalities to become available from EnergyPlus. DesignBuilder and EnergyPlus include a library (or input file) of common shading devices and performance characteristics with a clear distinction between various types of shading devices and input data meaning that manufacturers data can be added and user libraries can be created. In both software packages, the user can assign an operation profile specifically to the desired blind, which, in this project, it was planned to be operated similar to the heating schedule. In DesignBuilder, internal shading devices are not explicitly catered for, but they can be added to the window as an extra layer. Similarly, EDSL Tas has a library for common shading devices and performance characteristics but there is not a clear distinction between various types of shading devices. A schedule profile can be defined for the shading layer by using substitute elements within the software. However, this process is not as user friendly as the other two software packages as it is not done automatically by the software especially when the profile is dependent on solar radiation. Additionally, EDSL Tas does not consider the perimeter gaps and openness factor of the shading device in its model and lacks the required input which is an effective factor when focusing on the thermal retention effect of shading devices. IES VE has a different input parameter for shading devices compared to the other three software packages discussed here. For example, the other software packages require conductivity and emissivity as shading inputs but this software requires thermal resistance (R-value). Furthermore, there is not a library for shading performance data within the software and it only includes the maximum and minimum range of input values. For example, within the software, it is stated that *Nighttime resistance* is typically between 0.00 and 2.50 m^2K/W.

Sensitivity analysis was performed to evaluate the effect of total room infiltration and blind input parameters on the models' simulated results including the window internal surface temperature, window heat loss and energy consumption. Table 30 presents the variants considered in the sensitivity analysis.

Table 30: Sensitivity Analysis Variants

ID	Variant	Description
1	Window shading Conductivity (W/mK)	Increased the conductivity from 0.04 to 2 (W/mK)
2	Emissivity	Increased from 0.1 to 0.9
3	Shade to glass distance (m)	3a Increased from 0.1 m to 0.3 m (maximum) 3b Decreased from 0.1 m to 0.01 m (minimum)
4	Shade top opening multiplier	Increased from 0 to 0.1 m
5	Shade bottom opening multiplier	Increased from 0 to 0.1 m
6	Shade left-side opening multiplier	Increased from 0 to 0.1 m
7	Shade right-side opening multiplier	Increased from 0 to 0.1 m

8	Shade airflow permeability	Increased from 0 to 0.25 m (0.00 to 0.05 is considered as low openness factor, 0.05 to 0.1 is considered as medium and more than 0.1 is considered as a shading with high air permeability. Openness factor can be as high as 0.32 in rare cases. (DesignBuilder, 2018; PolarShade, 2019)
9	Room Infiltration	Decreased from 1.89 to 0.25 ACH
10	Nighttime Resistance	10a Decreased from 0.47 to 0 m^2K/W (minimum) 10b Increased from 0.47 to 2.5 m^2K/W (maximum)
11	Daytime Resistance	11a Decreased from 0.47 to 0 m^2K/W (minimum) 11b Increased from 0.47 to 2.5 m^2K/W (maximum)
12	Shading Coefficient	Increased from 0.37 to 0.95 (maximum)

These variants were similarly altered in each model to investigate the sensitivity of the model against each parameter. Table 31 presents the average difference between the daily (from 18:00 to 08:00 am following day) window internal surface temperature of the base case model and the new model generated after altering the variant. Table 32 and Table 33 present these average differences for window heat loss and energy consumption whilst maintaining temperature at 24 °C.

Table 31: Differences in window internal surface temperature (°C) between the base case model and the altered model

Variant ID	**DesignBuilder (°C) (compared to base case)**	**EnergyPlus (°C) (compared to base case)**	**IES VE (°C) (compared to base case)**	**EDSL Tas (°C) (compared to base case)**

1	Decreased by 1.8 (9.86%)	Decreased by 1.05 (5.74%)	-	Decreased by 2.51 (12.96%)
2	Decreased by 0.89 (4.78%)	Decreased by 0.73 (3.95%)	-	Increased by 0.35 (1.79%)
3	3a No change 3b Decreased by 0.49 (2.64%)	3a No change 3b Decreased by 0.66 (3.59%)	-	3a No change 3b No change
4	No change	No change	-	-
5	No change	No change	-	-
6	Increased by 0.64 (3.30%)	Increased by 0.70 (3.69%)	-	-
7	Increased by 0.64 (3.30%)	Increased by 0.70 (3.69%)	-	-
8	Increased by 3.43 (15.55%)	Increased by 4.06 (18.09%)	-	-
9	With Blind: Increased by 0.16 (0.87%) Without Blind: Increased by 0.24 (1.78%)	With Blind: Increased by 0.02 (0.11%) Without Blind: Increased by 0.04 (0.32%)	With Blind: Increased by 0.04 (0.21%) Without Blind: Decreased by 1.69 (16.76%)	With Blind: Increased by 0.03 (0.15%) Without Blind: Increased by 0.04 (0.34%)
10	-	-	10a Decreased by 6.56 (35.61%) 10b Decreased by 8.28 (44.95%)	-
11	-	-	11a No change	-

			11b No change	
12	-	-	Increased by 1.31 (6.64%)	-

Table 32:Differences in window heat loss (W/m²) between the base case model and the model with applied variant

Variant ID	DesignBuilder (W/m²) (compared to base case)	EnergyPlus (W/m²) (compared to base case)	IES VE (W/m²) (compared to base case)	EDSL Tas (W/m²) (compared to base case)
1	Increased by 5.41 (32.75%)	Increased by 3.45 (21.63%)	-	Increased by 10.65 (44.39%)
2	Increased by 2.81 (20.19%)	Increased by 5.24 (29.55%)	-	Increased by 3.58 (21.14%)
3	3a No change 3b Increased by 1.34 (10.73%)	3a No change 3b Increased by 1.89 (13.10%)	-	3a No change 3b No change
4	No change	No change	-	-
5	No change	No change	-	-
6	Increased by 5.99 (35.03%)	Increased by 5.52 (30.63%)	-	-
7	Increased by 5.99 (35.03%)	Increased by 5.52 (30.63%)		-
8	Increased by 36.08 (76.46%)	Increased by 35.63 (74.03%)		-

9	With Blind: Increased by 0.10 (0.93%) Without Blind: Increased by 2.01 (4.54%)	With Blind: Increased by 0.02 (0.14%) Without Blind: Increased by 0.37 (0.86%)	With blind: Increased by 0.07 (0.33%) Without Blind: Increased by 3.91 (7.18%)	With Blind: Increased by 0.03 (0.22%) Without Blind: Increased by 0.64 (0.94%)
10	-	-	10a Increased by 24.35 (51.87%) 10b Decreased by 0.68 (3%)	-
11	-	-	11a No change 11b No change	-
12	-	-	Increased by 0.07 (0.31%)	-

Table 33: Differences in energy consumption (kWh) between the base case model and the model with applied variant

Variant ID	**DesignBuilder (kWh) (compared to base case)**	**EnergyPlus (kWh) (compared to base case)**	**IES VE (kWh) (compared to base case)**	**EDSL Tas (kWh) (compared to base case)**
1	Increased by 0.31 (1.49%)	Increased by 0.19 (0.96%)	-	Increased by 0.64 (5.19%)
2	Increased by 0.17 (0.81%)	Increased by 0.31 (1.51%)	-	Increased by 0.12 (1%)
3	3a No change 3b Increased by 0.08 (0.39%)	3a No change 3b Increased by 0.12 (0.59%)	-	3a No change 3b No change

4	No change	No change	-	-
5	No change	No change	-	-
6	Increased by 0.38 (1.83%)	Increased by 0.35 (1.74%)	-	-
7	Increased by 0.38 (1.83%)	Increased by 0.35 (1.74%)	-	-
8	Increased by 2.30 (10.04%)	Increased by 2.27 (10.20%)	-	-
9	With Blind: Decreased by 7.63 (37.01%) Without Blind: Decreased by 6.73 (32.69%)	With Blind: Decreased by 6.53 (32.74%) Without Blind: Decreased by 5.97 (30.57%)	With Blind: Decreased by 9.19 (65.77%) Without Blind: Decreased by 8.24 (56.54%)	With Blind: Decreased by 6.39 (46.38%) Without Blind: Decreased by 5.80 (54.63%)
10	-	-	10a Increased by 1.91 (12.43%) 10b Increased by 0.98 (7.28%)	-
11	-	-	11a No change 11b No change	-
12	-	-	Decreased by 1.28 (9.48%)	-

Reviewing the results presented in Table 31, Table 32 and Table 33 shows that altering shading fabric parameters values such as conductivity or emissivity could affect the window surface temperature and window heat loss which are vital elements when assessing thermal comfort. However, these elements did not significantly impact the room energy consumption in the models. Altering certain input values seems to have no impact on the results. For instance, increasing the shade to glass distance for more than 0.1 m did not alter the results. In DesignBuilder and Energy Plus, decreasing this value could slightly change the output results, but did not alter the results in EDSL Tas. Additionally, in DesignBuilder and EnergyPlus (which consider perimeter gaps of shading devices), altering top and bottom gaps did not change the results. In DesignBuilder and EnergyPlus, changing the side perimeter gaps had a slight effect on the window heat loss, the window surface temperature and energy consumption. The next analysed factor was the openness factor of the blind which was considered in DesignBuilder and EnergyPlus. This factor had more effect on all three output results and increased window heat loss by more than 35.63 W/m^2, window surface temperature by more than 3.43 °C and could increase energy consumption by more than 2.27 kWh. This highlights the effect of the openness factor of the blind in comparison with the perimeter gaps, shade to glass distance and fabric improvements in thermal retention projects. In IES VE, four calculated input values are specified for shading modelling; from these four values, only additional thermal resistance is considered key for reducing heat loss. The other three factors including Daytime resistance, Shading coefficient and short-wave radiant fraction are mainly considered for daytime simulations. It should be noted that these values can affect the thermal mass of a building and its furniture during the day which can affect the nighttime thermal properties but they are less significant compared to the nighttime resistance. Observing variant number 10 illustrates that reducing nighttime resistance to zero could alter the energy consumption by 1.91 kWh, decrease the window internal surface temperature by 6.56 °C and increase the window heat loss by 24.35 W/m^2. Changing this value to the maximum which is 2.5 m^{2}K/W, decreased window surface temperature by 8.28 °C but did not considerably change other parameters.

In all four models, ventilation heat loss (room infiltration which was originally 1.89 ACH), was reduced to 0.25 ACH which is a default value in most of the software packages. This was investigated in both with and without blind scenarios. In all four software packages (Figure 99), in the presence of a blind, reducing total ventilation and infiltration did not affect the internal surface temperature of the window and window heat loss considerably but it decreased the energy consumption by at least

6.39 kWh. In the absence of a blind, reducing room infiltration did not affect window temperature and window heat loss in most of the models but in IES VE, it could reduce window internal surface temperature by 1.69 °C and increase window heat loss by 3.91 W/m^2. When using IES VE changes in energy consumption as a result of reducing infiltration in both with and without blind scenarios was at least 1.50 kWh higher than the other three software packages.

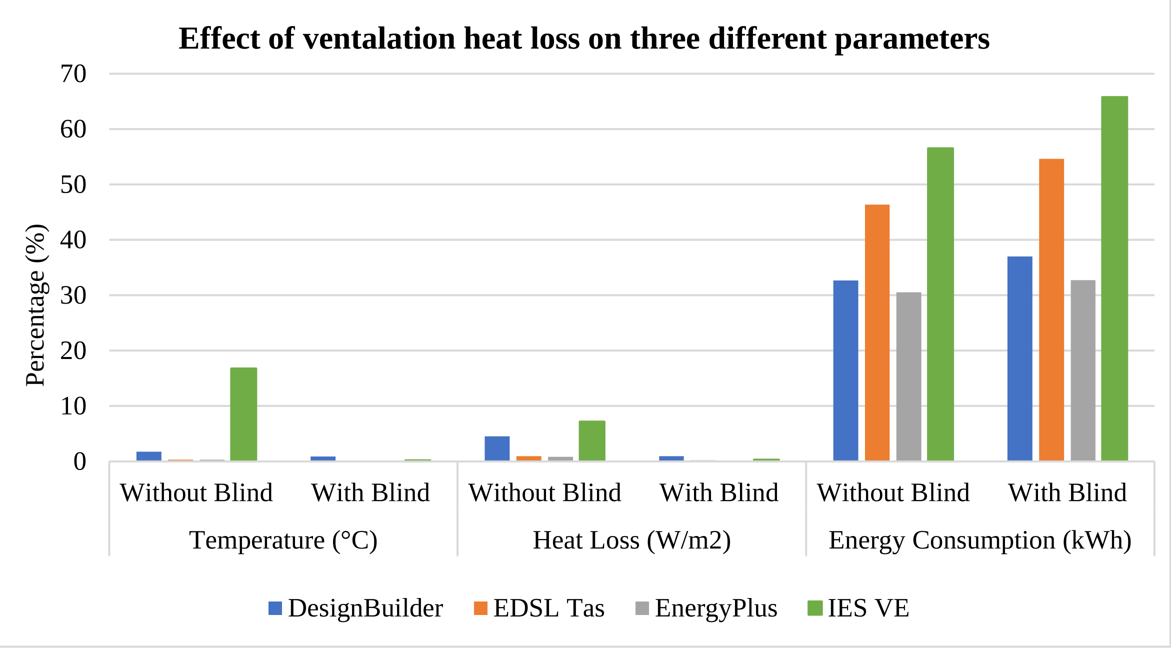

Figure 99: Effect of ventilation heat loss on three different parameters

In summary, as mentioned in previous chapters, infiltration of shading devices and the building itself play an important role when it comes to thermal retention. This was illustrated here in the software models; blind fabric enhancements such as thermal conductivity and emissivity did not impact all three parameters as significantly as blind infiltration. Furthermore, improving the room infiltration is more effective in comparison with blind infiltration in terms of energy consumption efficiency.

Although the simulation results of IES VE were not far from the other models generated, it requires different input parameters. The other software packages require the raw values for shading parameters, but IES VE requires some calculated input. Taking this difference into account, having a calculated input method increases the probability of mistakes being made due to reliance on users' manual input as this software does not possess a complete library of calculated input values in its software or website.

6.7 Conclusion

Comparing simulation results generated from the four BEMS software packages that are commonly used in the UK with each other and with the real-world data collected from Case Study 2 showed that all software packages were able to predict window surface temperature and window heat loss with a similar pattern and trend to the real-world measured values but none of them could predict energy consumption to maintain internal air temperature at 24 °C similar to the measured values. In terms of the window surface temperature, EDSL Tas had the lowest error count whilst IES VE had the highest errors in both with and without blind scenarios. For window heat loss, in the presence of a blind, the IES VE model had the lowest error value and in the absence of a blind, the EDSL Tas model had the least errors. For energy consumption, EDSL Tas and IES VE models in the presence of a blind had the fewest error values and in the absence of a blind, EnergyPlus and DesignBuilder models had the fewest errors. The errors of each model are different for each parameter and it is not clear whether these errors are caused by the modellers' assumptions or it is due to the embodied calculations and deficiencies in the software (Strachan, et al., 2016; Robert, et al., 2019).

After reviewing the shading input for each software package, it was concluded that IES VE required completely different inputs compared with the other three software packages. While the shading inputs for the other three software packages can be obtained directly from the manufacturer's datasheet, these inputs for IES VE require a calculation by the modeller. This increases the possibility of errors made by the user in most of the models generated with IES VE. It is important to note that according to the survey results presented in CHAPTER 5, IES VE is the most commonly used software package within the UK so it is vital that this software provides the users with a more complete shading library to reduce the possibility of mistakes. In all other three software packages, a comprehensive shading library is available but in IES VE due to the lack of an available library for shading, there is a potential and high probability that modellers do not consider internal shadings in their models and if they do, the input values are not fully accurate.

It is observed that the blind infiltration parameter used in the applicable dynamic thermal models including EnergyPlus and DesignBuilder has a slightly more positive impact compared to the effect of fabric specification enhancements. Furthermore, it was observed that the room infiltration factor had a more significant impact on energy efficiency in comparison with the air permeability of the blind. This is more important in retrofit projects as solely adding a blind can not improve energy consumption values. However, whether software packages like EnergyPlus and DesignBuilder which included blind infiltration values as input data or IES VE and EDSL TAS that do not include blind infiltration values are used, due to the issue of not being able to explicitly show the proportion of window infiltration from the total room infiltration value which is where most of the heat loss occurs in Case Study 2, then none of the software packages can truly replicate the real-world measure data in terms of heating energy consumption. To overcome this issue, experienced modellers who are aware of this issue and are aware of the window infiltration impact, may tweak and modify the total infiltration value to a lower number in software packages like IES VE or EDSL TAS that are lacking in this area to compensate for the gap. It must be noted though that this approach is still very unscientific and based on assumptions so it is highly recommended that this gap is addressed through a joint effort between the manufacturers and software vendors. This is to ensure a reference value is determined for the various blind / window products when the room is fully sealed and there are no other elements in the room that can cause infiltration. Also to improve the accuracy and reduce errors in the models specifically regarding heating energy consumption analysis ensuring embedded guidelines within the software for the modellers and then for the obtained reference values to be ultimately added to the software calculation methods, is vital.

It is recommended to investigate the effect of shading devices on heat loss both in real-world settings and in simulated models especially regarding energy consumption as the software packages were unable to predict the effect of the blind similar to the real-world measurements. This can be tested with a different type of heating system using various software packages with a focus on energy consumption levels throughout the test.

6.8 Summary

In this chapter, the real-world Case Study 2 was modelled with four software packages and the simulated results were compared with the measured values from Case Study 2. The main findings from this chapter are presented here:

- All of the software packages have the ability to predict and model the window surface temperature and window heat loss patterns when a blind is present quite close to the real-world data but none of them can predict the effect of blind on the room energy consumption.
- The air permeability and infiltration of the blind are more effective than the fabric specification itself with relation to heat loss.
- The room ventilation heat loss has a bigger impact on the rooms' energy consumption in comparison with the blind infiltrations; however none of the software packages were able to illustrate what proportion of the room ventilation heat loss (infiltration) related to the window area which in turn resulted in the simulated models differing from the measured data when considering the heating energy consumption trends in the room.
- All three software packages including DesignBuilder, Energy plus and EDSL Tas have a comprehensive shading library but the lack of this type of library is evident in IES VE. This is more important when IES VE shading input requires calculations that most of the modellers are not fully aware of and where they may require additional training to avoid mistakes being made.

CHAPTER 7

Conclusions

7.1 Introduction

The UK government has committed to a Net Zero energy building target recommended by the Climate Change Committee, so it is vital to take advantage of the benefits of window coverings in managing heat gain and loss through the fenestration areas of a building as much as possible. However, the UK is still lagging behind other developed countries in use of shading devices within buildings. In this thesis, to better understand this issue, the status of using shading devices in the UK built environment was investigated which highlights the level of knowledge and interest of the UK building industry professionals regarding these devices.

This thesis also analyses the use of shading devices as a practical method for reducing building energy consumption for heating purposes and improving thermal comfort. This research highlighted the importance of the shading industries' and especially shading specifiers' awareness regarding shading devices. This was illustrated through use of a non-sealed blind which had minimum impact on improving the indoor environment elements such as the internal operative temperature; however a sealed blind combined with some other considerations was able to positively alter the indoor environment elements. Additionally, this research study investigated the most commonly used BEMS software packages in the UK. This shows that the dynamic thermal results generated with these packages have a direct impact on the early stages of the building design especially regarding the application of shading devices in buildings. Furthermore, in this thesis, it was highlighted that most of the building energy modellers are not satisfied with the solar shading database/library available in the software that they are using in relation to shading device input data.

The final results of testing and validating/comparing the simulated results generated with the UK's most common BEMS software packages against the real-world data showed that although these software packages are all able to illustrate the effect of adding an internal cellular blind on window surface temperature and window heat loss, none of them could reflect this when considering the heating energy consumption values. This was found to be mainly due to the infiltration of the windows where the software was not able to distinguish what percentage of that is due to the window itself.

The main purpose of this chapter is to show how this thesis has managed to fulfil and address the core research challenges and reach the aim and objectives set out in CHAPTER 1. In addition, it details the original contribution to knowledge this thesis has provided whilst stating recommendations and future research requirements.

7.2 Achievement of Research Objectives

The research questions have been broken down into five objectives. This section illustrates how this thesis has answered the research questions and addressed the aim and objectives of this thesis outlined in Section 1.2.

1. **To provide a critical literature review of the mechanisms behind the heat transfer when using shading in buildings, the use of shading devices in the UK built environment and the dynamic thermal models generated with various BEMS software packages when modelling shading devices for thermal retention purposes**

CHAPTER 2 discussed the need for the UK to use various methods to reduce heating energy consumption within the built environment and the barriers which prevent use of shading devices in comparison to other developed countries. In addition, a critical literature review was performed on the mechanisms of a buildings' heat transfer with regards to heat loss through the windows. Furthermore, the case studies related to the use of shading devices for improving building energy efficiency both experimental and simulated was reviewed which highlights the need for software validation against the real-time measured data to investigate the capability of software tools in modelling shading devices.

2. **Using a survey to assess the knowledge and interest amongst the UK built environment industry professionals with a focus on shading devices and their application**

This objective was fulfilled by the survey conducted within the UK building industry professionals who have specific experience with shading devices which was outlined in CHAPTER 3. The survey focused on achieving a better understanding of the general knowledge and interest regarding shading devices amongst the key decision-makers of the building industry. The questions aimed to identify the most frequently used types of shading device, the frequency and application of use in addition to the perceived challenges that using shading devices pose within the industry. The results showed that there is a certain degree of knowledge of the benefits of shading devices mainly towards overheating but not necessarily heat loss. Also one of the main conclusions found from this survey was that key industry professional groups like architects have not got the level of awareness regarding the benefits of shading devices for thermal retention purposes needed to influence the early stages of the building design.

3. **Identifying the most common BEMS software tools used in the UK building industry by executing a survey focusing on BEMS software packages. The results of this survey will help to identify the driving factors influencing decision-making in the early stages of the building design regarding the use of shading devices and also assist in identifying the level of satisfaction of the modellers in conjunction with various parameters of each software**

CHAPTER 5 is able to satisfy the above objective in the form of a survey conducted within the UK building industry professionals who have specific experience working on BEMS software tools in relation to shading devices. As these modellers have a key role in the inclusion of shading devices early on in the design of a building, their feedback and thoughts regarding the software packages themselves and assessing their satisfaction criteria can go a long way to tackle some of the challenges seen. The most commonly used BEMS software tools were identified through this survey (IES VE, EnergyPlus, EDSL TAS and DesignBuilder) and various elements of the user experience especially related to modelling shading devices were assessed. One of the main conclusions was that there seems to be a clear gap in the shading device input data and database within these software tools which ultimately alters the accuracy and consequently can impact their application in terms of incorrectly specified and frequency of use in buildings.

4. **Conduct real-world data collection projects to investigate the effect of adding both sealed and non-sealed internal cellular blinds on thermal retention in buildings**

To complete this objective two sets of experimental projects were conducted as stated in CHAPTER 4 whereby both sealed and non-sealed blinds were installed within domestic and non-domestic buildings to assess the impact on thermal retention. Results from these experimental case studies show that the non-sealed blind had very little impact on thermal retention whereas the sealed blind assisted in both reducing heat loss and heating energy consumption. The key conclusion from these tests can be the importance of the type of shading device used and the surrounding environment as they can significantly impact how and where shading devices are used in buildings.

5. **Validate the UK's most commonly used BEMS software packages against the real-time data collected from a thermal retention case study conducted to evaluate the software tools' capability in illustrating the effect of shading devices**

CHAPTER 6 outlines the details of the comparison made between Case Study 2 in CHAPTER 4 whereby data was collected in a real-world setting that shows the impact of using a sealed cellular internal blind within a non-domestic building and dynamic thermal models generated by the four most frequently used BEMS software packages in the UK (IES VE, EnergyPlus, EDSL TAS and DesignBuilder). This investigation was key in identifying any gaps between what is seen in reality and the software tools' capability to accurately match the real-world data. From the results of the survey shown in CHAPTER 5, modellers had indicated gaps in the BEMS software packages database so validating the corresponding models against the real-world data can unearth in more detail where the actual shortcomings are for each of these software tools. The resulting comparison showed that all the BEMS software tools followed the trend of real data in terms of heat loss and window internal surface temperature but fell short in terms of correctly predicting energy consumption trends due to the software packages' inability to highlight the proportion of infiltration related to the window.

7.3 Contribution to Knowledge

This section outlines the original contribution to the knowledge of this research work. This research makes contributions by:

- The survey conducted within BEMS software modellers in relation to the use of shading devices identified a few key findings which are considered a contribution to knowledge. The results from the survey stated that modellers use external shading devices in their models the most and following on from this showed a clear gap in appreciation and awareness of the benefits of internal shading devices regarding thermal retention. It also highlighted the dissatisfaction with the shading device database included in the most commonly used BEMS software packages (IES VE, EnergyPlus, EDSL TAS and DesignBuilder).
- Conducting two experimental real-world case studies in both domestic and non-domestic buildings using sealed and non-sealed cellular internal blinds highlighted the importance of shading device selection and correct installation. Case Study 1 using a non-sealed blind installed by an industry professional showed gaps in knowledge and awareness of the correct selection and installation of shading devices. The results showed no real impact on thermal retention whereas the second case study showed an improvement in thermal retention values when a sealed blind was used and the surrounding environment was more air-tight.
- The survey conducted to better understand the industry professionals' understanding of the application of shading devices showed a general consensus of the industry shift towards more automated and motorised shading devices and also a clear lack of awareness of industry groups regarding the benefits of shading devices in managing thermal retention and not just reducing overheating. One other key contribution to knowledge from this survey relates to identifying the dependency of the building design, the application and installation of shading devices to the most commonly used BEMS software tools (IES VE, EnergyPlus, EDSL TAS

and DesignBuilder) which further illustrates the need to improve the accuracy and robustness of these software packages.

- One further key contribution to knowledge was when the dynamic thermal models from all four main BEMS software tools (IES VE, EnergyPlus, EDSL TAS and DesignBuilder) were compared with the real-world data from case study 2 in terms of thermal retention and heating energy consumption, this scale of comparison itself is quite unique. Additionally, the results of this comparison identified detailed areas of the software tools not exposed before whereby in general they were able to predict the trend seen in Case Study 2 in terms of window internal surface temperature and window heat loss but unsuccessful across the board when assessing heating energy consumption values. This specifically highlighted the need for the software vendors in collaboration with the building/shading industry to better and more accurately illustrate the window infiltration values and not just the total infiltration as this gap has a direct impact on the software packages' inability to predict the heating energy consumption as well as the other parameters.

7.4 Recommendations for Future Work

- Further experimental real-world testing is needed to enable better comparison between sealed and non-sealed blinds whereby the setting and testing environment is identical to enable accurate analysis
- Alternative energy-efficient enhancement methods within buildings such as electrochromic glazing and vacuum glazing to be real-world tested and compared to conventional internal shading device test results
- Larger scale real-world experimental tests (larger spaces/settings) with alternative heating systems to be conducted and compared with corresponding dynamic thermal models generated by the BEMS software packages
- Investigate the impact of multiple longwave radiation stages on building thermal resistance

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APPENDICES

Appendix A: Shading Devices Survey

Shading Devices Survey

Q1 What is your name and preferred means of contact? (Optional)

- ☐ Name ____
- ☐ Email ____
- ☐ Telephone Number ____
- ☐ Address ____

Q2 Which field are you working in? (if you are not sure please choose the nearest option)

- ○ Building Services Engineering / Facade Engineering /Sustainability Engineering
- ○ Architectural Practice
- ○ Academia and Research
- ○ Manufacturing and Retail (Shading Industry)

Q3 How many years have you been working in this field?

- ○ Less than 5 years
- ○ 5-10 years
- ○ 11-20 years
- ○ More than 20 years

Q4 What is the name of the company / institute you are working for? (Optional)

____

Q5 Which type of shading products do you regularly use / design / install ? (Please select as many options as you wish)
(Interstitial shading: Interstitial Blinds are another name for integrated blinds, integral blinds or sunshade blinds. They are Venetian blinds sandwiched between two panes of glass in the form of a sealed double glazed unit.)

- ☐ Internal shading products
- ☐ External shading products
- ☐ Interstitial shading products

Q6 How frequently do you specify or recommend shading products for buildings / projects?
(Dynamic / Automated solar shading= uses technology to automate and control external and/or internal solar shading products by means of an intelligent building control system. It receives real-time input from sensors, such as sun, wind and temperature and combines this with pre-set data and thresholds based on the requirements from both facility managers and tenants.

Motorised shading products= shading products that function (raise and lower) via a motor and cordless solutions, which means no physical interaction is required)

	All of the projects	More than half of the projects	About half the projects	Less than half of the projects	None of the projects	Not Applicable
Interior shading (Manual)	○	○	○	○	○	○
Interior shading (Motorised)	○	○	○	○	○	○
Interior shading (Automated)	○	○	○	○	○	○
Exterior shading (Manual)	○	○	○	○	○	○
Exterior shading (Motorised)	○	○	○	○	○	○
Exterior shading (Automated)	○	○	○	○	○	○
Interstitial shading (Manual)	○	○	○	○	○	○
Interstitial shading (Motorised)	○	○	○	○	○	○
Interstitial shading (Automated)	○	○	○	○	○	○

Q7 Why do you think shading products are installed in buildings? (Please select as many option as you wish and answer this question even if you are not directly involved with the shading industry)

	External Shading	Internal Shading	Interstitial shading
Design and making the building more aesthetically pleasing	☐	☐	☐
To reduce overheating (Thermal comfort)	☐	☐	☐
To reduce heat loss (Thermal comfort)	☐	☐	☐
As an energy saving method for cooling	☐	☐	☐
As an energy saving method for heating	☐	☐	☐
Control of daylight (to reduce glare)	☐	☐	☐
Add security	☐	☐	☐
Provide privacy	☐	☐	☐

Q8 In the past 5 years, have you noticed any increase or decrease in the use of shading products?

	Increase	About the same	Decrease	Not applicable / Not known
Internal Shading (Manual)	○	○	○	○
Internal shading (Motorised)	○	○	○	○
Internal shading (Dynamic / Automated)	○	○	○	○
External shading (Manual)	○	○	○	○
External shading (Motorised)	○	○	○	○
External shading (Automated)	○	○	○	○
Interstitial shading (Manual)	○	○	○	○
Interstitial shading (Motorised)	○	○	○	○
Interstitial shading (Automated)	○	○	○	○

Display This Question:

If In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Internal Shading (Manual) [Increase]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = External shading (Motorised) [Increase]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Interstitial shading (Motorised) [Increase]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Interstitial shading (Manual) [Increase]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Internal shading (Motorised) [Increase]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Internal shading (Dynamic / Automated) [Increase]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = External shading (Manual) [Increase]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = External shading (Automated) [Increase]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Interstitial shading (Automated) [Increase]

Q9 For those products that you believe had increased in use, what do you think the reasons for these increases are? (Please select as many options as you wish)

- [ ] Due to having more scientific evidence of being an energy saving method for cooling systems

- [ ] Due to having more scientific evidence of being an energy-saving method for heating systems

- [ ] Due to having more scientific evidence of on the benefits of shading products in reducing thermal loss

- [ ] Due to having more scientific evidence of on the benefits of shading products in reducing overheating

- [ ] Due to changes in building regulations enabling the use of more shading products

- [ ] Increase in public knowledge regarding the benefits of shading products leading to more demand

- [ ] Being more cost efficient than other similar products (i.e. EC Glass)

- [ ] Shading products are now considered as an integral part of buildings where previously was considered as used aesthetics purposes only

Display This Question:

If In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Internal Shading (Manual) [Decrease]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = External shading (Motorised) [Decrease]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Interstitial shading (Motorised) [Decrease]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Interstitial shading (Manual) [Decrease]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Internal shading (Motorised) [Decrease]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Internal shading (Dynamic / Automated) [Decrease]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = External shading (Manual) [Decrease]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = External shading (Automated) [Decrease]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Interstitial shading (Automated) [Decrease]

Q10 For those products that you believe have decreased in use, what are the reasons for these decreases? (Please select as many options as you wish)

- ☐ Being less cost efficient than other similar products (i.e. EC Glass)
- ☐ More innovative products are on the market
- ☐ Due to the public's desire to have less obstructive views in buildings
- ☐ Lack of substantial evidence from building energy modelling software packages proving the benefits of shading products
- ☐ Planning and building regulation issues
- ☐ Shading products are deemed as part of the aesthetic design and are seen as an extra cost for buildings

Display This Question:

If In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Internal Shading (Manual) [About the same]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = External shading (Motorised) [About the same]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Interstitial shading (Motorised) [About the same]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Interstitial shading (Manual) [About the same]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Internal shading (Motorised) [About the same]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Internal shading (Dynamic / Automated) [About the same]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = External shading (Manual) [About the same]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = External shading (Automated) [About the same]

Or In the past 5 years, have you noticed any increase or decrease in the use of shading products? = Interstitial shading (Automated) [About the same]

Q11 For those products where you believe have been no change in the level of use, what are the reasons for this stability? (Please select as many options as you wish)

- ☐ Minimal change to building regulations
- ☐ Lack of new evidence showcasing clear advantages and disadvantages of shading products
- ☐ Demand for shading products has remained stable due to the lack of culture change in using shading products
- ☐ Products work well and therefore there is no need to seek alternatives

---

Display This Question:

If For those products that you believe have decreased in use, what are the reasons for these decreas... = More innovative products are on the market

Q12 Following your previous answers, the decrease in the use of shading products is due to having more innovative products on the market, what innovative products are being used more frequently than shading products? (Please select as many options as you wish)?

▢ Electrochromic Glazing (EC)

▢ Kinetic or Intelligent Facade (Kinetic or intelligent building envelope adapts itself to its environment by means of perception, reasoning and action. This innate adaptiveness enables an envelope to cope with new situations and solve problems that arise in its interaction with the environment.)

▢ Others , please specify ____

Display This Question:

If Which field are you working in? (if you are not sure please choose the nearest option) = Building Services Engineering / Facade Engineering /Sustainability Engineering

Or Which field are you working in? (if you are not sure please choose the nearest option) = Architectural Practice

Or Which field are you working in? (if you are not sure please choose the nearest option) = Academia and Research

Or Which field are you working in? (if you are not sure please choose the nearest option) = Manufacturing and Retail (Shading Industry)

Q13

What percentage of the window area budget of a building will be typically used for shading products?

- ○ 1-10%
- ○ 11-25%
- ○ 26-50%
- ○ More than 50%
- ○ It is not included in any part of the building budget
- ○ Other parts of the building budget, please specify

____

Q14 In your opinion, how much have local planning and building regulations influenced the use of shading products over the past 5 years? (Please answer this question even if you are not directly involved with the industry)

	Significantly	To some degree	Not at all	Not applicable / Not known
Internal shading	○	○	○	○
External shading	○	○	○	○
Interstitial shading	○	○	○	○

Q15 For which of the following areas, do you use performance data to assist in specifying shading products?

- ▢ To control light for visual comfort and reduce glare (Tvis)
- ▢ To control heat retention (U values)
- ▢ To control solar gain (Gtot)
- ▢ To control UV (Tuv)
- ▢ Not using performance data
- ▢ Other, please specify ____

Display This Question:

If For which of the following areas, do you use performance data to assist in specifying shading pro... = To control light for visual comfort and reduce glare (Tvis)

Or For which of the following areas, do you use performance data to assist in specifying shading pro... = To control heat retention (U values)

Or For which of the following areas, do you use performance data to assist in specifying shading pro... = To control solar gain (Gtot)

Or For which of the following areas, do you use performance data to assist in specifying shading pro... = To control UV (Tuv)

Or For which of the following areas, do you use performance data to assist in specifying shading pro... = Other, please specify

Q16 Where do you get the performance / design data of shading products from?

- [ ] Manufacturer's data / Company catalogue
- [ ] European Solar Shading Database (ES-SDA)
- [ ] Modelling software, please specify

____

- [ ] Others, please specify ____

Q63 Have you ever compared the **energy cost savings** of shading with "high specification glass", "air-conditioning" or "heating" to demonstrate the benefit of your proposed option? (i.e. The cheaper option for customers)?

	Yes	No	Not applicable
High specification glass	○	○	○
Cooling system(i.e. Air Conditioning)	○	○	○
Heating system	○	○	○

Q62 Have you ever compared the **carbon reduction** of shading with "high specification glass", "air-conditioning" or "heating" to demonstrate the benefit of your proposed option? (i.e. The cheaper option for customers)?

	Yes	No	Not applicable
High specification glass	○	○	○
Cooling system(i.e. Air Conditioning)	○	○	○
Heating system	○	○	○

Display This Question:

If Have you ever compared the energy cost savings of shading with "high specification glass", "air-c... = High specification glass [Yes]

Or Have you ever compared the energy cost savings of shading with "high specification glass", "air-c... = Cooling system(i.e. Air Conditioning) [Yes]

Or Have you ever compared the energy cost savings of shading with "high specification glass", "air-c... = Heating system [Yes]

Or Have you ever compared the carbon reduction of shading with "high specification glass", "air-cond... = High specification glass [Yes]

Or Have you ever compared the carbon reduction of shading with "high specification glass", "air-cond... = Cooling system(i.e. Air Conditioning) [Yes]

Or Have you ever compared the carbon reduction of shading with "high specification glass", "air-cond... = Heating system [Yes]

Q18 What information did you use to perform this comparison? (Please select as many option as you wish)

▢ Software / Simulation, please specify: ________________________

▢ Energy data

▢ Rule of Thumb

▢ Others, please specify: ____

Q20 Are you aware of the following organisations / associations / resource:

	Yes	No
BBSA (British Blind and Shutter Association) https://bbsa.org.uk/	☐	☐
ES-SO (European Solar Shading Organisation) https://www.es-so.com/	☐	☐
ES-SDA (European Solar Shading Database) https://www.es-so-database.com/index.php/database	☐	☐
Shade IT https://www.shadeit.org.uk/	☐	☐

Q21 Do you have any comments or suggestions (positive or negative) for the shading products industry? (optional)

____

Appendix B: Ethics Approval Letter

The original ethical approval for this survey is provided here.

London South Bank
University

Direct line: 020 7815 7492

E-mail: seethics@lsbu.ac.uk

Ref: Eng_25Oct2018

Thursday 14th March 2019

Dear Ms. Bahareh Salehi,

RE: Improving energy efficiency in buildings via experimental and simulation methods through the use of shading products

Thank you for submitting this Ethics application.

I am pleased to inform you that full Chair's Approval has been given by Dr. Daqing Chen, on behalf of the School of Engineering.

I wish you every success in your research.

Yours sincerely,

Dr. Daqing Chen

Chair, Research Ethics Coordinator

School of Engineering

This ethics approval was renewed on the 20th of November 2020 and is valid until 2024. The renewed ethics approval is written below:

Dear Bahareh

Application ID: ETH1819-0061

Project title: Doctoral Research Project

Lead researcher: Mrs Bahareh Salehi

Thank you for submitting your proposal for ethical review.

I am writing to inform you that your application has been approved.

Your project has received ethical approval from the date of this notification until 20th November 2024.

Yours

Daqing Chen

Appendix C: Information Sheet

Information Sheet

Study title

Assessment of industry/professional’s knowledge regarding solar shading devices

Invitation

You are being invited to take part in a research study that is part of a Doctoral Research scheme supported by London South Bank University. Before you decide whether to participate, it is important for you to understand why the research is being done and what it will involve. Please take the time to read the following information carefully and discuss it with others if you wish. Do not hesitate in contacting the researcher if you have any questions or if you would like more information. Please take your time to decide whether or not you wish to take part.

What is the purpose of the study?

The purpose of the study is to better understand the knowledge and experience of the people working with various shading products (i.e. blinds and shutters) in both domestic and commercial buildings. The results of this questionnaire will be used to formulate the methodology of the research work and also assist in identifying the most suitable shading product to utilise in different settings. Within this study, we seek your experience and thoughts about the use of blind and shutters in buildings. Completing this questionnaire will take about 5 minutes once the survey has started.

Why have I been invited to participate?

You have been chosen based on your knowledge and expertise in the building industry specifically your experience with shading products will be very valuable to us.

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason at any point up to the research being accepted for publication simply by contacting the researcher, Bahareh Salehi. (salehib@lsbu.ac.uk)

What will happen to me if I take part?

You will be asked to fill the questionnaire which will take about 5 minutes once the survey has started.

What are the possible disadvantages/risks of taking part? (where appropriate)

Participating in the research is not anticipated to cause you any disadvantages or discomfort. The potential physical and/or psychological harm or distress will be the same as any experienced in everyday life. If filling the questionnaire causes any distress you can suspend it.

What are the possible benefits of taking part?

Whilst there are no immediate benefits for those people participating in the project, it is hoped that this work will have a beneficial impact on the building energy industry. In addition, participation can have direct input into the research which in turn, can assist with future key decision making and legislation in the building energy environment.

Will the data collected in this study be kept confidential?

All information which is collected about you and other participants will be kept strictly confidential. Any information about you which is shared with others (e.g. with other members of the research team) will have your name removed so that you cannot be identified from it. You will be assigned a participant number for you to keep safe so you are unidentifiable from the data collected. This information will facilitate your data removal if at a later date you choose to withdraw from the study.

Data generated by the study must be retained in accordance with the University's Code of Practice. All data generated in the course of the research must be kept securely in paper or electronic form for a period of 10 years after the completion of a research project. Electronic data files (from which you cannot be identified) will be stored in a password secured file. Only members of the research team will have access to this file.

What will happen to the results of the research study?

Results of the research will be analysed and be used in the thesis of the PhD of the researcher which then will be submitted for publication in an academic journal or may be presented at conferences. You will not be identified in any report or publication. Your institution/company will not be identified in any report or publication unless you want your name or name of the company to be published. If you wish to be given a copy of any reports resulting from the research, please get in touch with the lead investigator, Bahareh Salehi. (salehib@lsbu.ac.uk)

Who is organizing and funding the research?

The research is supervised by Bahareh Salehi (salehib@lsbu.ac.uk), Dr Deborah Andrews (deborah.andrews@lsbu.ac.uk), Prof Issa Chaer (chaeri@lsbu.ac.uk) and Dr Aaron Gillich (gillicha@lsbu.ac.uk) all of them work in the Department of Engineering at LSBU. It has also been supervised by Dr Elizabeth Newton (liz.newton@lsbu.ac.uk) from the Department of Psychology at LSBU.

Who has reviewed the study?

This study has been reviewed and approved by the School of Engineering, Ethics Panel at London South Bank University.

Who should I contact if I have any concerns about this research?

Please contact the Chair of the University Research Ethics Committee, (ethics@lsbu.ac.uk), if you have any concerns arising from the research project.

Contact for Further Information

If you would like further information about this study, please get in touch with Bahareh Salehi.

School of Engineering, London South Bank University,103 Borough Road, London,

SE1 0AA.

Email: salehib@lsbu.ac.uk

Thank you

Thank you for taking the time to read the Information Sheet and participate in this study.

Researcher: Bahareh Salehi.

Appendix D: Consent Form

Consent Form

Dear Participant, thank you very much for agreeing to participate in this interview. The information provided by you in this questionnaire will be used for research purposes. It will not be used in a manner that would allow identification of your individual responses. **(Please Tick the Box that Applies)**

	Yes	No
I have read the attached information sheet on the research in which I have been asked and agree to participate and have been given a copy to keep. I have had the opportunity to discuss the details and ask questions about this information.	○	○
I agree to take part in the above study.	○	○
I understand that my personal involvement and my particular data from this study will remain strictly confidential. Only researchers involved in the study will have access	○	○
I understand the project is for research purpose only, and not for any commercial purpose.	○	○

Use of my Information **(Please Tick the Box that Applies)**

	Yes	No
I understand my personal details such as phone number and address will not be revealed to people outside the project.	○	○
I agree for the data I provide to be stored (after it has been anonymised) in a specialist data centre and I understand it may be used for future research.	○	○
I hereby fully and freely consent to participate in the study which has been fully explained to me	○	○
I understand that I am free to withdraw from the study at any time, without giving a reason	○	○

Appendix E: Written Debriefing Form

Written Debriefing Form

Thank you for your participation. We hope you enjoyed the experience. This form provides background about our research to help you know more about why we are doing this study. Please feel free to ask any questions or to comment on any aspect of the study.

You have just participated in a research study conducted by Bahareh Salehi. (salehib@lsbu.ac.uk)

The purpose of the study is to better understand the knowledge and experience of the people working with various shading products (i.e. blinds and shutters) in both domestic and commercial buildings. The results of this questionnaire will be used to formulate the methodology of the research work and also assist in identifying the most suitable shading product to utilise in different settings.

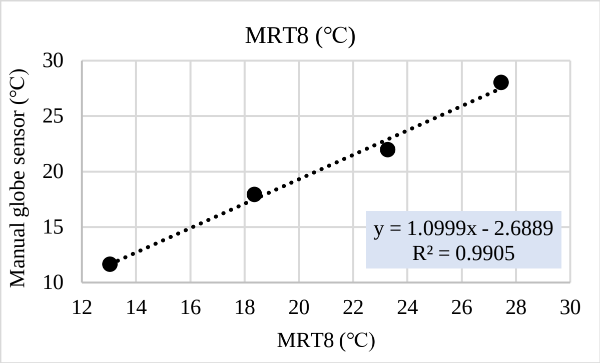
As you know, your participation in this study is voluntary. If you so wish, you may withdraw after reading this debriefing form, at which point all records of your participation will be destroyed. You will not be penalized if you withdraw. If you have questions about the research, please e-mail Bahareh Salehi, salehib@lsbu.ac.uk.

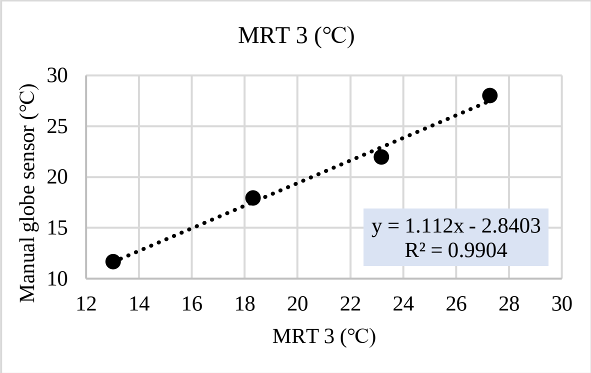
Please keep this part of the sheet for reference.

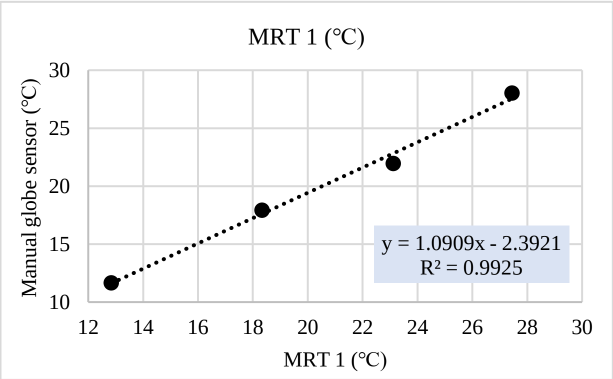
- ○ Please tick if you have read the above information.

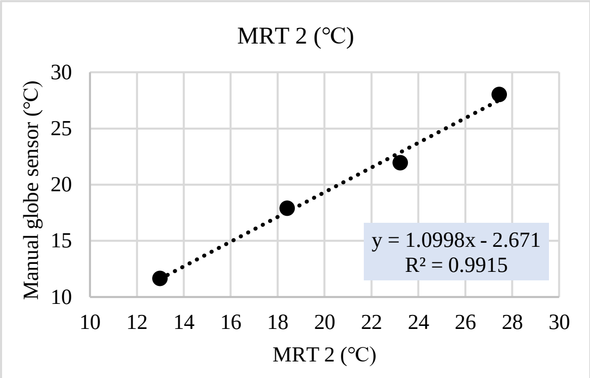
Appendix A: Globe Sensors Calibration

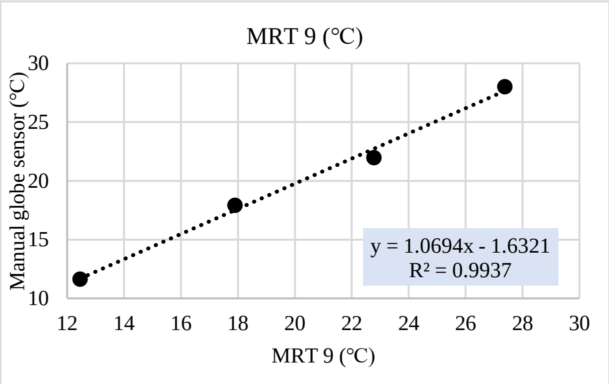
Calibration results for all of the operative temperature sensors used in this study are presented in this appendix.

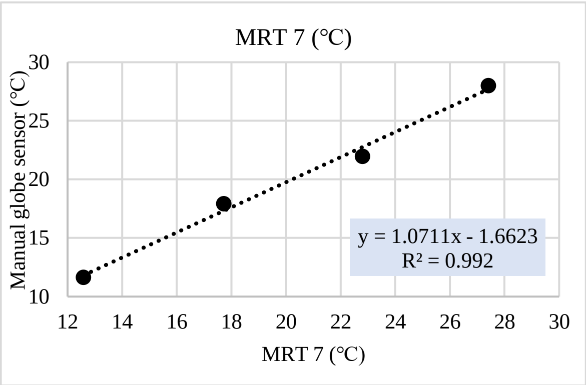


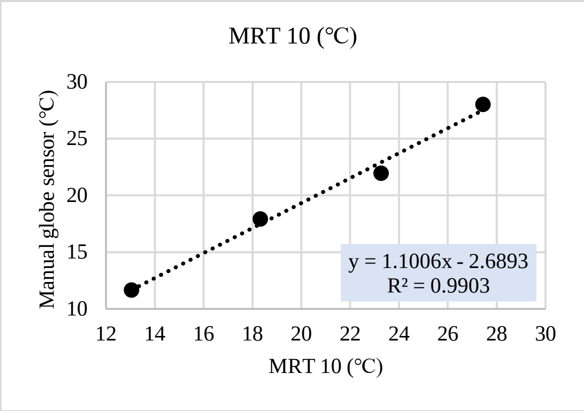


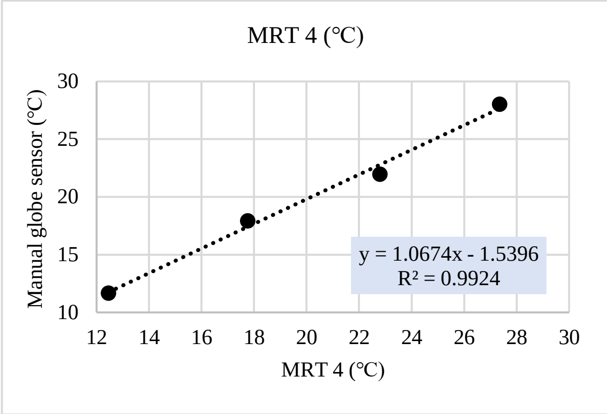









MRT 10 (°C)
Manual globe sensor (°C)
30
25
20
15
10
12 14 16 18 20 22 24 26 28 30
MRT 10 (°C)
y = 1.1006x - 2.6893
R² = 0.9903


MRT 4 (°C)
Manual globe sensor (°C)
30
25
20
15
10
12 14 16 18 20 22 24 26 28 30
MRT 4 (°C)
y = 1.0674x - 1.5396
R² = 0.9924

Appendix B: Air Permeability Test Result

A registered certificate of air permeability test issued by Acoustic Associates Sussex Ltd is presented here.

Registered Certificate of Air Permeability Test

Acoustic Associates

ATTMA — The Air Tightness Testing & Measurement Association

UCRN: 10878049

Test Credentials

Issued by:	**Acoustic Associates Sussex Ltd**						
Address:	8 Highdown House Shoreham Airport Shoreham-by-Sea England BN43 5PB	**Technician:**	David Kendal				
		Registration No:	15965				
		Qualification:	1	2	3	PH	EA
			✓			✓	
		For clarification on technician qualifications please visit https://www.bcta.group/attma/members					
Telephone:	01273 455074						
Email:	air@aasussex.co.uk						
Report reference:	J3033						

Building Details

Building identifier:	**103**			
Address:	Borough Rd, London, Greater London, SE1 0AA			
Type:	Non-Dwelling	**Description:**	Educational	
Construction:	Concrete Frame	**Warm roof:**	Yes	
Size:	**Footprint (m²)**	**Envelope (m²)**	**Volume (m³)**	**Storey**
	13.14	65.31	30.9	1
Ventilation:	System 4 - Continuous Mechanical Extraction with Heat Recovery			
Primary heating:	Gas	**Air conditioning:**	None	
Mastic sealing:	External Walls Only (inc. sanitary ware)			

Test Details

Date:	**15/01/2021**		
Retest:	No	**Lodgement Type:**	Final Test
Data acquisition:	Manual	**Test Type:**	Zone Test
Temporary sealing:	Mechanical ventilation sealed.		
Deviations:	none		

Test Results

This is to certify that the above name building has been tested by a registered provider in accordance with ATTMA TSL1 or TSL2 subject to the above statements regarding temporary sealing and deviations from these test standards.
This certificate is a short form report. If a full compliant report is required please contact the company that issued the certificate. Enquiries about this certificate should be made to: Scheme Manager, ATTMA, First Floor, Flint Barn Court, Church Street, Amersham, Buckinghamshire, England, HP7 0DB or visit www.bcta.group/attma

Results | **Notifications**

Design Air Permeability:	4.00 $m^3.h^{-1}.m^{-2}$ @50Pa
Air Permeability (AP_{50}):	17.89 $m^3.h^{-1}.m^{-2}$ @50Pa

Is the air permeability less than or equal to the design air permeability?

✗ The result achieved has failed to meet the Design Air Permeability requirement.

Air Flow Coefficient (C_{env}):	81.000	**Air Flow Exponent (n)**	0.68
Air Leakage at 50 Pa (Q50):	1169	**Coefficient of Determination (r^2)**	0.984

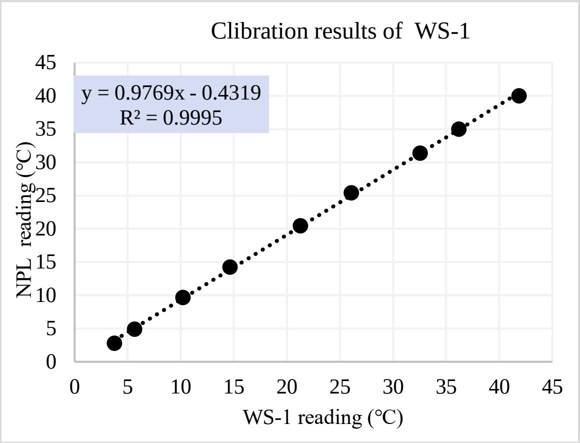
BCTA

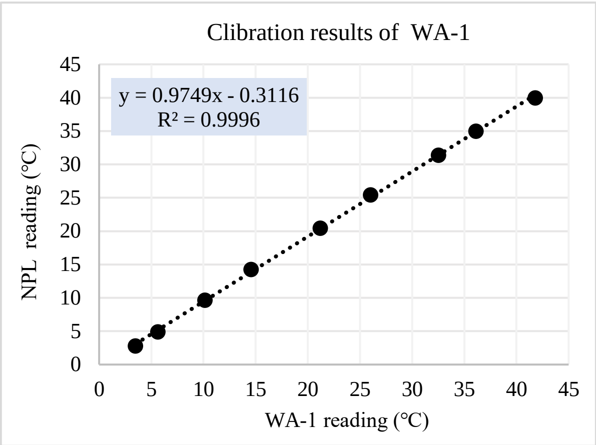
ATTMA is part of the Building Compliance Testers Association (BCTA). The BCTA is a trade association for companies that conduct on-site testing and operate within controlled, audited schemes.

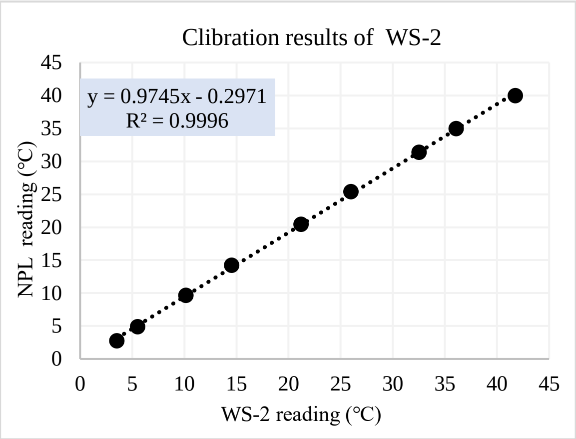
Enquiries should be made to: BCTA, First Floor, Flint Barn Court, Church Street, Amersham, Buckinghamshire, England, HP7 HP7 0DB or visit www.bcta.group

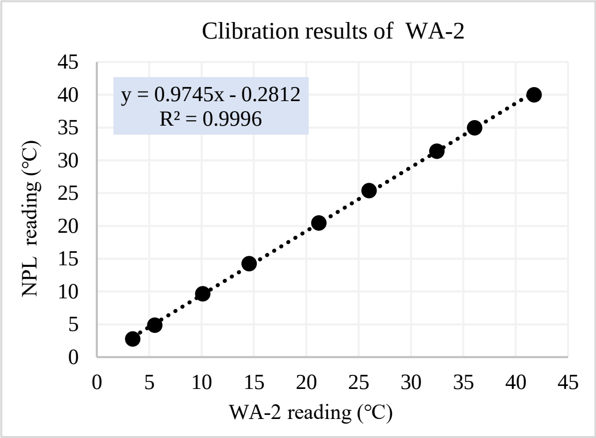
Appendix C: Thermocouples Calibration

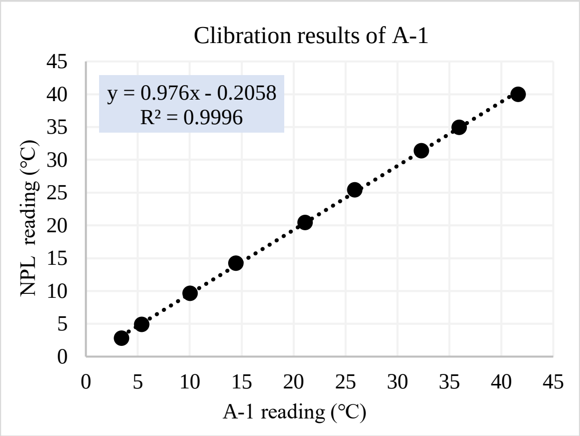
The calibration results for all of the temperature sensors used in this study are presented in this appendix.

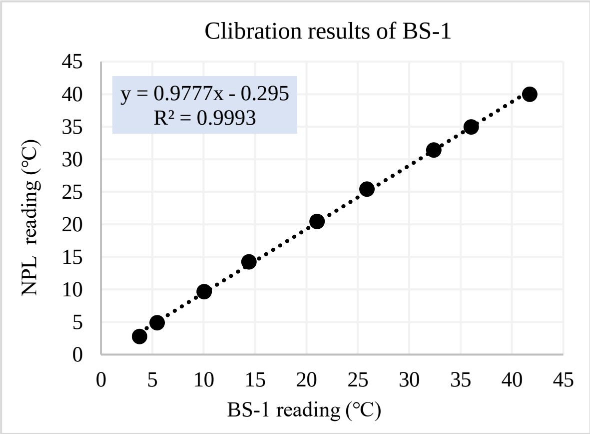


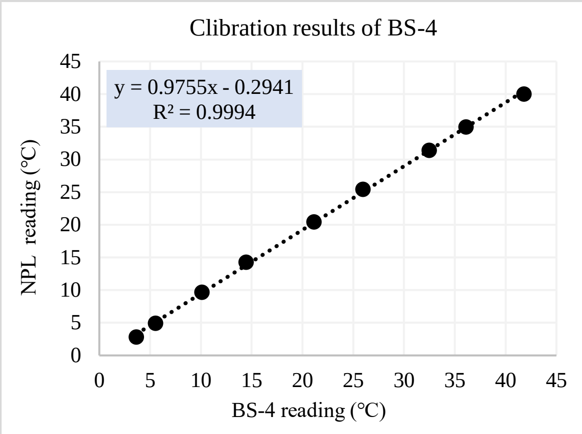


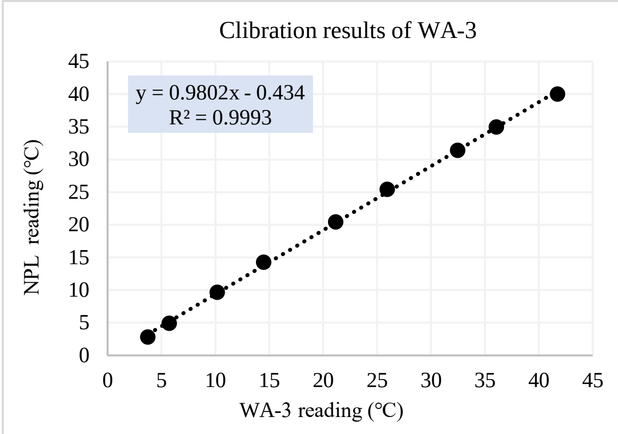


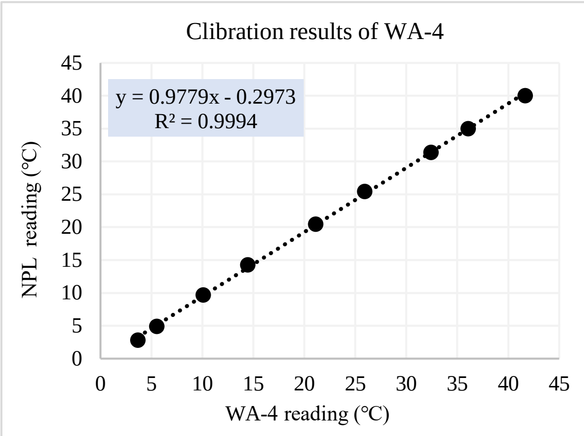


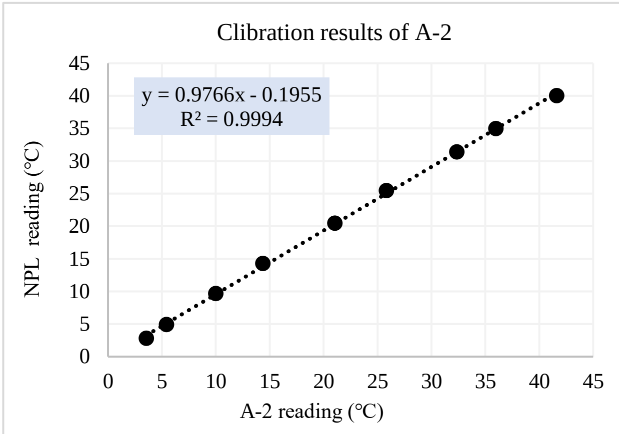


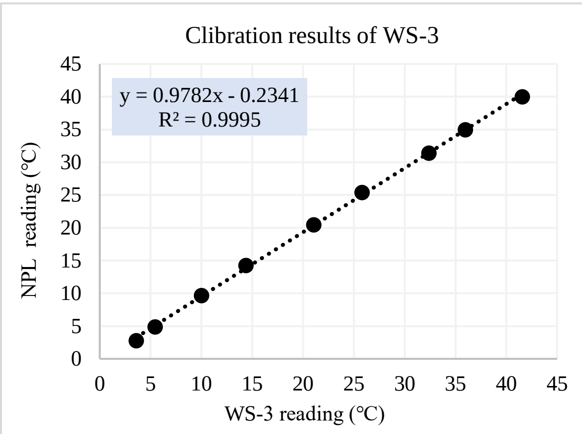


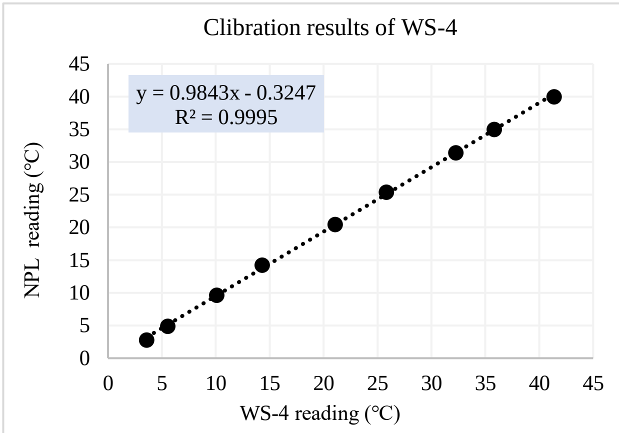

Clibration results of BS-4
y = 0.9755x - 0.2941
R² = 0.9994
NPL reading (°C)
BS-4 reading (°C)

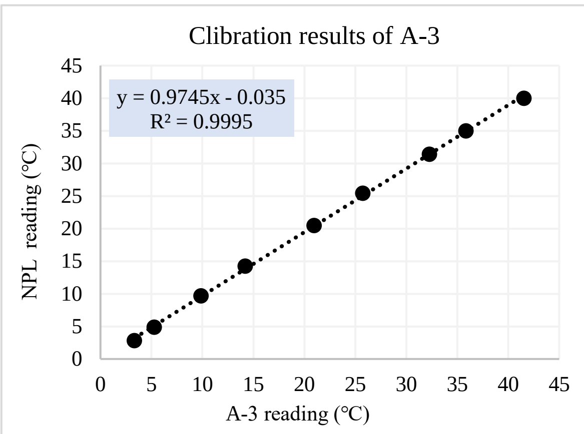

Clibration results of WA-3
y = 0.9802x - 0.434
R² = 0.9993
NPL reading (°C)
WA-3 reading (°C)

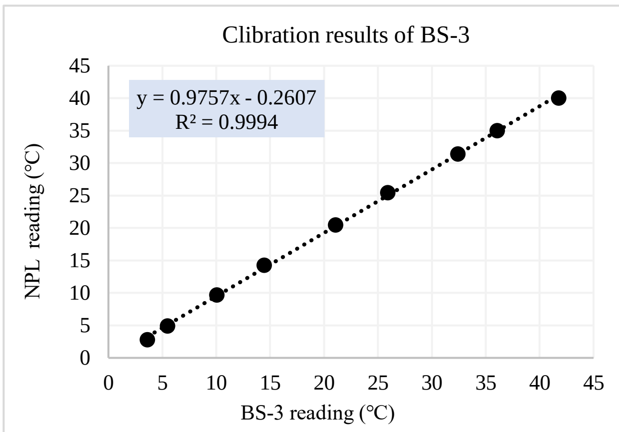

Clibration results of WA-4
y = 0.9779x - 0.2973
R² = 0.9994
NPL reading (°C)
WA-4 reading (°C)

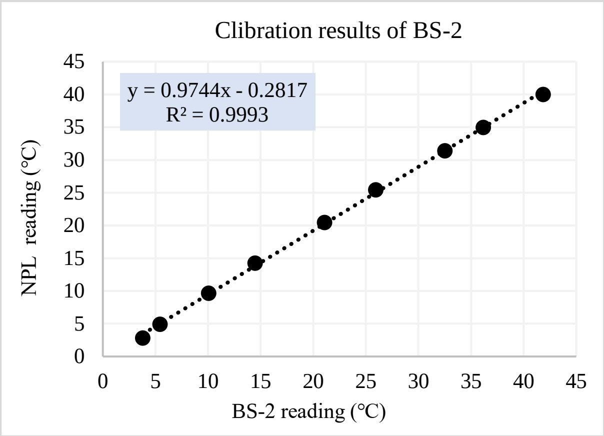

Clibration results of A-2
y = 0.9766x - 0.1955
R² = 0.9994
NPL reading (°C)
A-2 reading (°C)


Clibration results of WS-3
y = 0.9782x - 0.2341
R² = 0.9995
NPL reading (°C)
WS-3 reading (°C)


Clibration results of WS-4
y = 0.9843x - 0.3247
R² = 0.9995
NPL reading (°C)
WS-4 reading (°C)


Clibration results of A-3
y = 0.9745x - 0.035
R² = 0.9995
NPL reading (°C)
A-3 reading (°C)


Clibration results of BS-3
y = 0.9757x - 0.2607
R² = 0.9994
NPL reading (°C)
BS-3 reading (°C)


Clibration results of BS-2
y = 0.9744x - 0.2817
R² = 0.9993
NPL reading (°C)
BS-2 reading (°C)
0
5
10
15
20
25
30
35
40
45

Appendix D: BEMS Software Survey

Q1 What is your name and preferred means of contact? (Optional)

- ☐ Name ____

- ☐ Email ____

- ☐ Telephone Number ____

- ☐ Address ____

Q2 Which field are you working in? (if you are not sure please choose the nearest option)

- ○ Building Services Engineering / Facade Engineering /Sustainability Engineering

- ○ Architectural Practice

- ○ Academia and Research

Q3 How many years have you been working in this field?

- Less than 5 years
- 5-10 years
- 11-20 years
- More than 20 years

Q5 How frequently do you consider the below shading products during the modelling phase of your projects?

	All of the projects	More than half of the projects	About half the projects	Less than half of the projects	None of the projects
Internal Shading (Inside building)	○	○	○	○	○
External Shading(Outside building)	○	○	○	○	○
Inter-pane Shading (Between two layers of glass)	○	○	○	○	○

Display This Question:

If How frequently do you consider the below shading products during the modelling phase of your proj... != Internal Shading (Inside building) [None of the projects]

Or How frequently do you consider the below shading products during the modelling phase of your proj... != External Shading(Outside building) [None of the projects]

Or How frequently do you consider the below shading products during the modelling phase of your proj... != Inter-pane Shading (Between two layers of glass) [None of the projects]

Q6 What are the main reasons why you consider shading products in your modelling projects? (Please choose as many options as you wish)

- ☐ Shading products are the key components of a building
- ☐ Thermal comfort benefits
- ☐ Energy efficiency benefits
- ☐ Regulatory and compliance obligations
- ☐ Client requirements

Q7 Which software packages do you have experience in for building energy modelling and simulation? (Please choose as many options as you wish)

- ☐ EnergyPlus
- ☐ IES VE
- ☐ eQUEST
- ☐ TRNSYS
- ☐ ESP-r
- ☐ BIM
- ☐ Sefaira
- ☐ TAS
- ☐ IDA ICE (EQUA ESBO)
- ☐ DesignBuilder
- ☐ In-house software (developed by a company/institute), please specify: ________________________________

- [ ] Others, please specify: ____

- [ ] Not using a software package

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... != Not using a software package

Q8 Which software packages are you currently using for building energy modelling and simulation? (Please choose as many options as you wish)

- [ ] EnergyPlus
- [ ] IES VE
- [ ] eQUEST
- [ ] TRNSYS
- [ ] ESP-r
- [ ] BIM
- [ ] Sefaira
- [ ] TAS
- [ ] IDA ICE (EQUA ESBO)
- [ ] DesignBuilder
- [ ] In-house software (developed by your current company/institute), please specify: ____
- [ ] Others, please specify: ____

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = EnergyPlus

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = EnergyPlus

Q9 How many years have you been working with EnergyPlus?

○ Less than 1 year

○ 1-5 years

○ 6-10 years

○ More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = EnergyPlus

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = EnergyPlus

Q10 How satisfied are you with the below criteria when using EnergyPlus?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = EnergyPlus

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = EnergyPlus

Q11 Is weather data embedded into EnergyPlus?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into EnergyPlus? = Standard weather data [No]

Or Is weather data embedded into EnergyPlus? = Future weather data [No]

Q12 If weather data is not embedded into EnergyPlus, what weather data do you use?

____

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = EnergyPlus

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = EnergyPlus

Q13 Do you use EnergyPlus to model shading products?

○ Yes

○ No

Display This Question:

If Do you use EnergyPlus to model shading products? = Yes

Q14 Which of the below statements represent how comprehensive the shading product database within EnergyPlus is? (Please choose as many options as you wish)

- ☐ Various types of shading products are available in the software database to select from
- ☐ Requires manual modelling of the solar shading (model/draw by myself)
- ☐ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within Ene... = Requires importing from other software or applications

Q15 If you need to import shading product modelling, which software packages do you use?

____

Display This Question:

If Do you use EnergyPlus to model shading products? = Yes

Q16

Do the resulting shading product models in EnergyPlus illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = IES VE

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = IES VE

Q17 How many years have you been working with IES VE?

- ◯ Less than 1 year
- ◯ 1-5 years
- ◯ 6-10 years
- ◯ More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = IES VE

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = IES VE

Q18 How satisfied are you with the below criteria when using IES VE?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = IES VE

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = IES VE

Q19 Is weather data embedded into IES VE?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into IES VE? = Standard weather data [No]

Or Is weather data embedded into IES VE? = Future weather data [No]

Q20 If weather data is not embedded into IES VE, where is it derived from?

____

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = IES VE

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = IES VE

Q21 Do you use IES VE to model shading products?

○ Yes

○ No

Display This Question:

If Do you use IES VE to model shading products? = Yes

Q22 Which of the below statements represent how comprehensive the shading product database within IES VE is?(Please choose as many options as you wish)

- ☐ Various types of shading are available in the software database to select
- ☐ Need to draw solar shade by myself
- ☐ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within Ene... = Requires importing from other software or applications

Q23 If you need to import shading product modelling, which software packages do you use?

____

Display This Question:

If Do you use IES VE to model shading products? = Yes

Q24

Do the resulting shading product models in IES VE illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = eQUEST

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = eQUEST

Q25 How many years have you been working with eQUEST?

- ○ Less than 1 year
- ○ 1-5 years
- ○ 6-10 years
- ○ More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = eQUEST

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = eQUEST

Q26 How satisfied are you with the below criteria when using eQUEST?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = eQUEST

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = eQUEST

Q27 Is weather data embedded into eQUEST?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into eQUEST? = Standard weather data [No]

Or Is weather data embedded into eQUEST? = Future weather data [No]

Q28 If weather data is not embedded into eQUEST, where is it derived from?

____

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = eQUEST

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = eQUEST

Q29 Do you use eQUEST to model shading products?

○ Yes

○ No

Display This Question:

If Do you use eQUEST to model shading products? = Yes

Q30 Which of the below statements represent how comprehensive the shading product database within eQUEST is? (Please choose as many options as you wish)

- ▢ Various types of shading are available in the software database to select
- ▢ Need to draw solar shade by myself
- ▢ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within eQU... = Requires importing from other software or applications

Q31 If you need to import shading product modelling, which software packages do you use?

____

Display This Question:

If Do you use eQUEST to model shading products? = Yes

Q32

Do the resulting shading product models in eQUEST illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = TRNSYS

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = TRNSYS

Q33 How many years have you been working with TRNSYS?

- Less than 1 year
- 1-5 years
- 6-10 years
- More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = TRNSYS

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = TRNSYS

Q34 How satisfied are you with the below criteria when using TRNSYS?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = TRNSYS

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = TRNSYS

Q35 Is weather data embedded into TRNSYS?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into TRNSYS? = Standard weather data [No]

Or Is weather data embedded into TRNSYS? = Future weather data [No]

Q36 If weather data is not embedded into TRNSYS, where is it derived from?

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Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = TRNSYS

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = TRNSYS

Q37 Do you use TRNSYS to model shading products?

○ Yes

○ No

Display This Question:

If Do you use TRNSYS to model shading products? = Yes

Q38 Which of the below statements represent how comprehensive the shading product database within TRNSYS is?(Please choose as many options as you wish)

- ☐ Various types of shading are available in the software database to select
- ☐ Need to draw solar shade by myself
- ☐ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within TRN... = Requires importing from other software or applications

Q39 If you need to import shading product modelling, which software packages do you use?

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Display This Question:

If Do you use TRNSYS to model shading products? = Yes

Q40

Do the resulting shading product models in TRNSYS illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = ESP-r

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = ESP-r

Q41 How many years have you been working with ESP-r?

- Less than 1 year
- 1-5 years
- 6-10 years
- More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = ESP-r

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = ESP-r

Q42 How satisfied are you with the below criteria when using ESP-r?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = ESP-r

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = ESP-r

Q43 Is weather data embedded into ESP-r?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into ESP-r? = Standard weather data [No]

Or Is weather data embedded into ESP-r? = Future weather data [No]

Q44 If weather data is not embedded into ESP-r, where is it derived from?

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Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = ESP-r

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = ESP-r

Q45 Do you use ESP-r to model shading products?

- ○ Yes
- ○ No

Display This Question:

If Do you use ESP-r to model shading products? = Yes

Q46 Which of the below statements represent how comprehensive the shading product database within ESP-r is?(Please choose as many options as you wish)

- ☐ Various types of shading are available in the software database to select
- ☐ Need to draw solar shade by myself
- ☐ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within ESP... = Requires importing from other software or applications

Q47 If you need to import shading product modelling, which software packages do you use?

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Display This Question:

If Do you use ESP-r to model shading products? = Yes

Q48

Do the resulting shading product models in ESP-r illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = BIM

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = BIM

Q49 How many years have you been working with BIM?

- ○ Less than 1 year
- ○ 1-5 years
- ○ 6-10 years
- ○ More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = BIM

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = BIM

Q50 How satisfied are you with the below criteria when using BIM?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = BIM

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = BIM

Q51 Is weather data embedded into BIM?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into BIM? = Standard weather data [No]

Or Is weather data embedded into BIM? = Future weather data [No]

Q52 If weather data is not embedded into BIM, what weather data do you use?

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Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = BIM

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = BIM

Q53 Do you use BIM to model shading products?

○ Yes

○ No

Display This Question:

If Do you use BIM to model shading products? = Yes

Q54 Which of the below statements represent how comprehensive the shading product database within BIM is?(Please choose as many options as you wish)

☐ Various types of shading products are available in the software database to select from

☐ Requires manual modeling of the solar shading (model/draw by myself)

☐ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within BIM... = Requires importing from other software or applications

Q55 If you need to import shading product modelling, which software packages do you use?

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Display This Question:

If Do you use BIM to model shading products? = Yes

Q56

Do the resulting shading product models in BIM illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	◯	◯	◯	◯
Energy Consumption (reducing heat loss)	◯	◯	◯	◯
Thermal Comfort (reducing overheating)	◯	◯	◯	◯
Thermal Comfort (reducing heat loss)	◯	◯	◯	◯
Glare reduction	◯	◯	◯	◯

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = Sefaira

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = Sefaira

Q57 How many years have you been working with Sefaira?

- ○ Less than 1 year
- ○ 1-5 years
- ○ 6-10 years
- ○ More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = Sefaira

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = Sefaira

Q58 How satisfied are you with the below criteria when using Sefaira?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = Sefaira

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = Sefaira

Q59 Is weather data embedded into Sefaira?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into Sefaira? = Standard weather data [No]

Or Is weather data embedded into Sefaira? = Future weather data [No]

Q60 If weather data is not embedded into Sefaira, what weather data do you use?

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Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = Sefaira

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = Sefaira

Q61 Do you use Sefaira to model shading products?

○ Yes

○ No

Display This Question:

If Do you use Sefaira to model shading products? = Yes

Q62 Which of the below statements represent how comprehensive the shading product database within Sefaira is? (Please choose as many options as you wish)

☐ Various types of shading products are available in the software database to select from

☐ Requires manual modeling of the solar shading (model/draw by myself)

☐ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within Sefaira is... = Requires importing from other software or applications

Q63 If you need to import shading product modelling, which software packages do you use?

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Display This Question:

If Do you use Sefaira to model shading products? = Yes

Q64

Do the resulting shading product models in Sefaira illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = TAS

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = TAS

Q65 How many years have you been working with TAS?

- ○ Less than 1 year
- ○ 1-5 years
- ○ 6-10 years
- ○ More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = TAS

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = TAS

Q66 How satisfied are you with the below criteria when using TAS?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = TAS

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = TAS

Q67 Is weather data embedded into TAS?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into TAS? = Standard weather data [No]

Or Is weather data embedded into TAS? = Future weather data [No]

Q68 If weather data is not embedded into TAS, what weather data do you use?

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Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = TAS

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = TAS

Q69 Do you use TAS to model shading products?

○ Yes

○ No

Display This Question:

If Do you use TAS to model shading products? = Yes

Q70 Which of the below statements represent how comprehensive the shading product database within TAS is?(Please choose as many options as you wish)

- ☐ Various types of shading products are available in the software database to select from
- ☐ Requires manual modeling of the solar shading (model/draw by myself)
- ☐ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within TAS... = Requires importing from other software or applications

Q71 If you need to import shading product modelling, which software packages do you use?

____

Display This Question:

If Do you use TAS to model shading products? = Yes

Q72

Do the resulting shading product models in TAS illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = IDA ICE (EQUA ESBO)

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = IDA ICE (EQUA ESBO)

Q73 How many years have you been working with IDA ICE (EQUA ESBO)?

◯ Less than 1 year

◯ 1-5 years

◯ 6-10 years

◯ More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = IDA ICE (EQUA ESBO)

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = IDA ICE (EQUA ESBO)

Q74 How satisfied are you with the below criteria when using IDA ICE (EQUA ESBO)?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = IDA ICE (EQUA ESBO)

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = IDA ICE (EQUA ESBO)

Q75 Is weather data embedded into IDA ICE (EQUA ESBO)?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into IDA ICE (EQUA ESBO)? = Standard weather data [No]

Or Is weather data embedded into IDA ICE (EQUA ESBO)? = Future weather data [No]

Q76 If weather data is not embedded into IDA ICE (EQUA ESBO), what weather data do you use?

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Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = IDA ICE (EQUA ESBO)

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = IDA ICE (EQUA ESBO)

Q77 Do you use IDA ICE (EQUA ESBO) to model shading products?

○ Yes

○ No

Display This Question:

If Do you use IDA ICE (EQUA ESBO) to model shading products? = Yes

Q78 Which of the below statements represent how comprehensive the shading product database within IDA ICE (EQUA ESBO) is?(Please choose as many options as you wish)

☐ Various types of shading products are available in the software database to select from

☐ Requires manual modeling of the solar shading (model/draw by myself)

☐ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within IDA... = Requires importing from other software or applications

Q79 If you need to import shading product modelling, which software packages do you use?

____

Display This Question:

If Do you use IDA ICE (EQUA ESBO) to model shading products? = Yes

Q80

Do the resulting shading product models in IDA ICE (EQUA ESBO) illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = DesignBuilder

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = DesignBuilder

Q81 How many years have you been working with DesignBuilder?

○ Less than 1 year

○ 1-5 years

○ 6-10 years

○ More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = DesignBuilder

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = DesignBuilder

Q82 How satisfied are you with the below criteria when using DesignBuilder?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = DesignBuilder

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = DesignBuilder

Q83 Is weather data embedded into DesignBuilder?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into DesignBuilder? = Standard weather data [No]

Or Is weather data embedded into DesignBuilder? = Future weather data [No]

Q84 If weather data is not embedded into DesignBuilder, what weather data do you use?

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Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = DesignBuilder

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = DesignBuilder

Q85 Do you use DesignBuilder to model shading products?

◯ Yes

◯ No

Display This Question:

If Do you use DesignBuilder to model shading products? = Yes

Q86 Which of the below statements represent how comprehensive the shading product database within DesignBuilder is?(Please choose as many options as you wish)

▢ Various types of shading products are available in the software database to select from

▢ Requires manual modeling of the solar shading (model/draw by myself)

▢ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within Des... = Requires importing from other software or applications

Q87 If you need to import shading product modelling, which software packages do you use?

____

Display This Question:

If Do you use DesignBuilder to model shading products? = Yes

Q88

Do the resulting shading product models in DesignBuilder illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = In-house software (developed by a company/institute), please specify:

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = In-house software (developed by your current company/institute), please specify:

Q89 How many years have you been working with your in-house software?

- ○ Less than 1 year
- ○ 1-5 years
- ○ 6-10 years
- ○ More than 10 years

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = In-house software (developed by a company/institute), please specify:

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = In-house software (developed by your current company/institute), please specify:

Q90 Why did you or your company/institute develop your in-house software rather than using other readily available packages?

- ☐ Related to security reasons
- ☐ Related to ease of use
- ☐ Other packages did not meet the requirements, please specify ________________

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = In-house software (developed by a company/institute), please specify:

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = In-house software (developed by your current company/institute), please specify:

Q91 How satisfied are you with the below criteria when using your in-house software?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = In-house software (developed by a company/institute), please specify:

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = In-house software (developed by your current company/institute), please specify:

Q92 Is weather data embedded into your in-house software?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into your in-house software? = Standard weather data [No]

Or Is weather data embedded into your in-house software? = Future weather data [No]

Q93 If weather data is not embedded into your in-house software, what weather data do you use?

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Display This Question:

If Which software packages do you have experience in for building energy modelling and simulation? (... = In-house software (developed by a company/institute), please specify:

Or Which software packages are you currently using for building energy modelling and simulation? (Pl... = In-house software (developed by your current company/institute), please specify:

Q94 Do you use your in-house software to model shading products?

- ○ Yes
- ○ No

Display This Question:

If Do you use your in-house software to model shading products? = Yes

Q95 Which of the below statements represent how comprehensive the shading product database within your developed software is?(Please choose as many options as you wish)

- ☐ Various types of shading products are available in the software database to select from
- ☐ Requires manual modeling of the solar shading (model/draw by myself)
- ☐ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within you... = Requires importing from other software or applications

Q96 If you need to import shading product modelling, which software packages do you use?

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Display This Question:

If Do you use your in-house software to model shading products? = Yes

Q97

Do the resulting shading product models in your developed software illustrate any effect in terms of energy consumption or thermal comfort in your in-house software?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	○	○	○	○
Energy Consumption (reducing heat loss)	○	○	○	○
Thermal Comfort (reducing overheating)	○	○	○	○
Thermal Comfort (reducing heat loss)	○	○	○	○
Glare reduction	○	○	○	○

Display This Question:

If Which software packages are you currently using for building energy modelling and simulation? (Pl... = Others, please specify:

Q98 How many years have you been working with ${Q351/ChoiceTextEntryValue/13}?

- Less than 1 year
- 1-5 years
- 6-10 years
- More than 10 years

Display This Question:

If Which software packages are you currently using for building energy modelling and simulation? (Pl... = Others, please specify:

Q99 How satisfied are you with the below criteria when using ${Q351/ChoiceTextEntryValue/13}?

	Satisfied	Neither satisfied nor dissatisfied	Dissatisfied
User friendly	○	○	○
Reliability	○	○	○
Cost	○	○	○
Compatibility	○	○	○
Accuracy	○	○	○
Shading Products portfolio	○	○	○

Display This Question:

If Which software packages are you currently using for building energy modelling and simulation? (Pl... = Others, please specify:

Q100 Is weather data embedded into ${Q351/ChoiceTextEntryValue/13}?

	Yes	No
Standard weather data	○	○
Future weather data	○	○

Display This Question:

If Is weather data embedded into ${q://QID351/ChoiceTextEntryValue/13}? = Standard weather data [No]

Or Is weather data embedded into ${q://QID351/ChoiceTextEntryValue/13}? = Future weather data [No]

Q101 If weather data is not embedded into ${Q351/ChoiceTextEntryValue/13}, what weather data do you use?

____

____

____

____

____

Display This Question:

If Which software packages are you currently using for building energy modelling and simulation? (Pl... = Others, please specify:

Q102 Do you use ${Q351/ChoiceTextEntryValue/13} to model shading products?

◯ Yes

◯ No

Display This Question:

If Do you use ${q://QID351/ChoiceTextEntryValue/13} to model shading products? = Yes

Q103 Which of the below statements represent how comprehensive the shading product database within ${Q351/ChoiceTextEntryValue/13} is?(Please choose as many options as you wish)

▢ Various types of shading products are available in the software database to select from

▢ Requires manual modeling of the solar shading (model/draw by myself)

▢ Requires importing from other software or applications

Display This Question:

If Which of the below statements represent how comprehensive the shading product database within ... = Requires importing from other software or applications

Q104 If you need to import shading product modelling, which software packages do you use?

____

Display This Question:

If Do you use ${q://QID351/ChoiceTextEntryValue/13} to model shading products? = Yes

Q105
Do the resulting shading product models in ${Q351/ChoiceTextEntryValue/13} illustrate any effect in terms of energy consumption or thermal comfort in your modelling project?

	Positive effect (Decrease)	Negative effect (Increase)	No effect	Never checked
Energy Consumption (reducing overheating)	o	o	o	o
Energy Consumption (reducing heat loss)	o	o	o	o
Thermal Comfort (reducing overheating)	o	o	o	o
Thermal Comfort (reducing heat loss)	o	o	o	o
Glare reduction	o	o	o	o

Q106 Do you have any comments or suggestions (positive or negative) for the shading products industry? (optional)

____

Appendix E: Information Sheet – BEMS Software Survey

Information Sheet

Study title

Building Energy Modelling and Simulation Software Packages with regards to Shading Products

Invitation

You are being invited to take part in a research study that is part of a Doctoral Research scheme supported by London South Bank University. Before you decide whether to participate, it is important for you to understand why the research is being done and what it will involve. Please take the time to read the following information carefully and discuss it with others if you wish. Do not hesitate in contacting the researcher if you have any questions or if you would like more information. Please take your time to decide whether or not you wish to take part.

What is the purpose of the study?

The purpose of the study is to better understand the capabilities of the Building Energy Modelling Software Packages in relation to shading product modelling. The results of this questionnaire will be used to formulate the methodology of the research work and also assist in identifying the most suitable software packages to utilize. Completing this questionnaire will take about 10 minutes once the survey has started.

Why have I been invited to participate?

You have been chosen based on your knowledge and expertise in the building industry specifically your experience with building energy modelling will be very valuable to us.

Do I have to take part?

It is up to you to decide whether or not to take part. If you do decide to take part, you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part, you are still free to withdraw at any time and without giving a reason at any point up to the research being accepted for publication simply by contacting the researcher, Bahareh Salehi.
(salehib@lsbu.ac.uk)

What will happen to me if I take part?

You will be asked to fill the questionnaire which will take about 10 minutes once the survey has started.

What are the possible disadvantages/risks of taking part? (where appropriate)

Participating in the research is not anticipated to cause you any disadvantages or discomfort. The potential physical and/or psychological harm or distress will be the same as any experienced in everyday life. If filling the questionnaire causes any distress you can suspend it.

What are the possible benefits of taking part?

Whilst there are no immediate benefits for those people participating in the project, it is hoped that this work will have a beneficial impact on the energy industry and there will be the feeling of well-being associated with being part of this. In addition, the participation can have direct input into the research which in turn can assist with future key decision making and legislation in the building energy environment.

Will the data collected in this study be kept confidential?

All information which is collected about you and other participants will be kept strictly confidential. Any information about you which is shared with others (e.g. with other members of the research team) will have your name removed so that you cannot be identified from it. You will be assigned a participant number for you to keep safe so you are unidentifiable from the data collected. This information will facilitate your data removal if at a later date you choose to withdraw from the study.

Data generated by the study must be retained in accordance with the University's Code of Practice. All data generated in the course of the research must be kept securely in paper or electronic form for a period of 10 years after the completion of a research project. Electronic data files (from which you cannot be identified) will be stored in a password secured file. Only members of the research team will have access to this file.

What will happen to the results of the research study?

Results of the research will be analysed and be used in the thesis of the PhD of the researcher which then will be submitted for publication in an academic journal or may be presented at conferences. You will not be identified in any report or publication. Your institution/company will not be identified in any report or publication unless you want your name or name of the company to be published. If you wish to be given a copy of any reports resulting from the research, please get in touch with the lead investigator, Bahareh Salehi. (salehib@lsbu.ac.uk)

Who is organizing and funding the research?

The research is supervised by Bahareh Salehi (salehib@lsbu.ac.uk), Dr Deborah Andrews (deborah.andrews@lsbu.ac.uk), Prof Issa Chaer (chaeri@lsbu.ac.uk) and Dr Aaron Gillich (gillicha@lsbu.ac.uk) all of them work in the Department of Engineering at LSBU. It has also been supervised by Dr Elizabeth Newton (liz.newton@lsbu.ac.uk) from the Department of Psychology at LSBU.

Who has reviewed the study?

This study has been reviewed and approved by the School of Engineering, Ethics Panel at London South Bank University.

Who should I contact if I have any concerns about this research?

Please contact the Chair of the University Research Ethics Committee, (ethics@lsbu.ac.uk), if you have any concerns arising from the research project.

Contact for Further Information

If you would like further information about this study, please get in touch with Bahareh Salehi.

School of Engineering, London South Bank University,103 Borough Road, London, SE1 0AA.

Email: salehib@lsbu.ac.uk

Thank you

Thank you for taking the time to read the Information Sheet and participate in this study.

Researcher: Bahareh Salehi.

Appendix F: Written Debriefing Form- BEMS Software Survey

Written Debriefing Form

Thank you for your participation. We hope you enjoyed the experience. This form provides background about our research to help you know more about why we are doing this study. Please feel free to ask any questions or to comment on any aspect of the study. You have just participated in a research study conducted by Bahareh Salehi. (salehib@lsbu.ac.uk)
The purpose of the study is to better understand the capabilities of the Building Energy Modelling Software Packages in relation to shading product modelling. The results of this questionnaire will be used to formulate the methodology of the research work and also assist in identifying the most suitable software packages to utilise. As you know, your participation in this study is voluntary. If you so wish, you may withdraw after reading this debriefing form, at which point all records of your participation will be destroyed. You will not be penalized if you withdraw.

If you have questions about the research, please e-mail Bahareh Salehi, salehib@lsbu.ac.uk. Please keep this part of the sheet for reference.

○ Please tick if you have read the above information.

Appendix G: Construction materials properties used in dynamic thermal Models

Table below presents the construction material details used in the dynamic thermal models according to each software packages' library.

Building Element	Software Package	Material (Inner to outer layer)	Thickness (mm)	Conductivity (W/m °C)	Density (kg/m^3)	U-value (W/m^2 K)	R-value (m^2.°C/W)
Internal floor/ceiling	EDSL Tas	Carpet	12.7	0.06	288.3	1.11	0.89
		Reinforced concrete	250	2.3	2300		
		Screed	50	1.15	1800		
		Ceiling air	200	0.01	0.0		
		Ceiling tile	15	0.09	250		
	EnergyPlus	Carpet	10	0.06	288	1.11	-
		Heavyweight concrete	250	1.95	2240		
		Lightweight concrete	50	0.53	1280		
		Ceiling air space	200	-	-		
		Acoustic tile	20	0.06	368		
	DesignBuilder	Carpet	12	0.06	160	1.11	0.89
		Cast concrete	250	2	2100		

		Screed	50	1	1800		
		Air layer	200	-	-		
		Ceiling tile	15	0.38	1120		
	IES VE	Carpet	10	0.06	160	1.11	0.71
		Reinforced concrete	250	2.00	1200		
		Screed	50	1.15	1800		
		Cavity air	200	-	-		
		Ceiling tiles	15	0.06	380		
External wall	EDSL Tas	Plasterboard,	20	0.07	400	0.60	1.64
		Cavity	50	0.024	1.293		
		Concrete	190	0.87	1800		
		Cavity	50	0.24	1.293		
		Concrete	190	0.87	1800		
		Lightweight concrete	30	0.1	400		
	EnergyPlus	Gypsum or plasterboard	20	0.58	800	0.63	-
		Wall air space resistance	50	-	-		
		Heavyweight concrete	190	0.38	2240		

		Wall air space	50	-	-		
		Heavyweight concrete	190	0.38	2240		
		Lightweight concrete	30	0.1	1280		
	DesignBuilder	Gypsum board	12.7	0.16	640	0.61	1.64
		Air layer	50	-	-		
		Cast concrete lightweight	200	0.38	1200		
		Air layer	50	-	-		
		Concrete cast-mediumweight dry	200	0.8	1300		
		Concrete cast-lightweight dry	30	0.22	720		
	IES VE	Plasterboard	20	0.21	700	0.61	1.48
		Cavity	50	-	-		
		Cast concrete	190	0.39	1200		
		Cavity	50	-	-		
		Cast concrete	190	0.39	1200		
		Concrete lightweight	30	2.31	1200		
Internal wall	EDSL Tas	Lightweight plaster	13	0.08	400	0.59	1.68
		Lightweight concrete	100	0.09	400		

		Lightweight plaster	13	0.08	400		
	EnergyPlus	Gypsum or plaster board	13	0.58	800	0.66	-
		Lightweight concrete	100	0.08	1280		
		Gypsum or plaster board	13	0.58	800		
	DesignBuilder	Gypsum board	13	0.16	640	0.614	1.62
		Concrete cast-very lightweight	100	0.1	470		
		Gypsum board	13	0.16	640		
	IES VE	Gypsum plasterboard	13	0.1	950	0.66	1.26
		Concrete	100	0.1	600		
		Gypsum plasterboard	13	0.1	950		
Windowpane (without blind)	EDSL Tas	Clear glass	6	1		5.81	0.17
	EnergyPlus	Clear glass	6	0.9		5.78	-
	DesignBuilder	Clear glass	6	0.9		5.77	-
	IES VE	Clear glass	6	2.7		5.70	-
Window frame	EDSL Tas	Aluminium	15	204	2700	3.84	0.26
	EnergyPlus	Aluminium Alloy	15			-	-
	DesignBuilder	Aluminium	15	160	2800	-	-

	IES VE	Aluminium	-(percentage)	-		-	-
Door	EDSL Tas	Hardwood	52	0.18	2100	1.82	0.54
	EnergyPlus	Hardwood	52	0.16	680	1.80	0.50
	DesignBuilder	Plywood	52	0.16	690	1.84	0.49
	IES VE	Plywood	52	0.14	560	1.84	0.37