Thermal Comfort and Air Quality Control in UK Student Accommodation

Understanding the interactions between heating and ventilation systems,
occupant experience, and indoor environmental conditions

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I, Anthony Marsh, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.

Abstract

The UK must radically curb greenhouse gas (GHG) emissions, whilst simultaneously adapting its infrastructure to cope with a warming climate. A vital area in which both of these issues must be addressed concurrently is in buildings. One building type that has seen rapid development in the UK is purpose built student accommodation (PBSA). However, some critical knowledge gaps exist regarding the operational performance of PBSA. Plugging these gaps will help practitioners understand how to deliver PBSA that are both lower energy in operation and more comfortable.

A case study research design was used to investigate the in-use performance of two recently built PBSA developments by monitoring indoor environmental quality, radiator use, and window opening, alongside conducting surveys and semi-structured interviews with the building's residents. The aim of the study was to investigate whether occupants could adequately control the indoor conditions, and also what effect their actions had on the internal environment and heating demand.

The results showed that the occupants were generally satisfied with the thermal conditions in the heating season. However, thermal control was typically achieved by opening windows regularly, often for long periods, and frequently whilst the heating was on. Five behavioural causes of consistent winter window opening were identified. These were to prevent overheating, inadequate ventilation, poor understanding of the controls, lack of responsiveness of the heating system, and lack of financial implications. Heat losses via window opening were modelled and estimated to be as high as 44%

of the total heat losses in certain rooms.

In contrast, during summer, the majority of occupants could not control the thermal environment in their rooms. Overheating was widespread, severe and often prolonged. The surveys and interviews revealed that the vast majority of occupants were too hot. For many participants this was a major issue affecting their comfort, well-being and even academic performance.

The study showed that design shortcomings, rather than occupant behaviour were primarily responsible for the conditions. Important lessons for the future design of PBSA are identified.

Impact Statement

Hundreds of thousands of students live in purpose built student accommodation (PBSA) in the UK, and new PBSA developments continue to be built regularly. However, critical knowledge gaps exist regarding the environmental and energy performance of PBSA in practice. Plugging these knowledge gaps, and feeding it back to the appropriate stakeholders, should help to deliver future PBSA that are both lower energy in operation and more comfortable. Thus simultaneously reducing the environmental impact of PBSA, whilst improving the indoor conditions for the inhabitants who live, study and socialise in them.

Through monitoring indoor environmental conditions and occupant practices in PBSA, in conjunction with interviews and surveys with occupants, this research has produced several new insights on important PBSA performance issues. These issues include those related to occupant well-being and comfort (e.g. stuffy indoor conditions, or the inability of occupants to remove unwanted heat), alongside those related to operational energy usage (e.g. the frequent opening of windows during cold weather conditions).

The key findings have been fed back (through presentations and the production of a design guide) to the industrial sponsor of the PhD research; a large multi-national construction company that is a repeat developer of PBSA in the UK. The presentation of the results were focused on areas that were likely to resonate with practitioners, and offered practical solutions to the issues raised. Therefore one of the key impacts from this research is that the construction company have recently completed a PBSA building incorporating a number of the design recommendations made in this thesis.

The research findings also highlighted areas in which other key stakeholders in PBSA, such as universities and facilities management, could help deliver performance improvements. This included addressing social aspects of PBSA performance, like ensuring appropriate information, guidance and support is provided to PBSA occupants.

One of the methods through which the findings achieved impact with practitioners was by showing complex building performance processes on one chart. The combining of multiple parameters in one graphic was used to show interrelated relationships between several variables; outlining what occurred, why it occurred, the impact this had on internal conditions, and the affect on heating energy consumption. It could then be reasoned pictorially how addressing one building performance issue (e.g. stuffy bedroom conditions) could have secondary benefits in other areas too (e.g. reduced winter window opening and heating energy consumption).

It is planned that these multi-parameter investigation techniques will be disseminated to the academic community through two publications in built environment journals. These will cover PBSA occupant behaviour during the heating season, and during warm weather conditions respectively.

Finally, the PhD process has also provided the researcher with a wide variety of knowledge and skills that they did not possess previously. These are now being used in a professional engineering consultancy. Thus the knowledge and skills acquired during the PhD are continuing to have impact on a range of building performance problems.

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List of Acronyms

ACH Air Changes per Hour. 78, 118, 171, 172, 217, 283, 287, 308

ADF Approved Document F. 78

ADL Approved Document L. 93

AEC Architectural, Engineering and Construction. 39, 290

ASHRAE American Society of Heating, Refrigerating and Air-Conditioning Engineers. 183

BMS Building Management System. 114, 138, 151, 158

BPE Building Performance Evaluation. 106, 110

BRE Building Research Establishment. 133

BREEAM Building Research Establishment Environmental Assessment Method. 133, 136

BS British Standard. 162

BSJ British Services Journal. 109

BUS Building Use Studies. 116, 155

CARBHES Carbon Reduction in Buildings Home Energy Survey. 14, 96–98, 280

CCC Committee on Climate Change. 37

CFD Computational Fluid Dynamics. 75

CHP Combined Heat and Power. 93, 134, 137

CIBSE Chartered Institute of Building Services Engineers. 71, 87, 112, 119, 162, 164, 231, 267

CSA Case Study A. 132, 135, 139, 141–143, 148–151, 153, 155, 158, 168, 169, 175, 181, 182, 186, 189–192, 195, 198–200, 202, 203, 205–209, 213, 214, 217–219, 225–227, 231, 233, 234, 236–242, 244–246, 248, 249, 251, 256, 259, 261–263, 265, 267, 268, 272, 274, 275, 279, 280, 282–284, 288, 292, 294, 296, 298, 300, 309, 313, 314

CSB Case Study B. 135, 139, 141–143, 149–151, 153, 158, 159, 167, 169, 175, 181–185, 189–191, 193–198, 202, 203, 205–207, 210, 213, 218, 222, 226, 227, 229, 233, 234, 236–238, 240–242, 244, 248–250, 256, 259, 262, 265, 279–287, 292–294, 297, 300, 307, 309, 314

DEC Display Energy Certificate. 304

DHW Domestic Hot Water. 137, 244, 306

DSM Dynamic Simulation Model. 75, 303, 304, 315

EFUS Energy Follow up Survey. 96, 97

EHS English Housing Survey. 96

EN European Standard. 162

EUI Energy Use Intensity. 112

FM Facilities Management. 39, 76, 95, 142, 155, 158, 197, 202, 205, 244, 246, 261, 287, 305, 310, 313, 314

GHG Greenhouse Gases. 36, 37

HE Higher Education. 48

HEI Higher Education Institutes. 48–51

HMO Houses of Multiple Occupancy. 47, 53

HSE Health and Safety Executive. 80, 87, 185, 287

HVAC Heating, Ventilation and Air Conditioning. 86, 130

IAQ Indoor Air Quality. 40, 41, 43, 46, 53, 57–59, 76, 77, 79, 80, 87–90, 116, 122, 123, 128, 130, 144, 147, 155, 167, 179, 183, 212, 218, 220, 222, 229, 248, 272, 281, 282, 286, 289, 293, 310, 314

IEA International Energy Agency. 102

IEQ Indoor Environmental Quality. 36, 39–41, 43, 44, 46, 58, 99, 102, 103, 105, 111, 115, 116, 129, 130, 139, 143, 198, 282, 294, 304, 312, 315

LPA Local Planning Authority. 53, 54

LTHW Low Temperature Hot Water. 134, 137

MET Metabolic Equivalent Task. 85, 173

MEV Mechanical Extract Ventilation. 78, 138

MPS Multi Point Sampling. 83

MRA Multi Residential Accommodation. 47

MRT Mean Radiant Temperature. 145

MVHR Mechanical Ventilation Heat Recovery. 78, 116, 135, 174, 175, 219–222, 283

NCM National Calculation Methodology. 55

NDA Non-Disclosure Agreement. 290

NUS National Union of Students. 52

ONS Office for National Statistics. 65

PBSA Purpose Built Student Accommodation. 42–44, 46, 47, 49–59, 63, 64, 69, 76–78, 84, 88–96, 98–103, 105–107, 111–113, 115–119, 121–133, 139, 142–146, 155, 159, 160, 163, 167, 174, 177, 189, 202, 213, 215, 217, 228, 229, 231, 246, 251, 253, 254, 261, 270–276, 278–281, 283–285, 287–289, 293, 295–297, 299–301, 303–311, 313–315

PFT Perfluorocarbon tracers. 82

PMV Predicted Mean Vote. 60–63

POE Post-Occupancy Evaluation. 41–44, 46, 58, 59, 63, 64, 68, 75, 76, 106–109, 111–113, 115–117, 121, 123, 124, 127, 130, 132, 141, 272, 286, 290, 301–305, 312

PPM Parts Per Million. 79, 80, 88, 167, 183, 185, 210, 230, 285–287, 299

PROBE Post Occupancy Review of Building Engineering. 41, 109

RH Relative Humidity. 87–89, 146, 147, 159, 161, 183, 186, 229–231, 237–239, 243, 249, 297

RIBA Royal Institute of British Architects. 108

SAP Standard Assessment Procedure. 55, 93

SBS Sick Building Syndrome. 77, 79, 80, 286

SPT Social Practice Theory. 91, 92

STS Socio-technical System. 90

TM Technical Memorandum. 71, 75, 164, 165, 235–237, 276, 303, 307

TRV Thermostatic Radiator Valve. 94, 95, 114, 115, 117, 135, 138, 167, 197, 198, 210, 213, 261, 279, 284, 293, 310, 313, 314

UCL University College London. 141, 151, 152, 171

UFA Usable Floor Area. 220

UHI Urban Heat Island. 65

VOC Volatile Organic Compounds. 77

List of Symbols

$\boldsymbol{A}$ area of surface (m^2). 174

$\boldsymbol{C_R}$ CO_2 concentration in the outdoor air $(mg \cdot m^{-3})$. 170, 171

$\boldsymbol{C_p}$ Specific heat capacity of air (kJ/kgK). 174

$\boldsymbol{C}$ concentration of the tracer gas in the zone being measured (kg/m^3). 82, 170

$\boldsymbol{G}$ CO_2 emission rate of indoor sources $(mg \cdot h^{-1}$. 170, 172, 173

$\boldsymbol{HUM}$ HUMIDEX Number. 165

$\boldsymbol{H_k}$ rate of conductive heat loss $(Js^{-}1)$. 174

$\boldsymbol{H_v}$ rate of ventilation heat loss $(Js^{-}1)$. 174

$\boldsymbol{MVHR_{eff}}$ Efficiency of MVHR system (%). 175

$\boldsymbol{Q_t}$ volumetric rate of injection of the tracer gas (m^3/s). 82

$\boldsymbol{Q_v}$ volumetric flow rate of air out of space $(m^3 s^{-1})$. 174

$\boldsymbol{Q}$ volumetric flow rate (m^3/s). 82, 170–172

$\boldsymbol{\rho}$ Density of air (kg/m^3) - assumed to be 1.2 at 20°C. 174

$\boldsymbol{T_a}$ Air temperature $(°C)$. 145, 146, 159–161, 165–167

$\boldsymbol{T_{comf}}$ Comfort temperature (°C). 21, 164, 233, 237, 276, 277

$\boldsymbol{T_{dp}}$ Dewpoint temperature (°C). 161, 162, 165

T_{ed} Mean daily external temperature (°C). 158

T_i internal temperature (°C). 174

T_{op} Indoor operative temperature ($^{\circ}C$). 146, 160

T_o outdoor temperature (°C). 174

T_r Radiator surface temperature (°C). 166, 167

T_{rm} Exponentially weighted mean of the daily mean external temperature (°C). 158, 164, 237

T_r Radiant temperature ($^{\circ}C$). 145, 146, 160

T_s Surface temperature ($^{\circ}C$). 146

U thermal transmittance of surface (W/m^2K). 174

V_a indoor air velocity m/s. 160

V Effective volume being measured (m^3). 82, 170–172

α Constant between 0 and 1 which governs how the running mean temperature responds to the daily mean external temperature. 158

clo Unit of clothing insulation. 18, 22, 60, 208, 209, 238, 239

e Vapour pressure (Pa). 162

p Surface pressure (Pa). 162

q Specific humidity (g/kg). 161, 162

Chapter 1

Introduction

This chapter outlines the context for the research and the principal motivations for this thesis. After which the research aims, and questions are defined. It concludes by outlining the main structure of the thesis.

1.1 Research Context

1.1.1 Climate Change Mitigation and Adaptation

The release of Greenhouse Gases (GHG) from human activity is increasing global average surface air temperatures, disrupting weather patterns, and causing ocean acidification (IPCC, 2014). The UK faces increased risks from a warming climate that are widely considered to be significant (CCC, 2017). As such, the UK must radically curb GHG emissions, whilst simultaneously adapting its infrastructure to cope with a warming climate.

One area in which both of these issues must be addressed concurrently is in buildings. Buildings must be adapted to reduce GHG emissions, and to ensure adequate Indoor Environmental Quality (IEQ) as UK summertime mean temperatures rise (Holmes et al., 2019; Jones et al., 2008). Indeed, these two aims are intrinsically linked. It is therefore vital that measures taken to address one do not unintentionally exacerbate the other. This introduction will first cover the topic of emissions in the built environment, before returning to IEQ and how the two issues interact.

1.1.2 Decarbonisation in the UK

As part of the global effort to decrease GHGs the UK Government is statutorily committed to delivering net zero GHG emissions by 2050 (HMGovernment, 2008). The UK has made notable progress towards this goal. For instance, in 2017 CO_2 emissions were estimated to be 38% lower than in 1990 (BEIS, 2017). This equates to an average reduction of $12MtCO_2e$ a year.

Thus far the decrease in emissions can be primarily attributed to the combined effects of the transition towards lower carbon sources of electricity generation, cleaner industrial processes (due to energy efficiency, emission controls and a structural shift away from carbon intensive manufacturing), alongside a smaller, cleaner fossil fuel supply industry (CCC, 2018). However, the scope for further reductions from the power sector is diminishing. For example, coal supplied just 7% of the UK's electricity in 2017 (EIA, 2018), and is due to be phased out entirely by 2025 for plants without carbon capture and storage (BEIS, 2018a).

The UK has legally binding interim carbon budgets, such as a reduction in emissions of 57% by 2032 (HMGovernment, 2016). It has been estimated by the Committee on Climate Change (CCC) that meeting the 2032 target will require emissions to fall at broadly the same rate as between 1990 to 2017 i.e. $12MtCO_2e$ a year (CCC, 2015). Declining emissions from the power sector will continue to play a "a vital role in meeting carbon budgets" (CCC, 2015), but they will not be enough alone. The UK will need supplement these reductions with "more challenging measures, including switching to low-carbon energy sources in sectors beyond electricity generation" (CCC, 2015). One of the particularly challenging, yet crucial sectors to decarbonise will be the emissions arising from energy use in buildings.

1.1.3 Operational Building Emissions

In the UK buildings have been estimated to account for 34% of total GHG emissions (BEIS, 2017). This figure includes both indirect emissions (i.e. those arising from the power sector due to electricity use in buildings), as well as direct emissions (e.g. the combustion of natural gas in a boiler to provide space heating). The sector's overall share of emissions means that the decarbonisation of the built environment has been described as a "strategic environmental and infrastructure goal to which there is no obvious alternative" (Oreszczyn and Lowe, 2010).

However, as shown in Figure 1.1, limited progress has been made to date on reducing direct emissions from buildings. Indeed, direct emissions arising from the domestic building stock have not declined at all since 2014 (although the stock itself has expanded over this time) (Holmes et al., 2019).

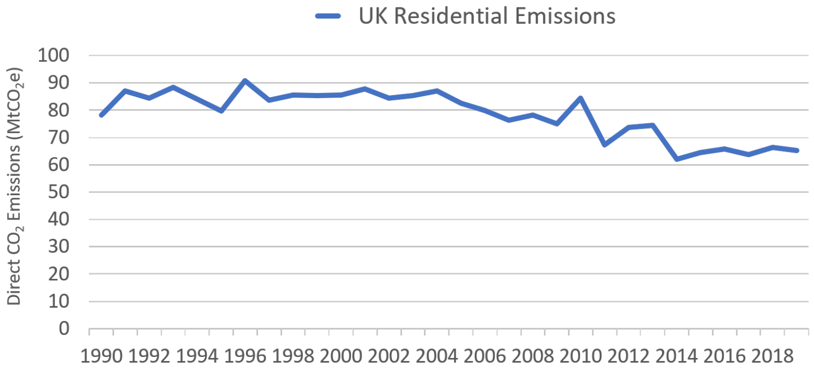

Figure 1.1: Direct CO_2 Emissions from Buildings 1990 - 2019 (BEIS, 2020a)

In the domestic sector space and water heating account for approximately 80% of final energy use (BEIS, 2018b). Thus reducing the demand for heat in buildings is one of the key areas identified for helping the UK achieve its carbon reduction targets (CCC, 2017). While there is still debate surrounding the exact mix of technologies that will be utilised to decarbonise space heating (e.g. electrification and heat-pumps, hydrogen, or biomethane, (BEIS, 2018b)) it is widely agreed that it will be necessary to make both new and existing buildings more thermally efficient (CCC, 2015). That is buildings will be required to deliver the same services (e.g. maintaining a certain indoor temperature), whilst using less energy. Such improvements arguably represent the "no-lose" option; they help to reduce total demand for heating (and can also be beneficial in smoothing out peak heating loads), regardless of the heating type eventually adopted.

In order to improve the thermal efficiency of new buildings the UK has put in place building regulations that requires all new domestic (Government, 2012) and non-domestic (HM Government, 2012) buildings to meet certain emissions targets at the design stage. However, once built, the operational performance of buildings in terms of energy usage, and therefore carbon emissions, often fails to meet design intentions (ZCH, 2013)

1.1.4 The Performance Gap

The difference between anticipated and actual performance has become known as the “performance gap”. It is the scale of this gap that is particularly concerning, for instance one large study showed that as-built energy usage in new build homes is on-average 2.5 times that predicted at the design stage (Innovate UK, 2016b). Yet, despite first being highlighted decades ago (Cohen et al., 2001), the performance gap remains a persistent problem, affecting new build domestic (Innovate UK, 2016b), non-domestic (Innovate UK, 2016b) and retrofit projects (TSB, 2013).

It is important for a combination of reputational, environmental and financial reasons that the gap is reduced. This issue affects not just the Architectural, Engineering and Construction (AEC) industries, but also clients, occupants and Facilities Management (FM) companies. Indeed, if the gap is not reduced, then it is doubtful whether the sector will be able to deliver the required emission reductions as part of the UK’s overall emission reduction strategy.

1.1.5 Indoor Environmental Quality

As mentioned at the outset of this chapter, it is important that in the drive to decarbonize the building stock sufficient attention is paid to the risks of such measures causing unintended IEQ consequences. An energy efficient building is not necessarily one that is also good for it users. There is evidence to suggest that envelope efficiency improvements, when combined with other developments in the property sector, such as an increase in the number of smaller, single-aspect properties, constructed from lightweight materials, can cause serious IEQ issues (Davies and Oreszczyn, 2012). This thesis will focus on two previously identified issues.

The first is the increased risk from overheating in UK dwellings (Wright et al., 2005; J et al., 2007; Beizaee et al., 2013; McGill et al., 2017). This can affect the health and well-being of occupants, particularly if sleep is degraded (Lomas et al., 2018a). As the UK climate continues to warm such incidences are likely to become more frequent. It is important that the prevalence, severity, and causes of overheating within different parts of the UK's building stock are investigated. Furthermore, it is equally important that the impact of overheating on occupants, and how they adapt to elevated temperatures is better understood.

Such evidence is crucial to ensure that new buildings are designed to cope with a warming climate. Indeed if buildings cannot be kept comfortably cool by passive measures alone, it is likely that occupants will resort to purchasing mechanical cooling units. Above a certain uptake level this is likely to cause a considerable increase in UK summer time energy demand (Peacock et al., 2010).

The second issue is the risk of Indoor Air Quality (IAQ) problems associated with reduced ventilation rates. Since the 1990's one of the key elements of improving the thermal efficiency of new buildings has been to make them more airtight (Sharpe et al., 2015). However, if buildings are made more airtight, without also ensuring adequate ventilation, this can lead to a variety of IAQ issues.

IAQ issues can include a "rise in relative humidity leading to increased house dust mites, mould, severity of asthma and allergies" (Shrubsole et al., 2014). It can also lead to increased window opening (with potential thermal performance implications), and increased indoor pollutant concentrations. Indeed, a report by the The Royal College of Physicians specifically highlighted the importance of improving our understanding of how increasing airtightness in buildings may be resulting in IAQ issues, and the corresponding effects on occupant health (Royal College of Physicians, 2016).

1.1.6 Post-Occupancy Evaluation

The introduction thus far has highlighted how new buildings in the UK must be both low-energy in practice (in order to meet the UK's legally binding climate change commitments), whilst delivering satisfactory IEQ (in order to protect the health and well-being of occupants). It has argued that one without the other is not sufficient, and that the two are inextricably linked. For instance, if the internal conditions within a building are deemed unacceptable by an occupant they are likely to undertake adaptive behaviour to restore comfort. This in turn may affect energy usage (e.g. the purchasing of an air conditioning unit to relieve overheating, or the over ventilating of a room with cold air during winter months to alleviate IAQ issues).

One method for examining the inter-connected issues of energy usage and IEQ is to conduct post-occupancy studies of building performance i.e. to investigate how real buildings are performing in practice. Using Post-Occupancy Evaluation (POE) has consistently proven to be an essential resource for highlighting important, and often unexpected findings in respect to the performance of buildings and their services. For example, the performance gap was first highlighted in a series of POE's undertaken as part of the Post Occupancy Review of Building Engineering (PROBE) project that began in 1995 and ended in early 2000s (Cohen et al., 2001).

Indeed, an insufficient quantity of real-world performance data is frequently mentioned as an important factor in the difference between the anticipated and actual performance of buildings (ZCH, 2013; BRE, 2013a). Moreover as the rate of innovation in buildings continues to increase (Göçer et al., 2015), these new materials, products, architectural styles, control systems and building services all need assessment. It is vital that objective evidence is compiled regarding the deployment of building innovations and their real-world performance, so as “successes can be built upon, and repeat mistakes avoided” (Leaman et al., 2010).

1.1.7 Student Accommodation

Building types that would be particularly suited to benefit from feedback through POE would be those with relatively homogeneous designs (therefore issues affecting one building are likely to be present in the wider stock), and rapid development rates (meaning that well-targeted feedback could impact upon a significant number of planned buildings). One such building type is Purpose Built Student Accommodation (PBSA).

The PBSA sector has received significant investment since the mid-1990s (KnightFrank, 2016; Savills, 2015), and according to industry forecasts this trend is expected to continue[1] (GVA, 2016). Indeed, in 2017 alone a record 30,000 new units were added (Cushman&Wakefield, 2018), and upwards of 600,000 students are now estimated to live in PBSA across the UK (HESA, 2018). The rapid development and commercialization of the PBSA sector has also encouraged a trend towards a standardised “product” (NUS, 2016) i.e. the design of new PBSA developments have become more uniform over time.

There is also some evidence suggesting that the design of new PBSA may render them particularly susceptible to overheating (Altan, 2010; RTA, 1995). While others have suggested that the all-inclusive utility fees, which are common in PBSA, may lead to wasteful energy practices (Quigley, 2016). Moreover, it has also been suggested that these practices may differ significantly from behavioural assumptions or predictions made at the design stage (Hernandez et al., 2014). However, the published information on the environmental and energy performance of this rapidly growing building type is still considered to be relatively limited (Vadodaria, 2012; Amber and Aslam, 2016). For instance, no studies of post-occupancy ventilation

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[1] Since this research was conducted and the thesis largely written the COVID-19 pandemic has occurred. At this stage the impact on the UK student accommodation market is uncertain. Therefore this thesis does not address this issue further other than to acknowledge that it is likely to have an affect on the demand for PBSA.

assessments were found for these building types in the UK.

It therefore seems both important and timely to investigate further energy usage and environmental performance in newly built PBSA developments. Crucially, it should also examine how energy usage and environmental performance both affect user behaviour, and are affected by user behaviour in PBSA. This evidence will help to improve the understanding of how to build comfortable, low-energy student accommodation in the future.

1.1.8 Summary

The introduction has highlighted how the UK is legally required to reduce carbon emissions, and that a fundamental component of any realistic scenario to achieve these reductions is to reduce operational energy usage in buildings. Yet there is a often a gap between anticipated energy usage in new buildings, and the as-built reality. Meanwhile there is also growing evidence that some of the design strategies that have been encouraged to minimise thermal losses in buildings may be causing unwanted IEQ issues. Two particular issues have been highlighted; overheating, and IAQ problems associated with restricted ventilation.

The introduction then concluded by suggesting how POE could be a suitable method to examine the interconnected issues of IEQ, and energy usage. It has proposed that conducting POE on PBSA buildings may be of particular value due to three important characteristics of the stock; high development rates, relatively homogeneous designs, and the postulation that the current designs of PBSA may be leading to overheating issues, and wasteful energy practices.

1.2 Research Aims & Questions

There are two primary aims for this research. The first aim is to investigate the interactions between occupants, the indoor environment, and control of the heating and ventilation systems throughout the heating season. The purpose being to understand the adequacy of both the conditions and the controls.

The second aim is to understand the various practices that occupants adopt to alleviate discomfort during warm weather periods. It will explore both the actions taken by occupants, and whether these delivered the desired effect i.e. to restore comfort. To achieve these aims the following research questions will be answered.

1. Can occupants control indoor environmental conditions in the heating season, what are the influencing factors, and how does their behaviour affect energy demand?

2. To what extent do occupants make use of the available adaptive opportunities to meet their thermal requirements during warm weather conditions, and what affect do these actions have on the building's internal environment?

1.3 Thesis Structure

The thesis is composed of nine chapters, followed by the Appendices and a Bibliography. The thesis chapters are described below:

- Chapter 1 has provided the context for the research, alongside outlining the aims of the study and the research questions.

- Chapter 2 presents a review of the literature; focusing on PBSA, IEQ, occupant control of IEQ, and POE.

- Chapter 3 restates the research's aims, and develops the research design and methodological approach for answering the research questions. It describes the case studies monitored in this thesis, followed by a section outlining the data collection and analysis methods.

- Chapter 4 is the first results chapter, and explores the conditions throughout the heating season.

- Chapter 5 is the second results chapter, and covers the conditions inside the buildings over the early spring to late summer period.
- Chapter 6 is the discussion, whereby the findings are contextualised and related back to the literature review.
- Chapter 7 summarises the key findings, implications and recommendations from the study, alongside providing a critical reflection on the study itself.

Chapter 2

Literature Review

The introduction has outlined the research questions to be addressed in this thesis. The central component of this research is whether occupants in new Purpose Built Student Accommodation (PBSA) buildings are being provided with effective control over the indoor conditions. Therefore the literature review will cover indoor conditions in domestic buildings, occupant control of indoor conditions, and, more specifically, PBSA buildings and their performance. These broad areas are divided into five sections.

The first section will provide an overview of the PBSA building type. The second, third, and fourth sections are primarily theory based. The second and third sections review the concepts of thermal comfort and indoor air quality IAQ respectively (including how to monitor and measure these parameters in occupied buildings), while the fourth section reviews occupant behaviour. This section focuses on the two primary methods that PBSA occupants have of controlling the IEQ conditions in their rooms; operating the heating system, and opening the window.

The fifth and final section focuses on POE; the methodological approach for answering the research questions. It begins by outlining the concepts and rationale for POE, but foremost it summarises the previous POE work conducted in PBSA buildings. This section establishes the gaps in our current understanding of PBSA performance that have been used to formulate the research questions.

2.1 Student Accommodation

This thesis is focused on buildings that have been built for the explicit purpose of housing significant numbers of students. It is not concerned with other types of student accommodation common in the UK, such as Houses of Multiple Occupancy (HMO)s. Student accommodation buildings are commonly referred to as "halls", "dorms", "digs", or more recently in developer terminology as Purpose Built Student Accommodation (PBSA). The term PBSA will be used throughout this thesis.

PBSA have similarities with other (Multi Residential Accommodation (MRA)) developments, such as care homes and school boarding houses in that they are buildings "containing separate residential units that share some centralized facilities" (CIBSE, 2003). However, there are certain characteristics that distinguish PBSA from other MRA developments that affect both their design, and how they are operated. These may include:

- Annual (or shorter) tenancies.
- High likelihood of intermittent or irregular occupancy patterns.
- Young average age of occupants (for many residents this may be their first time living away from home).
- High levels of "wear and tear".
- Lower staffing levels (particularly compared with care homes).
- Multipurpose uses (the vast majority of student residences are let outside of term time e.g. for summer conferences (NUS, 2016)).

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2.1.1 Student Accommodation in the UK

There is a large variety of different student residences in the UK. These range from 16th century residential colleges built at Britain's earliest universities, to modern high-rise city centre private developments. In order to help better understand the composition and characteristics of today's PBSA stock, it is useful to briefly review the history of student accommodation in the UK.

Before the 1960's the proportion of the UK's population attending Higher Education (HE) was estimated to be under 5% (Crawford et al., 2010). Furthermore, many of those attending were recruited locally, and so often lived at home (Tight, 2009). However, since the 1960's onwards there has been an almost continually rising HE participation rate in the UK (see Figure 2.1).

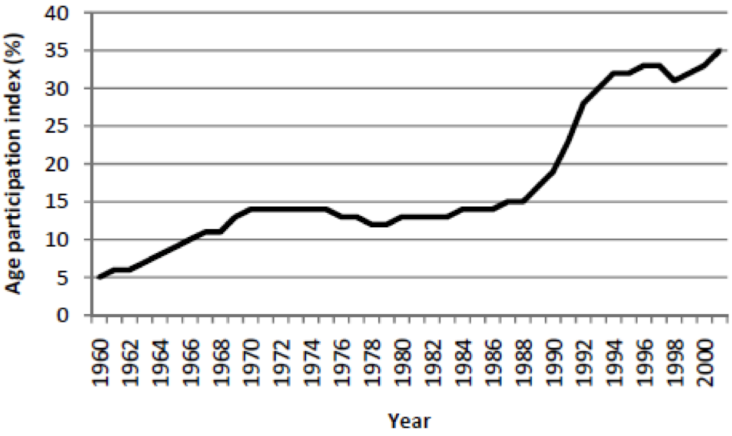

Figure 2.1: Long term trend in HE participation in the UK (1960 - 2000) (Crawford et al., 2010). The age participation index refers to the number of 17-30 year olds who attend university.

In 1963 the Robbins Committee on Higher Education first examined the issue of student accommodation (Robbins, 1963). It recommended that Higher Education Institutes (HEI) "should provide accommodation for a number equivalent to two thirds of the additional students in each year from 1962/3 to 1980/1". Thus began the first major development period for purpose built student residences.

The initial residences were built in the 1960's and 70's, and coincided with universities expanding their campuses. These buildings tended to be low-rise developments, located primarily on university campuses. They were managed by the university, normally contained shared bathrooms (and sometimes shared bedrooms), and were frequently catered (Tight, 2011). Residences from this period are often referred to as "digs". In line with construction practices at the time they are likely to have relatively inefficient building envelopes i.e.

low levels of insulation, low air-tightness and single-glazed windows (Davies, 2013). Over time, what remains of this stock will need to be either replaced or refurbished.

By the early 1980's severe funding constraints had curtailed the ability of HEIs to build new residences, even as total student numbers continued to rise (Tight, 2011; Bolton, 2012). In the mid 1990's investment began to increase again, but this time it was being driven largely by the private sector (Alamel, 2015). Private companies, either independently, or in partnership with HEIs, began to build and refurbish student residences across the UK.

In the early 2000's investment rose further still (GVA, 2016). Indeed PBSA was one of the few construction areas to remain relatively unaffected by the 2008 recession (KnightFrank, 2016), as covered in Section 2.1.2. These privately funded halls became known in the industry as PBSA. They are typically self-catered, and contain single rooms with en-suite facilities (NUS, 2016). The characteristics of the PBSA stock are outlined in more detail below.

2.1.2 PBSA Stock Characteristics & Trends

This section will outline some of the key characteristics and trends of the PBSA stock. The purpose of this section is to provide background information on PBSA, and also to make the case as to why they are an important building type to investigate.

2.1.2.1 Size

In the 2015/16 academic year there were 2.28 million full-time students studying in the UK (HESA, 2018). It is estimated that 28% of these (approximately 600,000 students) are currently accommodated in PBSA (NUS, 2016). Thus the total amount of students living in PBSA is roughly the equivalent to the population of a medium sized UK city.

Furthermore, total student numbers have roughly doubled since the 1990's (HESA, 2018). Proportionally, this expansion has been greatest amongst international students and postgraduates, whose numbers have risen roughly ten-fold in the last 15 years (HESA, 2018). Such students are particularly likely to desire “plug and play” accommodation as “they don’t want hassle, like sorting out their own council tax, and nor do their parents, who are often paying” (Bennet, 2015). Thus demand for PBSA has increased significantly over the last couple of decades, bringing about substantial new investment in the sector.

2.1.2.2 **Investment**

PBSA investment has grown steadily since the mid 1990s; rising to a peak of over £5.1 billion in 2015 (Taylor et al., 2016). The combined sector is estimated to be worth £46bn, and according to various real estate publications, UK PBSA is now recognised as a “mature and globally traded asset class” (Savills, 2015). Construction rates continue to remain high, for instance in 2018 over 30,000 new bed spaces were delivered; taking the total number of units to 630,000 (Cushman&Wakefield, 2018).

Despite some uncertainty regarding future UK student numbers (which has no doubt increased due to the COVID-19 outbreak), several property development consultancies were predicting at the beginning of 2020 that investment will remain high due to a “structural under-supply of PBSA in the UK market” (Knight-Frank, 2020). Therefore property developers appear to remain bullish on UK PBSA due to the “stable income stream on offer, with strong year-on-year rental growth prospects” (Knight-Frank, 2020). Indeed, as of December 2019 there were estimated to be “114,000 PBSA beds in the development pipeline” (Cushman&Wakefield, 2019).

2.1.2.3 **Ownership**

The principal ownership of student accommodation has undergone a radical transformation over the past decade. In 2006 HEIs operated 82% of all residences, but by 2015/16 this had shrunk to 49% (GVA, 2016). This trend has been driven by HEIs becoming increasingly unable to accommodate rising demand, whilst also seeking to reduce financial exposure to accommodation risks. At the same time attractive stable returns have been on offer for developers of PBSA (Tight, 2011). Due to these reasons it seems likely that the role of the private sector in student accommodation will continue to increase.

2.1.2.4 **Layout**

The principal type of student accommodation now available (both institutionally and privately) is self-catered accommodation in cluster flats with en-suite bathrooms (NUS, 2016). This involves groups of students arranged in clusters around a shared kitchen and living area. A typical example is shown in Figure 2.2.

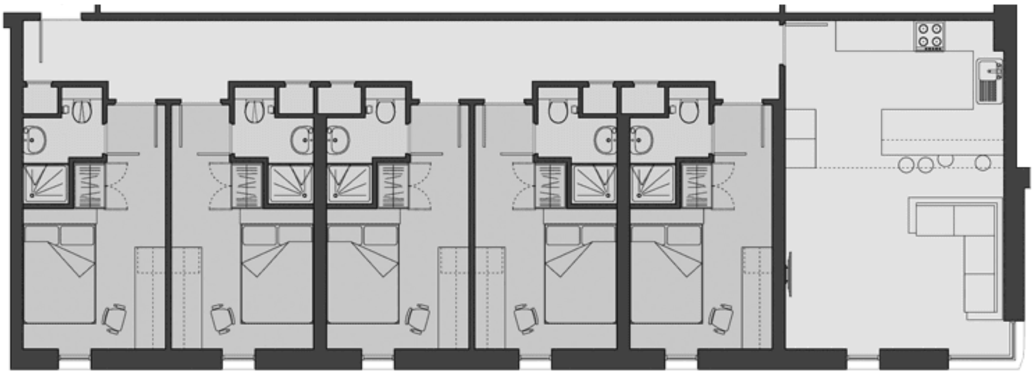

Figure 2.2: Typical six person PBSA flat layout.

An alternative design that is typically more common in low-rise semi-urban settings are townhouses (or mansionettes). In these buildings the communal front door is on the ground floor along with the kitchen and shared living spaces, while the bedrooms are located on the upper floors.

There are also other important trends in PBSA design. The total number of self-contained studios on offer has increased 184% in just 5 years; rising from 3% of total bed spaces in 2011 to over 9% in 2016 (NUS, 2016). At the same time the number of non-en-suites beds has declined rapidly, as HEIs and private providers have replaced accommodation built in the 1960s and 70s (Tight, 2011). Similarly, catered accommodation has been in steady decline; today it constitutes less than 8% of total provision, compared to 24% in 1994

(NUS, 2016). The majority of catered accommodation is now located at just a handful of universities that still operate traditional collegiate style systems (e.g. Oxford, Cambridge and Durham).

The other major defining characteristic of PBSA is the study bedroom (see Figure 2.3). This is required to be a multi-functional space; facilitating sleeping, studying, relaxing, socializing and eating, all within a relatively confined area. For instance, a typical en-suite study bedroom is estimated to be around 12-13m^2 (NUS, 2016). In addition, PBSA may offer a wide variety of different on-site facilities, such as laundries, gyms, cafes, shops, common rooms and communal work-spaces.

Figure 2.3: Typical ensuite studybedroom layout

2.1.2.5 Cost & Affordability

According to an National Union of Students (NUS) survey on accommodation costs, in 2018-19 the average weekly rent in PBSA was £147 (NUS, 2016). This is estimated to have risen by over 80% since 2006-7. The same trend is observed for both institutional and private accommodation, as shown in Figure 2.4.

Indeed, one in six of the country's most prestigious institutions now charge students more than the minimum maintenance loan for their cheapest accommodation option (Gray, 2018). While 20 out of the 24 Russell Group universities that offer accommodation to undergraduates leave students on the lowest maintenance loans with less than £1,000 to live on over the entire academic year (i.e. once housing costs have been deducted) (Gray, 2018).

Figure 2.4: Weekly average PBSA rental costs (1994 - 2018) (Goodman, 2018).

This is the equivalent of around £25 a week. As students are paying high rental costs to stay in PBSA it seems reasonable that they should provide acceptable internal environments i.e. comfortable temperatures, and adequate IAQ.

2.1.2.6 PBSA Planning Regulations

In England & Wales sections 55 and 333 of the Town and Country Planning Act 1990 defines which classes certain building types should fall within (HMGovernment, 1990). It therefore determines how different building types should be dealt with by the Local Planning Authority (LPA). However, PBSA developments do not fit neatly within these classes, and so it is classified as "Sui Generis" (i.e. outside any use class). Therefore specific planning policies are required by individual LPAs for PBSA, for example to impose certain standards, such as on studybedroom unit size.

LPAs differ in their planning approaches to PBSA. Most commonly, PBSA are treated as residential institutions (C2); the same category as care homes and school boarding houses. Yet some planners argue that as the majority of PBSAs are now cluster blocks (see Section 2.1.2.4) they more closely resemble individual HMOs (C4), but stacked one above another. Importantly, in terms of planning regulations, they are rarely classed as dwelling houses (C3). Although the rapid increase in the number of self-contained studios is further complicating the classing system, as some argue these should indeed be classed as C3 (Evans, 2016).

One of the key implications in terms of the financial viability of developments is that C2 developments are often exempt from affordable housing contributions, and in some cases, they are also not liable for community infrastructure levy's (South Northamptonshire Council, 2020). Additionally, LPAs may have rigid planning policies setting out appropriate locations for housing developments (C3), whereas C2 schemes may not necessarily be bound by these same planning policy constraints. Thus certain sites, such as city centres, may be available for PBSA development but not market housing.

In addition, LPAs will set certain requirements, for instance on space standards, daylighting and acoustics, that may only apply for dwellings (C3), but not for residential institutions (C2). Indeed, in certain PBSA developments it has been suggested that planners may be more malleable regarding factors such as daylighting and size restrictions due to the fact the "pattern of use is less sensitive to daylight than residential usage, as the length of tenure is temporary" [1] (Gray, 2018).

2.1.2.7 PBSA Building Regulations

Similarly to planning, PBSA do not fit neatly within UK building regulations, which specify "minimum standards for design, construction and alterations to virtually every building" (Government, 2012). These divide buildings into two broad categories; domestic and non-domestic. Somewhat counter-intuitively, PBSA are classified as "buildings other than dwellings" and as such fall into the non-domestic category.

The most important implications of this categorisation for this research is that PBSA fall under approved document Part L2A (rather than Part L1A) of the building regulations concerned with the conservation of fuel and power.

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[1] This statement was found in a report commissioned by architects in order to justify why the potential affect a new building may have on a nearby PBSA was acceptable; something to which Brent Council officers ultimately agreed.

The key difference being that PBSA are not required to achieve compliance via the Standard Assessment Procedure (SAP), but instead by following the National Calculation Methodology (NCM).

2.1.2.8 New Housing Model

This review has found evidence of similar buildings, with identical layouts, but branded as "co-living" schemes now being built and marketed purely to young professionals (Roue, 2017; Economist, 2017; Brignal, 2016). Indeed, some are promoting co-living schemes as part of the solution to the UK's housing crisis, and think that "it should and will grow" (Shafique, 2018). It remains to be seen how widespread and popular such schemes may become. Nevertheless, if it is to expand then it is important that the design of these developments should be informed by evidence from the in-use energy and environmental performance of existing PBSA.

2.1.2.9 Technical Characteristics

Only one report was found detailing the technical characteristics of a significant number of PBSA (Hopkison and James, 2006). The sample of PBSA buildings was provided by the energy and residence managers who contributed to a PBSA energy benchmarking [2] study. The 2006 study included 133 residences across 13 universities.

Of these residences, 100 had wet heating systems fed from central natural gas fired boilers, while 33 used individual electrical panel heaters. It is not clear whether this distribution of heating types is indicative of the wider stock. Although the fact that 53 of these residences were catered suggests the sample may not be particularly representative of today's PBSA stock (see Section 2.1.2.4).

After the workshop was held a report was produced to summarise the

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[2] Benchmarking studies can be used to assess the typical performance of particular building types. The aim is to help inform stakeholders about how their building is performing relative to something similar; this could be the same building (e.g. performance last year), other similar building types, or a prototypical building used as a common benchmark (Liddiard et al., 2008).

discussions. The report contains some useful insights on the design and operation of PBSA. These are summarised below.

The dominant energy demand in PBSA is space and water heating; accounting for on average approximately 80% of a residences total energy demand. However, the report did note that plug loads are increasing. This same trend was also noted in a wider 2008 review of energy benchmarks for non domestic buildings (Liddiard et al., 2008). The report also found that there was no relationship between a residence's age, and its energy performance. Indeed, one of the newest halls in the study was found to be the worst performing in terms of energy consumption, whilst one of the oldest was the best.

The workshop attendees also felt that electrical heating systems were generally preferable. This was predominantly due to the improvement in energy savings (in general the electrically heated residences outperformed their fossil fuel counterparts from an energy use perspective). The author's speculated that this was mainly due to rooms not being heated when they were unoccupied (most electrically heated residences are operated with timers) and that further savings may have been made "because it avoids the common problem of students opening their windows because residences are being over-heated" (Hopkison and James, 2006).

There were also other non energy related reasons that the attendees suggested for preferring electrical heating systems. These included the fact that they were popular with students as they are able to control their own heating system (rather than it being controlled centrally). They are also popular with finance directors as they are generally cheaper to install. In addition (although this was not mentioned in the report), as the carbon intensity of UK electricity generation continues to decline (see Section 1.1.1) it is likely that electrically heated halls will begin to outperform fossil fuel heated residences from a carbon emissions perspective.

The attendees also suggested that there was a direct relationship between energy performance, and effective controls and metering. The better performing halls allowed for control over the number of hours of heating, the areas heated, and in some cases, the heating could also respond to both internal and external temperatures. In contrast the worst performing halls were those with poor controls where the heating was either on 24/7, or came on at set times (irrespective of the temperature conditions). The best performing halls all tended to have maximum temperature policies (e.g. a maximum internal temperature of 20-21°C). However, there was some disagreement about whether it is fair to restrict heating hours for residents when utility bills are typically covered in the rental fees i.e. students are paying for the heating and yet have limited control of it.

There were some important details missing from the bench-marking study that could have been included. For instance, no details were provided on the ventilation strategies adopted in each of the residences, or the most common window types, and whether this had any relationship with energy performance. Nor were the environmental conditions inside PBSA discussed in much detail. For instance, no mention was made of the typical conditions inside PBSA, neither from a thermal comfort or IAQ perspective.

Furthermore, most of the findings were based purely on observations and speculation from residence and energy managers about what they felt were the likely causes of particular performance issues. For instance, the residence managers suspected that the opening of windows to prevent rooms overheating during the cooler months was a significant source of energy wastage, but no research or evidence was provided to support this assertion.

2.1.3 Summary

The above section has outlined the defining characteristics of PBSA buildings. It has shown that investment in new PBSA has risen sharply since the mid 1990's, and that this trend looks set to continue. At the same time the design of PBSA has become more homogeneous, and focused on the premium end of the market (with corresponding price increases). It has also highlighted how

PBSA do not fit neatly within either UK building or planning regulations.

The section concluded by reviewing the only technical stock level analysis that was found for UK PBSA. This report found space and water heating to be the dominant energy demands, and that electrical heating was considered preferable (particularly when combined with better controls and metering). In addition, several assertions were made by residence managers in the report about why particular energy performance trends may have occurred that are worth exploring further.

This section of the literature review has shown how PBSA is an important building type to investigate due to a unique collection of trends and features. These include the significant overall stock size, high development and construction rates, homogenisation of design, potential planning and regulatory issues, rapidly rising rental costs, and all inclusive fees (including utility bills). Further evidence to support the rationale for investigating this building type is included in Section 2.5.4 that reviews existing PBSA POE case studies.

2.2 Thermal Comfort

The first section argued why PBSA is an important building type to investigate. This thesis focuses on whether PBSA are delivering adequate IEQ conditions, and whether occupants are being provided with effective control over the conditions. The reason these particular areas were targeted is outlined in Section 2.5.4 in which previous PBSA POEs are reviewed.

Indoor environmental quality (IEQ) is the catch all term to refer to the quality of the environment in a building. This encompasses an array of different aspects, such as lighting, acoustic conditions, air quality, and thermal comfort. This review will focus primarily on thermal comfort and indoor air quality (IAQ). It will examine the conditions, and also whether the occupant's had effective control of the thermal conditions and IAQ.

The section below focuses on thermal comfort. The first subsection provides background on thermal comfort theory, while the remainder of the section focuses on overheating. This is due to the prevalence of overheating in previous PBSA POE studies, as shown in Section 2.5.4.5. IAQ is covered separately in Section 2.3.

2.2.1 Theoretical Background

Poor thermal conditions can affect the health, well-being and productivity of building occupants. Yet there is no absolute standard of thermal comfort; it is dependent upon a number of factors, and can differ from one person to another within an identical environment. An internationally accepted definition for thermal comfort is “the condition of mind which expresses satisfaction with the thermal environment” (ISO, 1987).

The perceptions of this environment depends upon the dynamic interplay between an array of environmental parameters (e.g. air and radiant temperature, airspeed and relative humidity), the occupant’s activity levels, how they are dressed, and their thermal comfort preferences. Hence thermal comfort depends upon a complex mix of physiology, psychology and culture. As such, it is not straight-forward to measure, and cannot be expressed simply in degrees centigrade. There are two main approaches for looking at thermal comfort in buildings; the heat balance and the adaptive approach. These are outlined below.

2.2.1.1 The Heat Balance Approach

The heat balance approach to thermal comfort combines the theory of heat transfer with the physiology of thermoregulation to determine a range of temperatures at which occupants are expected to be comfortable in a building. The range of comfort temperatures is based on experiments conducted in climate chambers. In these experiments subjects were asked under tightly controlled steady-state conditions about their thermal sensation on the seven-point scale, which is shown below in Table 2.1.

The results of these studies were used by Fanger and colleagues (Fanger,

Sensation	Value
Hot	+3
Warm	+2
Slightly Warm	+1
Neutral	0
Slightly Cool	-1
Cool	-2
Cold	-3

Table 2.1: ASHRAE Thermal Sensation Scale

1970) to develop equations in order to calculate the Predicted Mean Vote (PMV) of a large group of subjects for particular combinations of environmental conditions. The comfort zone is defined as the combination of parameters for which the PMV is within recommended limits of the neutral values.

In Figure 2.5 the comfort zone in blue represents the combination of dry bulb temperature and humidity that 90% of building occupants wearing 1 ***clo*** are likely to find acceptable (assuming the other input parameters remain constant). Whereby ***clo*** is a measure of thermal resistance. For instance, 1 ***clo*** is expected to allow a man at rest to maintain thermal equilibrium in an environment at 21°C in a normally ventilated room (Turner et al., 2010). Or to put it another way, it is approximately equivalent to wearing trousers, a long-sleeved shirt, and a long-sleeved sweater (American Society of Heating and Engineers, 1986).

Advocates of the heat balance approach suggest it is both feasible, and desirable to engineer and operate buildings to deliver indoor conditions that meet the narrow band of temperatures derived from climate chamber experiments (Gail and Dear, 1998). This approach treats all occupants and locations the same, and disregards adaptation to the thermal environment. It purports that there should be one set temperature band all year-round from which the internal conditions should only deviate within strict boundaries. In

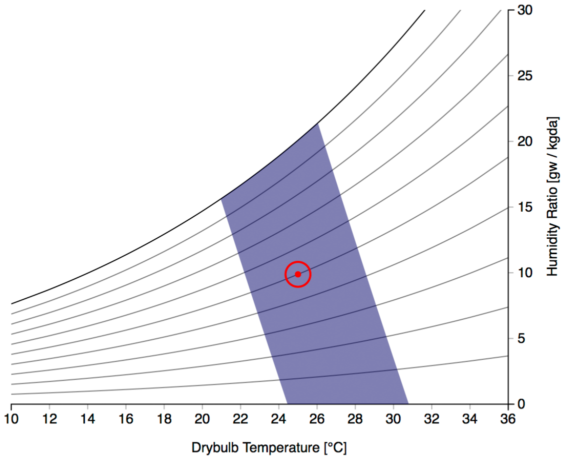

Figure 2.5: This psychrometric chart represents the combination of air temperature and humidity values that 90% of building occupants wearing 1 clo are likely to find acceptable.

this approach occupants are essentially passive. They do not need to adapt to varying environmental conditions inside buildings because the conditions will always be (relatively) constant.

2.2.1.2 The Adaptive Approach

An alternative approach suggests that comfort may be achieved for a wider range of temperatures than the PMV would indicate, provided that individuals have agency over the conditions themselves. This approach is based on field surveys that have shown how occupants (both consciously and unconsciously) will act to affect the heat balance of their body. This is known as “behavioural thermoregulation” (Humphreys et al., 2007). Such actions may affect the thermal environment (e.g. opening a window), the rate of heat loss from the body (e.g. changing clothing), or the rate of metabolic heat production (e.g. changing from a sedentary to an active activity).

This concept is summed up well by Nicol and Humphreys who state that “adaptive thermal comfort is a function of the possibilities for changes, as well as the actual temperatures achieved” (Nicol and Humphreys, 2002). In other words, an occupant’s comfort will depend upon whether they feel that they have the ability to exercise effective behavioural thermoregulation, as well as the conditions themselves. Indeed, according to Oselund’s research, just by being at home, and therefore in an environment that is familiar and under one's own control, individuals become less sensitive to temperature for their thermal comfort (Oseland, 1995).

Advocates of the adaptive approach suggest that, when confronted with real-life conditions (i.e. not those experienced in climate chambers), the PMV method for estimating comfort levels can be misleading. They suggest that comfort temperatures in buildings should be determined using an empirical relationship between external conditions and a band of internal temperatures within which occupants are unlikely to experience discomfort.

In this case the comfort band is related to the external temperature (as opposed to the heat balance approach in which it is fixed). As shown in Figure 2.6 below adaptive comfort theories have gradually become incorporated into the majority of international standards on thermal comfort in buildings e.g. ASHRAE 55, BS EN 15251.

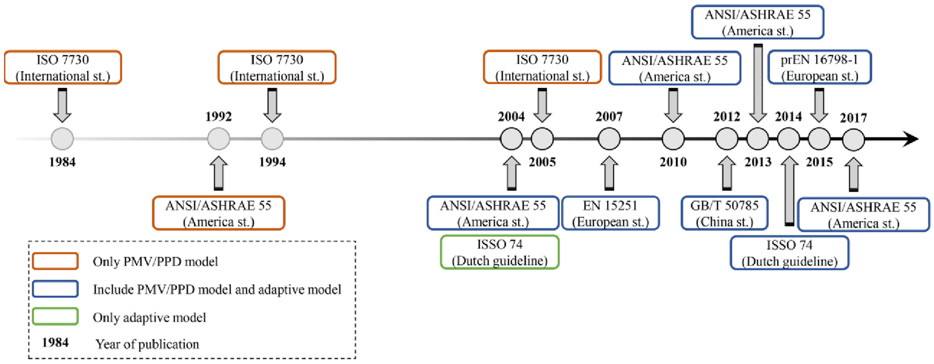

Figure 2.6: Chronology of the integration and refinement of thermal comfort models in regulatory documents (Carlucci et al., 2018)

The benefits of applying adaptive standards can include reduced energy costs (by increasing the flexibility of internal temperatures in response to the outdoor climate), reductions in capital investment cost (the sizing of building services may be reduced), as well as delivering improved comfort conditions (providing that occupants have the ability to exercise effective adaptive thermoregulation behaviour). Indeed, Nicol & Humphreys suggest that in the future thermal standards may specify a range of building characteristics that occupants can use to make themselves comfortable, rather than designating the indoor conditions themselves (Nicol and Humphreys, 2010).

It is adaptive thermal comfort theory that will be applied predominately in this thesis to assess the comfort conditions within PBSA. This is due to the fact that these are domestic free-running buildings (i.e. there is no mechanical cooling). Thus prescribing strict PMV style temperature limits is likely to be unrealistically prohibitive in terms of comfort conditions, particularly during warmer summer periods. That being said, this research does not simply assume that if the conditions remain within the adaptive comfort boundaries that they were acceptable; this is determined by the occupant's themselves. Rather that adaptive metrics will be used as an initial benchmark with which to evaluate the indoor environment and provide comparability with other studies.

2.2.1.3 Thermal Comfort and POE

In buildings in which comfort conditions are primarily delivered via occupants exercising adaptive behaviour (e.g. PBSA) it is important to understand whether adaptive measures are being utilised as anticipated, and that when they are used, they are delivering the intended effect (i.e. to restore comfort). For example, are windows opened regularly in response to warm weather conditions (or is their use prohibited by other factors), and when they are opened, does this supply sufficient cooler air into the space and/or provide an increase in airspeed to restore comfort?

POE can be used to assess whether buildings are providing suitable adaptive opportunities to deliver adequate thermal comfort. However, understanding such mechanisms requires relatively in-depth POE. For instance, occupant surveys or the monitoring of individual environmental parameters are unlikely to reveal the complex interactions between an occupant's comfort, the building's adaptive opportunities and the indoor conditions.

Designing a study which can reveal these complex interactions is an area that has been lacking from previous PBSA POE studies to date (see Section

2.5.4). Hence this thesis investigates not just the indoor conditions in PBSA, but also whether the "possibilities for change" (Nicol and Humphreys, 2002) are sufficient to provide adequate thermal comfort. In this study the assessment of thermal comfort is primarily focused on overheating.

2.2.2 Overheating

The reason this thesis focuses predominately on overheating is due to findings in the literature from monitoring studies conducted on new build PBSA (see Section 2.5.4.5), and a POE pilot study completed as part of the preliminary investigations into this building type. The evidence compiled thus far suggests that these buildings rarely get too cold, whereas incidences of overheating are common. This subsection will review the causes of overheating, alongside the methods to assess overheating in occupied buildings.

2.2.2.1 Defining overheating

Overheating has been defined as the "the phenomenon of a person experiencing excessive or prolonged high temperatures within their home, resulting from internal and/or external heat gains, which leads to adverse effects on their comfort, health or productivity" (ZCH, 2013). At its most extreme, sustained exposure to excessive heat can cause illness, and even fatalities. For instance, it is estimated that the 2003 summer heat wave resulted in an extra 2000 deaths across the UK (Brown et al., 2010). There is now growing evidence of overheating incidences occurring in UK dwellings (Wright et al., 2005; Pathan et al., 2017; Beizaee et al., 2013; McGill et al., 2017).

2.2.2.2 What is causing overheating?

The increasing risk from overheating in the UK has a number of drivers. These consist of long-standing changes (e.g. demographic shifts), more recent developments (e.g. alterations in dwelling design), and other factors that are principally associated with future increases in risk (e.g. rises in summertime temperature due to climate change). These drivers are covered discussed in greater detail below.

Societal Trends

One of the long-standing factors that has increased the risk to the UK population from overheating is urbanization. The UK is now largely urbanized, and yet continued movement from smaller to larger conurbations continues. For example, in 2017 the UK urbanisation rate was 83.14%, and had increased over 4% in 10 years (Statista, 2019). This increases both the total number of people, and the proportion of the UK population likely to be exposed to higher temperatures due to the Urban Heat Island (UHI).

The UHI is the phenomenon whereby temperatures are relatively higher in urban areas compared to surrounding rural areas due to, for example, urban surfaces storing heat in thermal mass, as well as anthropogenic heat sources. For example, average peak temperature differences between central London and a rural reference station located 30km away were 3°C over the summer of 1999 (Wilby, 2003). Furthermore, London's UHI effect is most pronounced at night; meaning that high temperatures are more likely to disrupt sleep.

The UK's population is also ageing. The Office for National Statistics (ONS) projects that in 50 years' time, there are likely to be an additional 8.6 million people aged 65 years and over (ONS, 2018). This increases the likelihood that those affected by elevated temperatures will suffer adverse health affects. Furthermore, elderly people may be less able to exercise adaptive behaviour, and indeed care homes themselves may not be well designed to limit overheating (Gupta et al., 2017).

Moreover British residents may be culturally unprepared to cope with warmer weather conditions. This is likely to manifest itself in two ways. One is a lack of understanding regarding how to keep dwellings cool during warm periods. This first point is exacerbated by the fact that many UK dwellings lack certain design characteristics that allow for passive cooling (e.g. external shutters) (Porritt et al., 2012). The second point is that UK residents may underestimate the risk of overheating to their health. For instance, while the importance of keeping care homes sufficiently warm is culturally ingrained, the requirement to keep them sufficiently cool may be less well-understood (Gupta et al., 2017).

Housing Trends

Compounding the risks from societal changes are a range of trends in the housing industry that can result in properties becoming more susceptible to overheating. The primary cause is often attributed (over simplistically) to recent improvements to the thermal efficiency of newly constructed dwellings. However, the overall picture as to why certain dwellings overheat is usually more nuanced, and influenced by additional design trends.

The additional design trends include a rise in the number of smaller, single aspect properties, that are often constructed from lightweight materials (Hacker, 2005). Inadequate window openings can further reduce the ability of the occupant to effectively "purge" ventilate their properties (Gupta et al., 2017; ZCH, 2013). The risk often becomes particularly acute when recent design trends are combined with thermal efficiency improvements. In this case the dwelling may overheat rapidly (e.g. due to low thermal mass or large glazing areas), and then lack the necessary mechanisms to remove the unwanted heat. Indeed, according to Lomas this combination of factors "can shift housing stocks into territory in which it ceases to function well" (Lomas et al., 2018a).

Climate Change

Finally, global warming is causing summertime mean temperatures in the UK to rise (Holmes et al., 2019). For instance, it has been estimated that, under a medium greenhouse gas emission scenario, summertime mean temperatures may increase by up to 4.2°C in Southern England by 2080 (Murphy et al., 2010). Building simulations have been used to assess how a range of dwelling types in London, Manchester and Edinburgh would perform under such conditions, and predicted that "increased thermal discomfort is likely to be a major problem for many existing buildings unless they are adapted for the changing climate" (Hacker, 2005).

Furthermore, global warming is expected to increase both the frequency, intensity and duration of heat waves in the UK (Jones et al., 2008). This is important because prolonged heat exposure can be particularly debilitating, especially if sleep is disrupted for several nights. For instance several epidemiological studies have shown that the effects on health from successive days of heat exposure far exceed that of just one day (Gosling et al., 2009; Montero et al., 2010; Semenza et al., 1996; Tan et al., 2007).

However, despite these trends it is important to emphasize that overheating is not an inevitability. With good design, and sufficient occupant education on adaptive practices, new dwellings can be both thermally efficient, and comfortable during warm weather conditions (Stefan, 2017). Indeed, there is no other choice but to deliver buildings that can perform both of these functions. Properties that are poorly designed to prevent overheating will make life increasingly uncomfortable for an ageing, urbanised population coping with a rapidly warming climate.

2.2.2.3 When is a building overheated?

The subsection below will review how to assess overheating in an occupied buildings. It will briefly review the methods used to conduct environmental monitoring in occupied buildings, as well as the statistical methods used to determine overheating once the data has been gathered. However, reviews of specific PBSA POE studies that have investigated overheating will be covered separately in Section 2.5.4.5.

Ask the Occupants

The critical verdict on overheating depends on whether the accumulation of warmth is such that the occupants are experiencing discomfort. As discussed previously in Section 2.2.1 this depends upon the thermal comfort preferences of the occupant, their clothing, what they are doing in that space, their ability to take adaptive action, and a combination of environmental conditions perceived by them. The environmental conditions are themselves determined by the interplay between the local climate, the building's characteristics, and the behaviour of the occupant. Thus overheating is a complex, subjective and dynamic experience, and any attempt to define strict conditions under which it has occurred is problematic.

Nevertheless, it seems reasonable to suggest that the most important assessment on overheating is that made by the occupants. Therefore, arguably the simplest and most suitable method to assess overheating is to ask the building's occupants. This may be done through surveys, interviews or focus groups. If the occupants judge that indoor temperatures are leading to adverse effects on their comfort, health or productivity, then the building is (at least on occasions) failing to provide acceptable thermal conditions.

However, assessing overheating through occupant feedback is not without challenges. These are principally concerned with survey and interview design. This includes how to ensure the timing is representative, the questions are well-understood, and the results interpreted fairly. Also, due to the subjective nature of overheating there is a comparability issue. For instance, it is possible that two dwellings with identical internal conditions may receive markedly different feedback from their occupants. In this case it would seem unreasonable to conclude that one dwelling overheated while the other did not.

Monitor the Conditions

Due to the issues outlined above it is also important to have procedures for assessing overheating in post-occupancy studies using physical methods. However, aside from the environmental conditions, there are certain factors relevant to overheating assessments that remain challenging to monitor. For instance, an occupant's thermal comfort will depend upon personal factors, such as their clothing and activity level.

In most POE studies these factors are recorded by either questioning the occupants (e.g. what do you normally wear in your home?), or logical assumptions (e.g. the occupant is likely to be sedentary when in the bedroom at night). Similar approaches are likely to be adopted in most studies due to the technical and ethical complications that would need to be overcome to monitor these parameters in occupied dwellings.

Once personal factors are excluded there is still an array of parameters that should be monitored to comprehensively assess the thermal environment within a space in an "ideal" set-up (see Section 2.2.1 on thermal comfort parameters). However, monitoring all these parameters for extended periods is often considered to be too invasive and technically difficult in order to be practical in occupied domestic buildings (Lomas et al., 2018a). For instance, an example of the monitoring equipment required for "standard-compliant determination of the comfort level" is shown below in Figure 2.7 (Testo, 2020). This apparatus includes both draught (air movement) and mean radiant temperature sensors, alongside the more conventionally monitored parameters, such as air temperature and relative humidity.

Figure 2.7: Example of equipment required for comprehensive indoor comfort assessment (Testo, 2020)

There a number of reasons it is difficult to use such equipment in domestic monitoring studies. Firstly, it is expensive; reducing the number of spaces that could be monitored. Secondly, it is unlikely to be reasonable or practicable for occupants to have these multi-component free-standing devices in their homes for long-periods (particularly in relatively confined spaces, such as PBSA bedrooms).

Therefore the majority of published monitoring studies make use of wall mounted sensors to monitor air temperature and relative humidity (Wright et al., 2005; J et al., 2007; Beizaee et al., 2013; McGill et al., 2017). In reality these sensors are likely to be recording “some (undefined) mix of air and radiant temperature with, possibly, a component of surface temperature (i.e. from conduction through the mounting surface)” (Quigley, 2016). Exactly what wall-mounted sensors are likely to be recording, and how best to position the sensors to accurately reflect the thermal conditions in a room will be covered in more depth in Section 3.4.2.

This form of temperature measurement is used because it is practically very difficult to measure pure dry-bulb or mean radiant temperature in occupied buildings. Plus, as argued by Lomas & Porrit, this set-up may actually record a temperature closer to that experienced by the occupants than pure dry bulb temperature (Lomas et al., 2018a). Furthermore, post-occupancy monitoring studies using such wall-mounted sensors have previously delivered valuable insights into overheating, such as the dwelling types most at risk (Beizaee et al., 2013; Lomas and Giridharan, 2012), how occupants adapt to overheating conditions (Baborska-Narożny et al., 2017), and to highlight particular building characteristics that can make dwellings more susceptible to overheating (Mavrogianni et al., 2014).

Adaptive thermal comfort theory suggests an occupant’s evaluation of overheating will also depend upon whether they have agency over the conditions i.e. can they exercise adaptive behaviour to restore comfort. Thus a more comprehensive representation of whether a building has overheated from the occupants perspective will also require monitoring of the adaptive opportunities available (e.g. window opening), and whether these are effective at restoring comfort (e.g. does opening a window reduce air temperature, and/or increase wind speed). These topics will be covered in the Section 2.4 of the literature review.

Analyse the Data

Once the environmental data is collected statistical analysis can be used to evaluate the likely extent of overheating. The majority of studies to date have used either static exceedance thresholds (such as the Chartered Institute of Building Services Engineers (CIBSE) Guide A (CIBSE, 2006)), and/or adaptive thermal comfort standards, such as the BS EN 15251 (CEN, 2007).

Static Overheating Tests

Static overheating tests provide an indication of overheating risk based on the number of times the hourly average temperature exceeds a certain threshold during occupied hours. The advantage of this approach is its simplicity, and the ability to compare overheating in different dwellings independently of local weather conditions. However, static exceedance thresholds do not account for the severity of overheating. For instance, an exceedance hour is identical whether the internal temperature was 1°C or 5°C above the threshold. Nor do they do account for how an occupant's thermal comfort preferences can vary in response to changes in external temperature (see Section 2.2.1 on adaptive thermal comfort theory).

Adaptive Overheating Tests

To address these deficiencies adaptive thermal comfort standards for overheating were subsequently introduced (e.g. BS EN 15251 (CEN, 2007)). These calculate a threshold temperature that should not be exceeded based on a running mean of the external temperature, and a factor related to the thermal sensitivity of the occupants (see Section 3.5.5.2 for methodological details).

Different criteria can then be applied to determine if the building is overheating. The most widely applied to date has been the CIBSE Technical Memorandum (TM) 52 (Nicol, 2013) criterion system (Nicol, 2013). See for instance (Vellei et al., 2017; McGill et al., 2017; Baborska-Narożny et al., 2017; Gupta et al., 2017). This can be used to assess three different facets of overheating; occurrences, severity and absolute upper limit acceptability.

Heat Stress

There is also an additional method that can be used to assess the internal conditions within buildings. This is whether the occupants are likely to be experiencing heat stress. Heat stress occurs when the body's means of controlling its internal temperature starts to fail (HSE, 2019). It can affect individuals in different ways, and some people are more susceptible to it than others. Typically heat stress is mainly concerned with work place environments, for instance, people who work in protective clothing and perform heavy work in hot and humid conditions could be at risk of heat stress. Yet, as Quigley shows (see Section 2.5.4.5), a domestic building affected by extreme incidences of overheating can cross a threshold into which heat stress becomes a genuine concern (Quigley, 2016).

One method for assessing whether heat stress is likely to occur is to use the humidex scale (Masterton and Richardson, 1979). Humidex is a measure of how hot one feels. It is an equivalent scale intended for the general public to express the combined effects of warm temperatures and humidity. It provides one number that describes how hot people feel. Much in the same way the equivalent chill temperature, or "wind chill factor" describes how cold people feel.

Humidex is used as a measure of perceived heat that results from the combined effect of excessive humidity and high temperature. This number can then be used to assess risk based on Table 2.2 below (Masterton and Richardson, 1979). The exact method for calculating the humidex will be covered in Section 3.5.5.2.

Humidex Range	Degree of Comfort
20-29	Comfortable
30-39	Some discomfort
40-45	Great discomfort; avoid exertion
45+	Dangerous; heat stroke possible

Table 2.2: The Humidex Scale

2.2.2.4 Challenges in Overheating Assessments

There are multiple reasons why overheating criteria may be difficult to apply precisely in occupied buildings. These are concerned with both the data collection and analysis. These are highlighted in several different studies and are summarised below.

Thermal sensitivity factors

As noted above BS EN 15251 requires the assessor to make a decision on if the building has sensitive occupants, and whether it is a new or existing building. Whether or not the building contains sensitive occupants may be obvious on occasions (e.g. it is a nursing home), but not so other times (e.g. a large block of flats with unknown occupants).

External temperature data

To complete adaptive overheating assessments outdoor temperature data must be collected. Weather stations are commonly used for this purpose. These are often situated in exposed locations (such as airports), so are unlikely to be representative of urban temperature conditions. The alternative is to use on-site sensors. These must be installed correctly to avoid bias from direct sunlight and local heat sources.

Monitoring period

The percentage of hours exceeding a certain threshold are designed to be assessed over a fixed period of time (usually a year). However, it is challenging to collect such complete data sets from occupied buildings, and so assessments are often applied over a segment of that period only. Therefore, depending on the timing of the assessment period, it is feasible that the same building could have significantly different overheating results.

Occupied hours

The criteria are only supposed to be applied during occupied hours. This is difficult to determine in dwellings, and so the majority of studies make an assumption about what is likely to constitute occupied hours within certain rooms. As such, there may be occasions during which the dwelling is occupied and overheating but it is not counted (and vice versa).

Sensor location

Typically, just one sensor is used per monitored room. Therefore the researcher will make a judgement about the location likely to represent the “average” conditions in the room, while attempting to avoid heat sources and direct sunlight. However, this assumes that the conditions in the room are relatively homogeneous (or at least that the differences are negligible).

Additional environmental parameters

The wall mounted sensors typically used in overheating evaluation studies are likely to be recording some unknown combination of air, radiant and (to a lesser extent) surface temperature, alongside relative humidity. As discussed previously, these are not all the parameters that determine an occupant’s thermal comfort.

For instance, an occupant in a room with a higher than usual air-speed (i.e they’re using a fan) may be comfortable even though the air temperature suggests an overheating problem. Overheating standards do attempt to factor in these additional environmental parameters (this is covered in Section 3.5.5.2 of the thesis). However, the simplifications and assumptions required to include these metrics (when they are not monitored) inevitably adds uncertainty to the assessment of overheating.

2.2.2.5 Can overheating be predicted?

This thesis is not principally concerned with the prediction of overheating at the design stage. Nevertheless, it seems appropriate to cover the topic briefly. This is done in order to highlight why such predictions are often fraught with uncertainty, and thus to build the case for why continued feedback on summertime conditions is necessary to inform both the design process, and the modelling of overheating risk.

The accurate prediction of internal temperatures in free-running buildings using a Dynamic Simulation Model (DSM) is particularly challenging during periods in which the difference between internal and external temperatures is negligible (Porritt et al., 2012; Symonds et al., 2017). This is because the temperature in the home becomes less dependent on heat flux thorough the envelope, and more affected by other factors, such as the modelling of ventilation, instantaneous radiant fluxes through glazing, internal heat gains, and the absorption of heat by the building's internal mass (Mavrogianni et al., 2014). The data needed to model such parameters are often "simply not available, are very uncertain, or impractically difficult and expensive to obtain" (Lomas et al., 2018a).

One of the primary reasons the modelling becomes far more challenging and uncertain is because the role of the occupants has changed from being a minor perturbation to the dominant factor. Once this occurs, deterministic simulation becomes almost impossible, and the role of simulation necessarily shifts to exploring options and sensitivities (Mavrogianni et al., 2014). Furthermore, the greater the attempt to accurately replicate the conditions in the dwelling, the more complex, time-consuming and expensive creating the model is likely to become (e.g. by using Computational Fluid Dynamics (CFD) to model occupant controlled ventilation). These issues are now being addressed through initiatives such as TM59 "the design methodology for the assessment of overheating risk in homes" which aims to improve the accuracy and reliability of overheating modelling in practice (CIBSE, 2017a).

As occupant behaviour is central to predicting overheating risk in naturally ventilated dwellings it seems pertinent to better understand how occupants react to elevated temperatures. POE can be used to help generate this knowledge. The buildings community needs to know what adaptive measures occupants are undertaking; what is the thermal implications of these actions; and is anything preventing occupants from taking actions that may be beneficial to reducing overheating risk. These findings can then be fed back to design teams (to reduce overheating risk through better design), to modellers (to increase the accuracy of overheating simulations) and to FM staff (to ensure the right procedures are in place, and information on effective adaptive behaviour is being adequately disseminated).

2.2.3 Summary

The section began by outlining the theoretical background to thermal comfort, and summarised the two main thermal comfort approaches in buildings. It has suggested that adaptive thermal comfort theory is more suited to assessing indoor conditions in PBSA. It then went on to argue that using POE is vital to assess whether occupants are making use of the adaptive opportunities as expected, and when they are used, that they are delivering the intended effect. At the core of this argument is the proposition that without feedback on both the use, and effectiveness of passive design measures, practitioners will remain unaware of whether routinely applied design strategies are delivering adequate thermal conditions.

The section went on to review overheating, including the primary causes, and means of assessment in occupied buildings. It outlined some of the challenges in conducting overheating assessments in occupied buildings, and suggested that it is best assessed by combining social (i.e. asking the occupants) and technical (i.e. monitoring the conditions) methods. Finally, it briefly summarised the difficulties of predicting overheating at the design stage, and highlighted the benefits of POE for improving both future designs, and the accuracy of modelling.

2.3 Ventilation & Indoor Air Quality

Section 2.2 above has reviewed how design changes that are meant to reduce heat losses can (if not adequately considered) cause thermal comfort issues, particularly during warm weather. Another key area that can be affected by efficiency improvements is whether increasingly airtight buildings provide sufficient ventilation to provide adequate IAQ.

Poor IAQ is known to affect the health, comfort and well-being of building occupants. It has therefore been linked with Sick Building Syndrome (SBS) (Sundell et al., 2010), reduced productivity in offices (Federspiel et al., 2002) and impaired learning in schools (Bakó-Biró et al., 2007).

Furthermore, poor ventilation can also lead to increased window opening, which may increase ventilation heat losses. The cold fresh air entering from outside must take the place of an equal volume of warm air leaving the dwelling, and must itself be heated up to room temperature. This can affect the overall thermal performance of the building. Indeed, if ventilation heat losses rise considerably these could negate the benefits of fabric efficiency improvements.

This review found limited evidence of IAQ analysis, and no evidence of ventilation measurements being conducted in occupied PBSA buildings in the UK (see Section 2.5.4). As such, there is limited understanding regarding whether UK PBSA are providing adequate ventilation, or whether the ventilation strategies are being operated as the designers intended. This section will review the theory of IAQ and ventilation; focusing on the methods that have been used previously to study these areas in other occupied buildings.

2.3.1 Indoor Air Quality

There is no universally agreed measure that quantitatively describes the quality of indoor air (Cony Renaud Salis et al., 2017), but poor IAQ is typically associated with the increased concentration of pollutants in the air (e.g. Volatile Organic Compounds (VOC)s, formaldehyde, radon and biological contaminants). Inadequate ventilation is often cited as a contributing factor to poor IAQ (Godish and Spengler, 1996). This is because inadequate ventilation may not bring in enough outdoor air to dilute emissions from indoor sources, and/or not remove sufficient indoor air pollutants out of the space. Therefore, although adequate ventilation does not guarantee satisfactory IAQ, inadequate ventilation makes poor IAQ considerably more likely.

2.3.2 Ventilation in UK Dwellings

Ventilation is required to dilute and displace indoor pollutants, as well as for purposes of thermal comfort and dehumidification. UK building regulations require that there is “adequate means of ventilation provided for the people in the building” (HM Government, 2010a). Approved Document F (ADF) to the building regulations provides the guidance on how this requirement can be met (HM Government, 2010b).

ADF splits ventilation into three components: extract ventilation, whole building ventilation and purge ventilation. Extract ventilation may be continuous or intermittent and is intended to remove pollutants at source (e.g. an extract fan in the bathroom to remove water vapour). Whole building ventilation is a nominally continuous air exchange intended to remove pollutants produced throughout the building. Purge ventilation provides manually controlled higher rates of ventilation to rapidly dilute pollutants and or water vapour, and should be available throughout the building.

ADF also provides details of systems that are assumed to meet the ventilation requirements stipulated in the document. This thesis will focus on two types; Mechanical Extract Ventilation (MEV), and Mechanical Ventilation Heat Recovery (MVHR). These are the two types of ventilation design used in the PBSA case studies investigated in this thesis (see Sections 3.3.1.3 and 3.3.2.3).

Although not specifically covered in ADF, occupant controlled ventilation (i.e. window opening) is also one of the primary means of controlling thermal conditions during warmer periods in the UK. Domestic comfort cooling is not common in the UK (Peacock et al., 2010)). It has been estimated that air change rates of between 4-5 Air Changes per Hour (ACH) are required for effective thermal comfort ventilation (NHBC, 2012). As such, whether the dwelling design allows for purge ventilation rates is a crucial component in determining the susceptibility to overheating. If purge ventilation rates cannot be achieved then occupants are less likely to be able to exercise effective adaptive behaviour to alleviate overheating conditions.

2.3.3 Carbon Dioxide Concentration & IAQ

CO_2 concentration in indoor environments has commonly been used as an indicator of ventilation, and as a proxy for IAQ e.g. (Sharpe et al., 2015; Offermann, 2010; Sundersingh and Bearg, 2003). These studies often monitor the amount of time that threshold CO_2 concentration levels (e.g. 1000(v) Parts Per Million (PPM)) are exceeded. However, the direct impact of elevated CO_2 concentrations have on health and cognitive performance appears uncertain.

Lowe et al. (2018) conducted an assessment of the evidence on the direct impact of CO_2 on human cognition. They found the evidence to be both limited, and mixed. For instance, "the literature on the subject amounts to only a few publications and includes both positive and null effects" (Lowe et al., 2018). As such, they concluded that there is a need for more studies, with larger sample sizes to investigate the effect of CO_2 concentration on performance.

Of particular interest to this study is whether poor overnight air quality could also impact on sleep quality and next day performance. This subject was researched in field trials in Denmark (Strøm-Tejsen et al., 2015). In this study participants slept in mechanically ventilated bedrooms, whereby the system was left on (average CO_2 concentration of 835PPM) and off (average CO_2 concentration of 2395PPM). The study found that when the overnight CO_2 concentration was lower the next-day reported sleepiness and ability to concentrate and the subjects' performance in a test of logical thinking was significantly improved (Strøm-Tejsen et al., 2015). However, it is worth noting that there were only 20 participants in the study.

In terms of health impacts there seems to be some agreement that the risk of SBS symptoms (e.g. headache, fatigue, and difficulty concentrating (Finnegan et al., 1985)) diminishes significantly with CO_2 concentrations decreasing below 800PPM (Seppänen et al., 2000). Conversely, above

5000PPM the effects of long-term exposure are likely to be relatively serious, with the UK's Health and Safety Executive (HSE) recommending a workplace exposure limit (the average value over an 8-hour period) of below 5000PPM (Great Britain: Health & Safety Executive., 2020).

However, between these two limits there does not appear to be widespread agreement on the health implications of elevated CO_2. Yet it is worth noting that despite the uncertainties many studies did find associations between elevated CO_2 levels (i.e. beyond 1000PPM) and SBS symptoms (Seppänen et al., 2000; Daisey et al., 2003; Norbäck and Nordström, 2008; Lu et al., 2015)

Central to the link between elevated CO_2 and IAQ is the concept of "stuffiness". The term is commonly assumed to refer to environments in which there is too much stale air (or conversely too little fresh air). Yet defining exactly whether an environment is deemed "stuffy" is not straightforward. Similarly to thermal comfort, it is likely to be subjective; with some occupants more sensitive than others. Furthermore, perceptions of stuffiness may also be conflated with thermal sensations (e.g. a warm, stuffy room). As such, it is important to define exactly what occupants mean by the term "stuffy" if used in surveys or interviews.

Several studies have researched the link between CO_2 and ventilation. According to Sharpe, a common "rule of thumb" is that a CO_2 concentration above 1000PPM suggests inadequate IAQ as CO_2 "keeps bad company" (Sharpe et al., 2015). The logic being that when when CO_2 levels are high, the ventilation rate is likely to be inadequate, meaning that the concentration of other pollutants and contaminants are more likely to be elevated.

However, previous studies have pointed out that concentrations of CO_2 below 1000PPM do not guarantee that the ventilation rate is adequate to control concentrations of indoor pollutant sources (Seppänen et al., 2000; Daisey et al., 2003). Nevertheless keeping CO_2 levels beneath 1000PPM in occupied spaces is now a target in multiple countries for non-industrial buildings e.g. Canada (Nathanson, 1995); Singapore (Institute of Environmental Epidemiology and Ministry of the Environment, 1996); Norway (Becher et al., 1999); China (Peng et al., 2017); and Germany (Lahrz et al., 2008).

Despite the uncertainties outlined above it seems uncontroversial to takeaway two broad conclusions. Firstly, an overly stuffy environment is unpleasant. Secondly, an internal environment with significantly elevated CO_2 levels is likely to be stuffy. Defining precisely what constitutes an overly stuffy environment, or significantly elevated CO_2 is more challenging and complex. Nevertheless, the literature suggests that elevated CO_2 levels should be avoided (particularly for prolonged periods), and that it is likely to indicate inadequate ventilation.

2.3.4 Measuring the Ventilation Rate

The ventilation rate in buildings consists of two components. Firstly, there is infiltration, which is the unintentional flow of air through a building's fabric. Secondly, there is ventilation; the deliberate movement of air into spaces to dilute and displace indoor pollutants. CO_2 levels give an indication of whether ventilation may be inadequate. They do not give a measurement of the ventilation rate itself, or the share of ventilation that is attributable to infiltration (i.e. what component of the ventilation rate is planned or unplanned).

One common method to measure the infiltration rate is to use pressurisation tests. These tests increase the pressure difference between inside and outside the building, and then measure the fan flow rate required to maintain this pressure difference. Some have suggested that the measured air change rate at 50Pa can be divided by 20 to estimate the infiltration rate under "normal" conditions.

However, the value of 20 should be used cautiously. It is not necessarily applicable to all buildings and climates. For instance, naturally ventilated buildings are particularly problematic due to how the instantaneous ventilation rate often deviates significantly from the average depending on the weather conditions (Jones et al., 2016).

An alternative method that can be used to measure either the infiltration rate or the ventilation rate (i.e. infiltration plus planned ventilation) is to use a tracer gas to "tag" the airflow in a volume of air. This is based on principles of the conservation of mass (Sherman, 1990). For example, in a simplified situation in which ventilation is measured within a single zone then the relationship between the tracer gas and the ventilation rate can be defined according to Equation 2.1. In order for Equation 2.1 to be valid a number of assumptions must be made; these are discussed in Section 3.5.7.2.

$$\frac{VdC}{dt} + QC = Q_t \tag{2.1}$$

$\boldsymbol{V}$ = the effective volume of the zone being measured (m^3); $\boldsymbol{C}$ = the concentration of the tracer gas in the zone being measured (kg/m^3); $\boldsymbol{Q}$ = the volumetric flow rate (m^3/s); $\boldsymbol{Q_t}$ = the volumetric rate of injection of the tracer gas (m^3/s).

2.3.4.1 Tracer Gas Selection & Measurement

There a number of characteristics required by the tracer gas. These include that it should be safe (i.e. no toxic, flammable), non-reactive, miscible with air (i.e has a similar density to air), and distinguishable from the constituents of air (Cui et al., 2014). In the literature a variety of gases have been used (e.g. SF_6, Perfluorocarbon tracers (PFT)s, CO_2). This is likely because no gas fits all these properties perfectly, and also because it depends upon the type of study being conducted (e.g. lab based, field based, unoccupied / occupied building). This research will use CO_2 as the tracer gas. The reasons are listed below.

CO_2 sensors are relatively cheap, and more available than more specialised gas sensors. Secondly, at standard temperature and pressure CO_2 has a similar density to air (Teknipoli, 2020). Thirdly, it is relatively safe for use in occupied buildings; the exposure limits for CO_2 are considerably higher than that required for ventilation measurements (Persily, 1997). Finally, humans exhale CO_2. This means that metabolic CO_2 can be used directly as a tracer gas (i.e. without the need for compressed gases). This makes it cheaper, and crucially it allows for the passive measurement of ventilation rates in occupied buildings over long periods.

There are multiple methods for measuring tracer gas concentration. This thesis will focus on the methods that are applicable to measuring the ventilation rate in occupied dwellings. In this case the Multi Point Sampling (MPS) technique is used (Batterman, 2017b). The MPS approach consists of taking a series of concentration measurements over the monitoring period. The time series data is then used to estimate the ventilation rate according to the theoretical relationships outlined above in Equation 2.1. Precise methodological details will be provided in Section 3.5.7.2.

There is no established agreement regarding the frequency with which concentrations measurements should be taken. For instance, these varied in the literature from between half an hour (Crump et al., 2005) to seconds (Cui et al., 2014). The required rate will depend upon both the ventilation rate, and the volume of the space. For example, a small space with a high ventilation rate will require a high sampling frequency or the entire decay may be missed. The guidance document on using metabolic CO_2 (see Section 2.3.4.2 below) suggests that at least five measurements of concentration should be taken for each measurement of ventilation (i.e. for a 20-minute decay the sampling frequency should be 4 minutes or less) (ASTM, 2018).

2.3.4.2 Ventilation Measurement using Metabolic CO2

Metabolic CO_2 was first used as a tracer gas to estimate the ventilation rate in a university library in 1980 (Penman, 1980). Since then it has been used in multiple studies in occupied buildings, including schools (Coley and Beisteiner, 2002), lecture theatres (Zhong et al., 2019) and dwellings (Crump et al., 2005; Guo and Lewis, 2016; Sharpe et al., 2015; Bekö et al., 2010). Consequently, the use of metabolic CO_2 is now an established technique, and a standard guide is provided for its use (ASTM, 2018). However, this review found no evidence of this method being applied in UK PBSA developments. Indeed, this review found no evidence of post-occupancy ventilation assessments in UK PBSA at all.

Experimental Configurations

There are three different experimental configurations using CO_2: concentration decay, constant injection and constant concentration (Liddament and Orme, 1998). These are outlined below in Table 2.3 (Batterman, 2017a).

Experimental Configurations	Description
Equilibrium Analysis	The injection rate of the tracer gas (i.e. metabolic CO_2) is maintained at a constant rate until equilibrium conditions have been established. Once equilibrium conditions have been reached the ventilation rate can be estimated using the mass balance equations.
Assumed Generation	The injection rate of the tracer gas (i.e. metabolic CO_2) is constant but equilibrium conditions are not reached. Instead the rate of build up in CO_2 concentrations following occupancy is used to determine the ventilation rate.
Concentration Decay	The CO_2 concentration builds up while the room is occupied and then once the building becomes unoccupied the decay is used to estimate the ventilation rate.

Table 2.3: CO_2 Ventilation Assessment Experimental Configurations

There are a number of methodological challenges when using metabolic CO_2 as the tracer gas. The first is that the constant injection and constant concentration method require the rate of the tracer gas released into the measurement zone to be known. Hence in this case the rate at which humans exhale CO_2. The challenge with the CO_2 decay method is that it requires the space to be unoccupied when the measurement is conducted. Both of these issues will be covered below.

Metabolic CO_2 Generation

Using CO_2 as a tracer gas when a building is occupied means that it is necessary to know the rate at which CO_2 is exhaled (i.e. the rate at which the tracer gas is being generated in the space). This can be estimated for individuals using an equation. However in the majority of studies e.g. (Penman, 1980; Roulet and Foradini, 2002; Guo and Lewis, 2016; Bekö et al., 2010; Sharpe et al., 2015) an average metabolic CO_2 rate is assumed for the participants. These are based on the typical values, as shown in Table 2.4 below.

The metabolic CO_2 generation values shown in Table 2.4 are for the typical age of participants in this study. In Table 2.4 the metabolic rates are shown at 1 Metabolic Equivalent Task (MET) only. This is equal to the rate of energy produced per unit surface area of an average person seated at rest. Occasionally, some studies include reference to the likely activities undertaken in that room (e.g. overnight bedroom studies may assume that participants are sleeping).

Gender	Age	Mean Body Mass (kg)	BMR (MJ/day)	CO_2 Generation Rate (L/s)
Male	16 to 21	77.3	7.77	0.0037
Male	21 to 30	84.9	8.24	0.0039
Female	16 to 21	65.9	6.12	0.0029
Female	21 to 30	71.9	7.77	0.0031

Table 2.4: CO_2 generation rates at 273K and 101kPa for study the ages of participants in this study at 1 MET (based on the mean body mass in each age group) (Persily and De Jonge, 2017)

However, several studies have shown how the CO_2 generation rate of people is highly variable, and can depend on multiple variables (e.g height, weight, gender, age, fitness etc.) (Persily and De Jonge, 2017). Furthermore, an individuals CO_2 generation rate is itself variable and dependant upon multiple factors (e.g. activity, time since eating food, illness, alcohol consumption etc.), and it may not always be clear how many people are in the measurement zone.

An alternative to using tabulated values could be to assess the CO_2 generation of the study participants under varying activities. However this is likely to be technically, ethically and logistically challenging for a built environment researcher to conduct. The other alternative is to measure the ventilation rate when the space is unoccupied using the CO_2 decay method.

Determining Occupancy

As opposed to the constant injection and constant concentration methods, the decay method can be used when there is no source of tracer gas during the decay period (i.e. when using metabolic CO_2 the room can be unoccupied). Please note this method can also be used when the room is occupied (as discussed in Section 3.5.7), but the same practical difficulties apply regarding the uncertainties associated with assumed CO_2 generation rates.

The detection of occupancy in buildings is a broad and expanding field. There are many applications for which improved occupancy detection could be beneficial (e.g. better control of lighting or Heating, Ventilation and Air Conditioning (HVAC)). There are also a large number of parameters which have been used to detect occupancy, such as motion, illumination and noise, and many different machine-learning algorithms to infer occupancy from these parameters. There are also a number of ethical and data privacy considerations that must be made when using these methods in domestic settings.

Another option, and one adopted in multiple studies, is to use CO_2 as the occupancy estimation method e.g. (Parsons; Sun et al., 2011; Sowa, 2002). This has mainly been in buildings that are principally mechanically ventilated. It allows for measurement of CO_2 concentration at the inlet and outlet duct, alongside the flow rate of air. Tabulated CO_2 generation rates can be used to estimate the number of occupants presence by calculating the difference in CO_2 concentration between the inlet and the outlet air.

However, there are a number of sources of uncertainty when using this method. Such as whether doors and windows are open; the measurement zone's infiltration rate; the changing metabolic rate of occupants; the circulation of air within the measurement zone (i.e. is it well mixed), as well as the response time of the CO_2 sensors.

The section above has explored the practical difficulties and uncertainties of determining the ventilation rate in occupied buildings. The method adopted for estimating the ventilation rate in this study will be covered in Section 3.5.7. This also includes discussion around why this method was selected, and how the uncertainties are managed.

2.3.5 Humidity

Humidity is an important aspect of thermal comfort (see Section 2.2), and also IAQ. Excessive moisture and dryness can have negative consequences for occupants, and the building itself. As such, the HSE recommends that Relative Humidity (RH) should be kept between 40-70% in the workplace (HSE, 1992). Similarly CIBSE Guide A suggests that humidity levels in dwellings in the range of 40–70% RH are generally acceptable (CIBSE, 2003). This subsection will provide a brief summary on the importance of humidity control in buildings for occupant health and comfort.

The typical metric for analysing humidity in building is RH. In technical terms RH "is the actual amount of moisture expressed as a percentage of the saturation pressure at that temperature" (Alsmo and Alsmo, 2014). It describes how much water vapour is in the air, compared to how much it could hold at that temperature. In contrast absolute humidity describes the absolute mass of water contained in the air. This is typically either expressed per unit volume or per unit mass of dry air (e.g. g/m^3 or g/kg). The relationship between RH, absolute humidity and temperature is often visualised through psychometric charts (see Figure 2.5 in Section 2.2.1.1).

Research in the UK has often focused on overly humid indoor environments, and how to prevent them e.g. (Altamirano et al., 2009; Fletcher et al., 1996; Howieson et al., 2003; Stephen et al., 1997). This is a serious problem. Damp homes can provide ideal environments for bacteria, dust mites and harmful moulds (Arlian et al., 2001). These can contribute to allergies, asthma attacks and other health concerns (Waegemaekers et al., 1989). It is also a relatively widespread problem. For instance, a YouGov (polling company) and Shelter (housing charity) poll found that 39% of London's private renters have experienced damp or mould in their dwellings in 2016 (Shelter, 2016).

However, the indoor monitoring of new-build PBSA thus far (see Section 2.5.4) suggests that PBSA occupants are more likely to be affected by overly dry conditions. Low RH in buildings can also cause a range of issues for occupants. This can include dry skin, eye irritation, static shocks and the drying out of nasal passages (McIntyre, 1978). As well as causing discomfort, the drying out of nasal passages can also leave occupants more susceptible to cold viruses (Arundel et al., 1986).

Low RH can be a particular problem in winter. This is due to the fact that cold winter air can retain less moisture. Therefore although outside RH might be high, the absolute amount of moisture retained in the air is low. As this outdoor air enters a warm environment the RH falls. Furthermore the warmer the indoor environment (and hence the greater the temperature differential between the outdoor and indoor air) the greater the fall in RH.

There are multiple methods for increasing the humidity of indoor air. These can include specific equipment (such as a humidifier), alongside simpler techniques e.g. letting clothes dry inside, or keeping the bathroom door open while showering.

2.3.6 Summary

The section began by highlighting the importance of adequate IAQ, and its relationship with ventilation. It then reviewed studies that have used CO_2 concentration as a proxy for IAQ and ventilation. The literature suggested that elevated CO_2 concentrations (e.g above 1000PPM) should be minimised. Furthermore, elevated CO_2 concentrations are also likely (but do not definitively) to indicate inadequate ventilation.

The section went on to review methods for assessing ventilation. It highlighted a range of challenges and uncertainties when measuring ventilation in occupied buildings. However, this thesis is not primarily concerned with methods of ventilation measurement, or how they can be improved. Rather it seeks to understand the limitations and uncertainties of different methods in order to select the most appropriate technique to be used in this particular application; the assessment of ventilation rate in a longitudinal study in occupied PBSA buildings.

The review identified that using CO_2 as the tracer gas is the most practicable solution, and that there are three experimental configurations that could be adopted; equilibrium analysis, assumed generation, and concentration decay. None of these methods are straightforward to apply precisely in occupied buildings.

The principal issue with the equilibrium analysis and assumed generation methods is that the generation of metabolic CO_2 is uncertain. The concentration decay method can be used without assuming metabolic CO_2 generation rates. However, if this approach is adopted, it then depends upon being able to determine whether the measurement space is unoccupied. Occupancy was found to be difficult to verify with certainty, particularly in domestic settings. The method selected in this study, and justification for the approach can be found in the Section 3.5.7.

Finally, the section covered humidity from an IAQ perspective. It suggested that the evidence to date indicates that PBSA are more likely to be affected by overly dry conditions (this is covered in Section 2.5.4.3). It highlighted the health and comfort issues associated with low RH. It also suggested why such conditions were more likely to arise in winter, and that buildings with high internal temperatures are likely to further exacerbate the problem.

2.4 Occupant Control

This thesis is concerned with the conditions in PBSA buildings, but also whether occupants have adequate control over the conditions, and what are the influencing factors. The following section will review the control of indoor conditions in buildings, focusing primarily on ensuring thermal comfort and adequate IAQ. It will also touch on other areas, such as visual or acoustic comfort where they affect control of the thermal comfort or IAQ (e.g. an occupant choosing not to open their window due to noise).

The occupant's primary means of control in PBSA buildings is the heater (thermal control) and the window (thermal and ventilation control). Hence these shall form the main two sections of this chapter on occupant control.

2.4.1 Occupant Behaviour

This thesis is primarily focused on the technical assessment of occupant behaviour. For example, monitoring the duration and frequency of window opening, its relationship with internal (and external) conditions, and how the opening of windows affects those conditions. However, it is important to emphasise that occupant behaviour is influenced by a multitude of factors. Most of which are not the environmental conditions themselves, and cannot be easily measured. Therefore before proceeding with the rest of the section it is worth briefly covering occupant behaviour, and the study of occupant behaviour.

As alluded to above the control over the conditions inside buildings is a Socio-technical System (STS). It depends upon the complex interactions between occupants, the buildings systems and the indoor (and outdoor) environment. Thus a large number of factors contribute to how an occupant chooses to interact with the building. These factors can be "external" (e.g. air temperature, wind speed), or "individual" (e.g. personal background, attitudes, preferences), as well as related to the building's properties (e.g. ownership, available heating devices).

Due to the sociotechnical nature of the research problem this thesis adopts a sociotechnical approach. This includes using methods from the social sciences (see Section 3 for details). However, it is not situated within an entirely social science framework. Therefore instead of providing an in-depth review of behavioural theories it will explore what factors may influence behaviour using some concepts from Social Practice Theory (SPT).

The reason SPT theory has been specifically raised is to highlight how particular behaviours are not always related to the environmental conditions inside (or outside) the building, and therefore may not be explainable via monitoring of the conditions alone. Indeed, behaviours may be unconscious (e.g. changes in posture), or related to social dynamics within a group (e.g. heater settings in communal spaces), and will not always be viewed as related to considerations of environmental conditions or energy usage. Thus occupant behaviour or "practices" can be defined as "coordinated entities of sayings and doings that are held together by different elements" (Gram-Hanssen, 2010). These have been categorised into four groupings:

1. Know-how and embodied habits;
2. Institutionalised knowledge and explicit rules;
3. Purposes, beliefs and emotions;
4. Technologies.

An example of an environmental control practice may be opening a window first thing in the morning. The reason an occupant performs this action could be because of one or more of the below:

1. They have always done this since being a child (Know-how and embodied habits);
2. The PBSA does not allow occupants to leave their bedroom doors open, and as such this is their only method of removing the stale air (institutionalised knowledge and explicit rules);
3. They believe that fresh air is good for them, or they enjoy to hear bird song in the morning (purposes, beliefs and emotions);

4. They cannot control the heating system in their room, and as such opening the window is the only means of cooling the room in the morning (Technologies).

There are many other theories that could also be used to analyse occupant behaviour. Reviewing these are beyond the scope of this thesis. The purpose of highlighting SPT theory is to stress that there are many reasons an occupant may undertake certain behaviours. Therefore the simplest (or building researcher biased) option (e.g. the occupant opens the window to reduce stuffiness) may not be correct. It also highlights the importance of speaking to occupants regarding their behaviour and thereby reducing the risk that subtleties in behavioural responses will be missed. This will be covered again in Section 3.

2.4.2 Heating Behaviour

One of the aims of this thesis is to investigate whether occupants in PBSA can control the conditions in their rooms during the heating season. It is also to understand how they use the controls, and the likely impact these behaviours have on energy demand. Alongside asking the occupants about these areas a set of variables will be determined that can be observed and measured to compare and contrast heating behaviours. Before outlining these variables it is important to understand the heating controls that are typical in PBSA.

2.4.2.1 PBSA Heating Controls

Heating controls have been defined as the “controls that allow the central or local regulation of temperature through the heating system” (Lomas et al., 2018b). This research concerns only controls for the delivery of heat into spaces (i.e. it does not consider the efficiency of heat conversion systems, such as boilers). The primary purpose of heating controls is “to ensure that thermally comfortable conditions are provided and that the system operates in a safe, reliable, efficient and maintainable manner” (Lomas et al., 2018b).

There are a multitude of different domestic control technologies that aim to improve the efficiency of heating. This may be by limiting duration of heating (e.g. not heating the space when unoccupied); constraining spatial variation in heating (e.g. heating occupied spaces only); and reducing the temperature to which a space is heated (e.g. turning off space heating at 21°C rather than 23°C). This thesis will focus on heating systems prevalent in PBSA.

No recent data set was found for PBSA stock characteristics. In a 2006 study (discussed in Section 2.1.2.9) of 133 residences, 100 had wet heating systems fed from central natural gas fired boilers, while 33 used individual electrical panel heaters (Hopkison and James, 2006). As no more recent data could be found it is assumed that the majority of UK PBSA are likely to contain one of these two heating systems.

It also seems likely that in new build PBSA wet-heating systems will have been the dominant technology type, although this may now be beginning to change. This is principally due to two reasons. Firstly, gas is often cheaper in terms of running costs; one unit of gas has been on average 3-4 times cheaper than a unit of electricity in the UK between 1996 to 2019 (BEIS, 2020b).

Secondly, the carbon factors in Approved Document L (ADL) of the UK building regulations means that using gas can represent an easier route to achieving compliance. For instance, in SAP 12 (still in use for building regulation compliance as of October 2020) the carbon emission factors for gas and electricity are 0.216 $kgCO_2e$ per kWh and 0.519 $kgCO_2e$ per kWh respectively (HMGovernment, 2014). Thus from a carbon emissions perspective it is easier to achieve compliance at the design stage using gas as the principal fuel for heating. In this authors experience regulations have also appeared to push many designers towards installing Combined Heat and Power (CHP) engines in PBSA alongside boilers.

Centrally controlled gas heating systems typically provide a certain level of heat to each room either continuously, or at pre-programmed times. They tend to be controlled by a single thermostat in a central location, and do not generally record an accurate temperature reading for all bedrooms. Instead, control in individual bedrooms is typically via Thermostatic Radiator Valve (TRV)s. These TRVs may or may not be adjustable by the occupants. It has been suggested that these systems may have a number of drawbacks (see Section 2.1.2.9). This research focuses on how these systems affect occupant comfort and control, as well as the how the controls are likely to impact on heating usage (i.e. it will not investigate other factors, such as maintainability, or utility costs).

The potential issues include the limited personal control they offer. This is despite the fact that the heating requirements of individual rooms may fluctuate considerably, for instance, due to orientation, occupancy patterns, or thermal comfort preferences. The other issue is that these systems push hot water around buildings to individual radiators via a series of pipes. Hot water will be circulated regardless of whether individual radiators are on or off. As such, heat will be lost via the pipework continually. In large PBSA, where there can be hundreds of bedrooms, many radiators may be turned off, and so the heat is lost unnecessarily. This may result in energy wastage and the overheating of spaces. It could also cause further energy wastage as occupants open their windows in response to overheated conditions.

The alternative heating type is electric resistance radiators in individual rooms. These can be centrally programmed to reach the same temperature. Each radiator has an individual digital thermostat regulating the temperature of each room. In some cases these radiators may also offer a “boost” function that allows an occupant to boost the temperature of their room (e.g. from 21°C to 23°C) for a limited period.

This heating type appears to offer a number of advantages. Firstly, the accurate temperature recording in each room via a digital thermometer should allow for better control i.e. it will be less likely that rooms will continue to be heated beyond the set temperature. Secondly, when a radiator is switched off, no energy is wasted driving unnecessary heat to it. Thirdly, these radiators can be provided with open-window detection technology (i.e. they automatically switch off if a window is left open). Fourthly, as the carbon intensity of UK electricity continues to decline (CCC, 2015), it is likely that in the near future they may also be the lower carbon option.

However, as outlined in Section 2.1.2.9 on PBSA stock characteristics, there is limited compelling evidence (e.g. systematic field trials) to support the suggestion that wet-heating system controls are inadequate in PBSA, or that direct electric systems would be preferable. The studies that have monitored heating in PBSA will be outlined in Section 2.5.4.2. One of the primary purposes of this thesis is to gather data to investigate the control of thermal conditions in PBSA. This should help enable the future design of PBSA heating systems and controls to be informed by an expanded evidence-base.

2.4.2.2 Monitoring Heating Behaviour

Although heating systems and controls vary between PBSA there are a number of parameters that are likely to be critical in assessing how occupants control the conditions in their rooms, and the adequacy of those controls. It should be noted that some of these variables may be controlled by an individual occupant (e.g. leaving a bedroom window open), a collection of occupants (e.g. the thermostat in a communal space), or by FM (e.g. the centrally controlled availability of heating). The key variables are listed below:

- Heating schedule; the times during the day in which the heating is on or off.
- Set-point temperature; the temperature the thermostat or TRV is “set” to maintain i.e. the internal temperature beneath which the heating would come on.
- The internal temperature; the internal temperature in the room over the heating season.
- Ventilation; the sources of ventilation sources and how they are used.
- Supplementary heating; are any supplementary heating devices used?

The previous studies that have monitored heating and/or indoor temperatures in UK PBSA are covered in Section 2.5.4.2. However, as noted previously, these are relatively limited. Therefore the remainder of this section will briefly review studies that monitored heating in domestic buildings in the UK. The purpose of reviewing these studies is to provide further context for the indoor conditions and heating controls in the PBSA monitored in this thesis, and how they compare with the wider UK domestic stock.

There are two relatively recent large-scale studies that have monitored domestic heating in the UK. These are the CARBHES and the Energy Follow up Survey (EFUS) that accompanied the 2011 English Housing Survey (EHS). The details of each study are provided in Table 2.5 below.

Name	Study Period	No. of Homes	Description
CARBHES	July 2007 - Feb 2008	427	Household interviews and 45-min internal temperature monitoring in living rooms and main bedroom
EFUS	Jan 2011 - Jan 2012	823	Household interviews and monitored internal temperatures in up to 3 rooms over one year

Table 2.5: CARB and EFUS Study Details

As shown in Table 2.5 neither study monitored the heat emitting devices directly. Instead internal temperature monitoring was used to infer heating usage, or alternatively household responses were used. Both data sets have been analysed by multiple researchers. This review has focused on the studies that provide useful context for heating usage in the PBSA under investigation.

The first piece of evidence that can be used for comparability between the monitored conditions in the PBSA under investigation in this thesis, and the wider UK domestic stock is a scatter plot of internal against external temperatures. These plots show both how warm the conditions are during the heating season, and also how the internal temperature varies with external temperature during warmer periods in the year. This relationship is shown below for the CARBHES data set (Kelly et al., 2013).

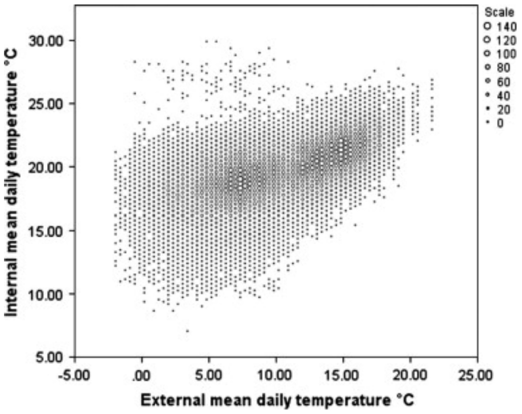

Figure 2.8: Scatter plot of mean daily internal temperature versus mean daily external temperature by dwelling for the CARBHES data set. The large hollow circles represent a concentration of observations (Kelly et al., 2013)

Figure 2.8 shows the mean internal temperature during colder periods to be around 17-20°C. However, internal temperatures are widely dispersed, with dispersal increasing as the temperature drops. One further interesting point to note is that it appears that "several households heat their homes to higher temperatures in the winter than in the summer" (Kelly et al., 2013).

Shipworth et al. (2010) used the CARBHES data set to estimate thermostat set-points, and the duration of heating hours monitored households. This was done based on the internal air temperature in living rooms. The authors estimated the mean set-point temperature to be 21.1°C (with a standard deviation of 2.5°C), while mean central heating usage on weekdays was estimated to be 8.2 hours (with a standard deviation of 1.5 hours).

The EFUS data set did not estimate thermostat set-points based on quantitative data but instead relied on user feedback. However, mean internal temperatures were analysed across the monitoring period. The mean monthly room temperatures during the heating season (October to April) were found to be 19.3°C for the living room, and 18.9°C for the bedroom (BRE, 2013b). Meanwhile the heating hours were found to be between 8.4-8.8 hours for householder responses, and between 8.8-9.5 hours when derived from the internal temperature data.

One final variable that is interesting to contrast with the findings in this thesis is the heating profiles of the households. Huebner et al. (2013) explored heating profiles using the CARBHES data set. They used the internal air temperature in the living room to estimate the probability of the heating system being on during the week and at weekends. The results are shown below in Figure 2.9.

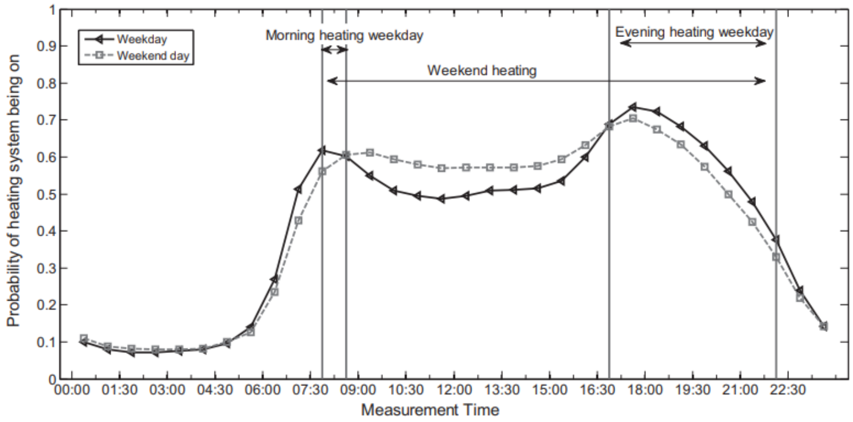

Figure 2.9: Average probability for the heating system being on or off for weekdays and weekends. The vertical periods indicate times in which BREDEM would assume heating to be on (Huebner et al., 2013)

These findings are compared against the conditions and heating usage in the monitored PBSA in Section 6.2.1. However, it is important to note that important differences exist between living rooms and bedrooms in typical households and PBSA study bedrooms. Study bedrooms are required to function as living rooms, bedrooms and studies all at once (as discussed in Section 2.1.2.4). As such, the internal conditions required and the demands on the heating systems are likely to be different.

Furthermore, none of these studies monitored window opening, and how this may have affected heating usage. This is a key area of investigation for

PBSA due to the suggestion that windows are opened regularly for thermal control (see Section 2.1.2.9).

2.4.3 Window Opening

Windows are opened for a multitude of reasons. For instance, four possible causes were identified for why an occupant may open their window in the morning in Section 2.4, and this list was not exhaustive. Thus behind the relatively simple concept of opening windows is "in reality a task that is influenced by many factors, which interact in complex ways" (Fabi et al., 2012). The IEQ framed rationale, which often feeds into modelling predictions of occupant behaviour, is that windows are opened let fresh air into the room (i.e ventilation) or (if outside temperature allows) to reduce room air temperatures.

As outlined in Section 2.5.4 only one limited study was identified investigating window opening practices in UK PBSA. Therefore this section will use evidence primarily from window opening studies that have occurred in domestic settings previously. It will begin by outlining the window types that are common in PBSA, and detailing their characteristics. This will be followed by a review of domestic window opening behaviour, including the variables that should be analysed, and the key behavioural drivers. This will be followed by consideration of the link between window opening and energy consumption.

2.4.3.1 PBSA Window Types

There is a large variety of window types available with different openings. Different window opening types have different properties regarding weather protection, maximum achievable ventilation rates, and the adjustability of opening areas. The choice of window opening types is likely to affect both the achievable ventilation rates, and the user's behaviour.

The design of windows in PBSA are often constrained by the preference to restrict openings. Window restrictors are legally required in health and social care environments with vulnerable adults and children (HSE, 2014). Although such restrictions do not explicitly cover student accommodation, educational establishments (and by extension private providers) tend to restrict openings to be between 100-150mm. This is for a combination of reasons that are likely to include; to prevent falls from height; to add extra security; and to reduce the ability of occupants to throw objects from their rooms.

This review found no evidence for any study researching window design in UK PBSA. Indeed the one PBSA benchmark study cited above in Sections 2.1.2.9 and 2.4.2.1 did not provide information on window types. A range of window opening types that are likely to be common in UK PBSA are displayed in Figure 2.10.

Figure 2.10: Typical PBSA window opening types (HNS, 2020)

However, due to the need to restrict openings sliding windows tend not to be used unless they have some form of grills or barrier in place across the opening. Indeed, such designs may prove advantageous in that they could provide greater effective opening areas while managing to maintain the same safety restrictions (see Figure 2.11 below).

Any window design that increases the opening area is likely to enhance single-sided natural ventilation. This occurs because the mean pressure difference across the opening increases when the height differential between the upper and lower opening area increases. This is particularly important in summer in which displacement (rather than wind driven) ventilation is likely to be the dominant driver on those hot, still days. This is discussed further in Section 6.3.2.

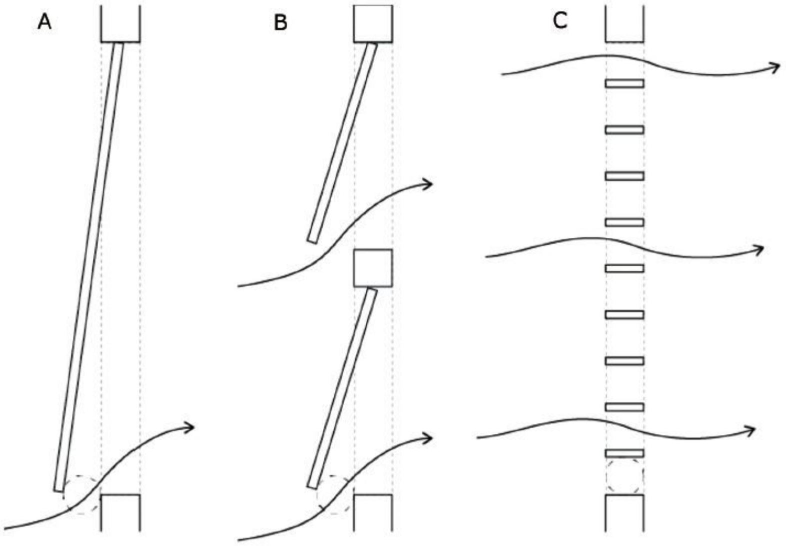

Figure 2.11: Alternative configurations of openable windows within the same structural openings. Vent openings are restricted to 100mm, but greater airflow can be achieved from configuration A to C respectively (Jones and Sharpe, 2019)

However, although no database or evidence could be found, it is this authors view that such opening types remain relatively uncommon in UK PBSA. Through discussions with designers and observations of UK PBSA it appears that the most common window types are top-hung and side-hung windows. These window types are likely specified due to factors such as cost and maintainability.

This thesis does not seek to analyse the aerodynamic performance of different window types, and therefore this review does not cover the methods or findings from this area further. Instead the research focuses on whether the windows that are commonly installed in UK PBSA are capable of meeting the occupant's needs in a real-world scenario i.e. over the course of a year do PBSA windows provide sufficient ventilation and allow for thermal control. It also seeks to understand how occupants use their windows in

PBSA to achieve these desired outcomes. As such, Section 2.4.3.2 below will review how these topics have been studied in domestic settings previously.

2.4.3.2 Domestic Window Opening Behaviour

Irrespective of the window type, field studies indicate that as long as the window design allows, occupants take advantage of continuous window opening adjustments to provide indoor comfort (Fabi et al., 2012). Many previous studies have investigated the key factors that influence occupants' window opening behaviour in buildings e.g. (Rijal et al., 2008; Herkel et al., 2008; Haldi and Robinson, 2008; Andersen et al., 2011).

An international review of these studies was undertaken for the International Energy Agency (IEA)-ECBCS Annex 8 on inhabitant behaviour with respect to ventilation (Dubrul, 1988). This included participants from Belgium, Germany, Switzerland, the Netherlands and the UK. It found that the "drivers" of window opening behaviour in domestic buildings can be categorised into five groupings. These are shown in Table 2.6.

Physiological	Psychological	Social	Physical Environmental	Contextual
Age	Perceived Illumination	Smoking	Outdoor Temperature	Dwelling Type
Gender	Temperature Preference	Presence at home	Indoor Temperature	Room Type
Health			CO2 Conc	Orientation
Clothing			Wind Speed	Time of Day

Table 2.6: Driving forces for energy-related behaviour with respect to ventilation/window operation in residential buildings (Fabi et al., 2012)

A review of window opening studies conducted by Fabi et al. (2012) concluded that window use has a "big impact both on the IEQ and on the energy consumed to sustain the desired IEQ level". Yet that there is a lack of consensus regarding the key drivers of window opening behaviour, and they are likely to vary according to multiple other factors, such as building type, climate and occupant age.

The review also identified a number of key gaps in the current understanding of window opening behaviour. Firstly, the majority of studies have focused on non-domestic buildings (e.g. offices). Secondly, studies have tended to focus on window state (e.g. open) rather than the change of state (e.g. closed to open). Finally, the review finishes by stating that "a significant effort should be addressed in the following years to better understand the dynamics of the relationship between indoor environment, occupant behaviour and energy consumption" (Fabi et al., 2012).

The literature reviewed in this section has suggested that window opening can have a "big impact" on IEQ. However, this has not been tested in UK PBSA. Hence this research will investigate how PBSA occupants are using their windows, why they are using them in this way (i.e. what drives their behaviour) and also how this affects the indoor environment. It will also investigate the relationship between window opening and energy consumption.

2.4.3.3 Window Opening and Energy Consumption

Opening a window during the winter heating season is likely to increase heat losses in dwellings. The scale of the losses will depend upon multiple factors. These include the size and type of opening (this will affect the ventilation rate), the length of time the windows are open, and the temperature differential between the inside and outside air.

Furthermore, the relative impact of window opening on a dwelling's total heat losses also depends upon the thermal performance of the dwelling itself. In dwellings that are more thermally efficient (i.e. one with a lower heat loss coefficient) the same window, operated in the same manner, will have a proportionally greater impact on the dwelling's performance when compared against a baseline scenario (e.g. one in which windows remain closed). Hence as the thermal performance of a dwelling improves the relative impact of window opening on heat losses grows.

However, despite the drive to limit heat losses in dwellings this review found relatively few field studies exploring the impact of window opening on heat losses. Two studies were identified that examined this question, each taking a different approach. These will be discussed below and the niche within this research sits identified.

One of the studies quantified the effect of window opening on the measured heat loss of a test house in Loughborough, UK (Jack et al., 2016). The test house is a small, timber framed, detached building but in 2000 to contemporary building standards. Blower door tests (to measure the ventilation rate) and co-heating tests (to measure the thermal performance of the dwelling) were performed on a the house with a range of window configurations. A linear relationship was observed between the window opening area and the ventilation rate. Therefore the additional heat loss due to window opening (ΔQ_w) could be estimated using Equation 2.2 below.

$$\Delta Q_w = C_p \times \rho \times \Delta v \times V \times (T_i - T_o) \tag{2.2}$$

ΔQ_w = additional heat loss due to window opening (W/k)
C_p = specific heat capacity of air (kJ/kgK)
ρ = density of air (kg/m^3) - assumed to be 1.2 at 20°C
Δv = is the additional ventilation due to window opening (converted to ACH)
V = is the internal volume of the house (m^3)
T_i = internal temperature (°C)
T_o = outdoor temperature (°C)

The additional heat losses were estimated for a variety of window opening behaviours. The findings showed that window opening could have a significant effect on total heat losses. For instance, if a window or windows with an opening area of $0.94m^2$ was "left open for 24 hours a days this would double the heat loss rate of the house" (Jack et al., 2016). However, the study's authors suggested that such behaviour was implausible.

The heat losses for the test house were also estimated based on modelling the window opening behaviour from field studies e.g. (Dubrul, 1988; Fox, 2008; Johnson and Long, 2005). In this case they found the losses from window opening to be relatively marginal (just 2.4% of the total heat losses). The authors concluded that window opening is unlikely to cause significant extra losses from the baseline performance of the dwelling unless the behaviour is relatively extreme (i.e. windows are open for long periods), and/or occurs in dwellings constructed to particularly high thermal performance standards.

The second study combined monitoring with modelling to estimate the effect of window opening in halls of residences in Boston, USA (Cedeno Laurent et al., 2017). In this study window opening was not monitored directly, but inferred from IEQ monitoring. The primary purpose of the study was to improve the accuracy of modelling window opening behaviour in building performance simulations.

The authors concluded that bedroom window opening does have a "significant influence on whole-building heating consumption", as it could constitute up to 10% of total heat losses (Cedeno Laurent et al., 2017). However, the paper did not mention the amount of time the windows would need to be open for losses of this size to occur. They also found that common modelling assumptions, such as "T-26°C", whereby windows are open only when indoor temperatures are higher than 26°C also "generated high deviations from real measurements, since for the winter season indoor temperatures are rarely higher than that threshold". Thus highlighting the importance of informing PBSA modelling with data collected from PBSA performance in practice.

2.4.4 Summary

This section began by acknowledging that occupant behaviour in buildings is complex, and affected by an extensive range of factors, many of which cannot be directly monitored. It then outlined the heating systems commonly found in UK PBSA, alongside defining the important parameters for monitoring heating behaviour. UK domestic heating behaviour studies were briefly reviewed for comparison with the PBSA findings in this thesis.

Window opening was covered next, including the types of windows common in PBSA, the drivers of window opening behaviour, and also the relationship between window opening and heating consumption. The section revealed a lack of studies (in domestic buildings as well as PBSA) that have sought to investigate heating behaviour alongside window opening, and how they affect one another. Due to the multitude of factors influencing "the dynamics of the relationship between indoor environment, occupant behaviour and energy consumption" (Fabi et al., 2012) it seems probable that this area is best addressed by combining quantitative and qualitative research methods (this is discussed in greater detail in Section 3). These relationships will be investigated in this research by conducting in-depth POE in occupied PBSA.

2.5 Post-Occupancy Evaluation

POE is a systematic process used to evaluate the performance of an occupied building. Such studies are also commonly referred to as Building Performance Evaluation (BPE). At its most fundamental, POE is an assessment of whether the building (or certain parts of it), are achieving in practice what they were designed to do. As such, it is an extremely broad concept, and is commonly used to refer to almost any study conducted on an occupied building. At the core of all POE is the relatively simple concept that investigating users' needs through systematic processes that "assess the human responses to buildings and other designed spaces is a legitimate aim of buildings research" (Preiser, 2001).

At a bare minimum, domestic buildings users will expect their residences to be "functional, comfortable, safe and will not impair their health" (Preiser, 2001). Nowadays, there is also the added necessity to reduce the environmental impact of buildings i.e. they should be energy efficient, and more generally sustainable (e.g. in terms of water usage, or waste production). Therefore a building's "performance" can be considered as its "capacity to meet any or all of these expectations" (Preiser, 2001).

The methods and techniques applied in POE studies can be extremely diverse, ranging from interviews and surveys, to physical measurements and quantitative analysis. However the fundamental component of the majority of POE studies is empirical fieldwork. POE normally entails visiting, observing and evaluating real buildings (Leaman et al., 2010), alongside holding discussions with the people who use and manage them. Thus POE is commonly associated with the academic approach that Robson refers to as "real-world research" (Robson, 2002) (these ideas shall be further explored in Section 3).

The section below will begin by highlighting why POE is important to improving building performance. It will outline some of the landmark studies that have shown the value of POE in revealing serious (and often surprising) performance issues in the past. The remainder of the section will outline the previous studies that have used POE to investigate PBSA performance.

2.5.1 Why do POE?

The exact reasons for undertaking POE will vary between projects, and will depend upon a mix of factors, such as research motivations, stakeholder interest, building typology, geographic location and local regulations (Hiromoto, 2015). In general, the scope of the work can be divided into three main purposes (Cooper, 2001).

- **Feedback** - to improve the performance of the existing building
- **Feed-forward** - to improve future building performance by providing feedback to the design team
- **Benchmarking** - to measure how well the building is performing in practice against certain sustainability indicators, or against similar

building types

Whether or not a building can be considered to be performing well depends upon the metric against which it is being evaluated. Three common metrics against which buildings are routinely evaluated are outlined below (Leaman et al., 2010).

- **Occupant Satisfaction** - What do the occupants think of the building
- **Environmental Performance** - Normally quantified through metrics such as waste production, water or energy usage
- **Financial Assessment** - Did the development deliver value for money, or return on investment

It has been shown that very few modern buildings perform well from all three perspectives (Leaman et al., 2010). Proponents of POE argue that one of the crucial steps in addressing performance shortcomings is to learn from existing buildings so that "successes can be built upon, and repeat mistakes avoided" (Leaman et al., 2010). After concluding the investigation it is equally important that the "lessons-learned" are effectively communicated back to the appropriate practitioners. The potential value in routinely conducting POE is now widely recognised, and therefore many industry bodies, practitioners and researchers have frequently suggested that some form of POE and learning should become standard practice within the design-build process. The aim is to turn a linear work flow process into a cycle of continuous improvement (see Figure 2.12 below).

Due to its proven benefits POE is receiving greater acceptance as a valid tool for industry, government and researchers to better understand the built environment, and how it operates in practice. This is evidenced by the fact that some form of post-occupancy or in-use evaluation is now mandated on all large public projects through *Government Soft-Landings* (The Cabinet Office, 2013), incorporated into the Royal Institute of British Architects (RIBA) plan of works (RIBA, 2013), and required under many local plans (see for instance its addition in London's latest plan (Dronkelaar et al., 2018)).

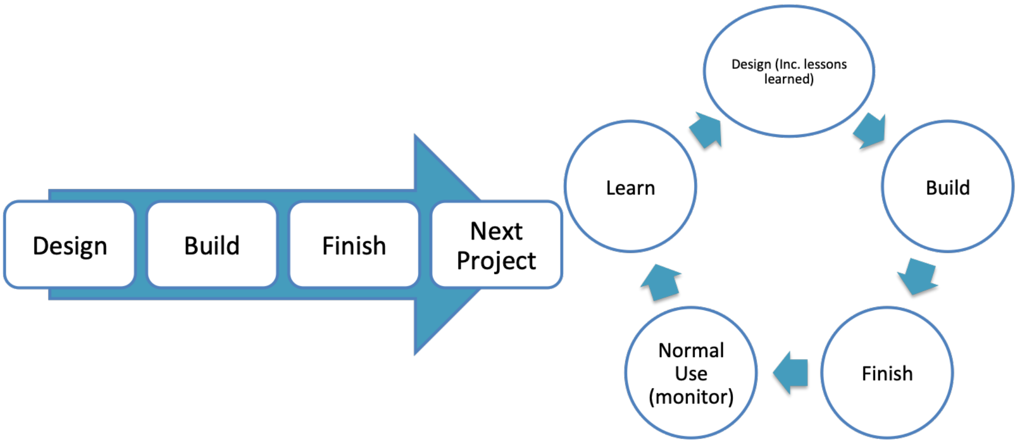

Figure 2.12: The Linear Construction Process and Feedback Improvement Cycle

Furthermore, the fundamental rationale for using POE is as compelling as ever. The UK must significantly reduce emissions arising from the operation of buildings, whilst simultaneously ensuring these buildings provide healthy and comfortable internal environments. While buildings continue to under-perform from both these perspectives (i.e. energy usage and occupant comfort) the need for POE to generate "valuable information to support the goal of continuous performance improvements" (Zimmerman and Martin, 2001) remains vital.

2.5.2 POE in the UK

Thus far the majority of POE work in the UK has focused on non-domestic buildings, especially offices and schools (Leaman et al., 2010; Cohen et al., 2001; Innovate UK, 2016a). There have been two major landmark studies evaluating building portfolios in the UK. In both studies, many buildings were shown to have performed poorly.

2.5.2.1 PROBE

The PROBE (Post-occupancy Review of Buildings and their Engineering) research project ran between 1995 and 2002. The team completed POEs on 23 non-domestic buildings that had been recently featured as "exemplar designs" in the British Services Journal (BSJ). The primary purpose was providing "feedback to building services engineers of generic and specific information on factors for success, and areas of difficulty and disappointment" (Cohen et al., 2001). The standardised approach involved occupant surveys, quantitative energy assessments, walk through surveys and reviewing technical papers.

Of the buildings evaluated just one was considered by the investigators to have been reasonably successful according to all three perspectives outlined above in Section 2.5.1 (e.g. sustainability, occupant feedback, and financial performance). As a result of the studies the investigators produced general recommendations for all key stakeholders in the building process. Fundamental to all these recommendations was the message that to achieve radically more sustainable buildings evaluations and feedback must become the norm (Leaman et al., 2010). These studies drew attention to the "performance gap" and are still consistently cited today when researchers examine building performance in practice (see for instance (Menezes et al., 2012; Göçer et al., 2015)).

2.5.2.2 Innovate UK BPE Studies

In January 2016 the Building Performance Evaluation (BPE) team released their final reports from a four year "flagship monitoring" program. The large study included both non-domestic (Innovate UK, 2016a) and domestic portfolios (Innovate UK, 2016b).

The domestic study investigated 76 homes, which "are all part of leading-edge developments where low-carbon design was a priority". It focused on the "buildings fabrics and its systems, and how satisfied occupants are with the properties" (Innovate UK, 2016b). The over arching finding across the study is that the integration of new technologies into buildings is often inadequate, and that control systems are often unnecessarily complex. The authors called for an increased focus on handover and commissioning in new homes as these "are essential for homes to achieve their design targets for energy". Once again the report highlights that without evaluations many practitioners responsible for designing, procuring, and installing new technologies may remain unaware of common deployment challenges, and the way such systems are actually being utilised by occupants.

2.5.3 POE in Academia

POE work does not fit comfortably within historical academic disciplines. It normally requires knowledge and skills to be adopted from multiple areas, and regularly relies on case studies and qualitative evidence (Turpin-Brooks and Viccars, 2006). Thus POE may be considered either "too challenging or merely anecdotal", which may reduce the likelihood of publishable outcomes (Leaman et al., 2010).

These factors might have dissuaded some researchers from pursuing this line of work. This in turn could have affected the rate at which rigorous evaluation procedures are developed. Indeed, similar practical research problems are judged to have affected many aspects of buildings and energy research (Oreszczyn and Lowe, 2010). The justification for using case studies in this research will be covered in Section 3.

Nevertheless, POE has still been widely used in academia, and often involves working collaboratively with practitioners and other stakeholders. Indeed there is a growing body of evidence of showing the benefits of POE. These range from first highlighting the performance gap in the PROBE studies (Cohen et al., 2001), to the discovery of heat bypasses in uninsulated cavity walls (Wingfield et al., 2008). While more recent evidence includes the finding that new technologies often do not operate as intended (Innovate UK, 2016a), or the importance of effective engagement with occupants during retrofit projects to improve performance outcomes (Chiu et al., 2014). Thus POE has repeatedly demonstrated its value in wide ranging areas for highlighting serious, and often unexpected, performance issues.

2.5.4 PBSA POE

This section will conclude by examining POE studies that have occurred in PBSA. The review will focus on areas related to IEQ in PBSA, alongside control of the conditions. It aims to draw together common themes, and highlight any research gaps. The search strategy that has been used to find the studies is shown below in Table 2.7.

Prefixes	Suffixes	Databases
Student halls	Post-occupancy evaluation	Google scholar
Student accommodation	Energy	Science direct
Student residences	Environment	Web of Science
Student dormitories	Building performance evaluation	Google
PBSA	Thermal comfort	

Table 2.7: PBSA POE Search Strategy

The initial search included POE studies conducted in PBSA around the world. However, the majority of these studies were not considered of sufficient relevance to this thesis (due to differing study objectives, building types, and climates), and so for brevity and applicability to this research, the review has focused on studies from the UK and Ireland.

2.5.4.1 Energy Efficiency

Of the studies that have produced Energy Use Intensity (EUI) statistics (RTA, 1995; Vadodaria, 2012; Innovate UK, 2013; Hernandez et al., 2014) all had lower heating demand than the current "good practice" CIBSE general accommodation benchmark (see Table 2.8) (CIBSE, 2008). However, it should be noted that both benchmarks in Table 2.8 are now dated, as much of the data was collected during the 1980's and 1990's as part of the Energy Efficiency Best Practice Programme (Falkners, 2000).

These studies also highlighted an important energy performance finding for PBSA. This is that once fabric efficiency standards reach a certain level, it is unlikely that further improvements to the building's envelope will continue to be the most cost effective energy conservation measure. For instance, in Roebuck Hall personal plug-in equipment and hot water use were the first and second largest energy loads respectively, accounting for approximately 65% of final energy use (Hernandez et al., 2014).

Accommodation	Gas ($kWh/m^2/yr$)	Electricity ($kWh/m^2/yr$)
DEC General Accommodation	300	60
ECG Good Practice	200	45
Constable Terrace	70	104
Richard Feilden House	0	155
Woodland Court	139	63
Roebuck Hall	53	36

Table 2.8: PBSA Energy Use Comparison studies

This finding lead the investigator's to conclude that "there are few technical measures that can be applied to further reduce building energy load from a design perspective" (Hernandez et al., 2014). Indeed, the investigators considered that the reason heat demand was greater than predicted (25 kWh/m^2/yr instead of the design target of 15 kWh/m^2/yr) was "likely due to students' preferences and behaviour in operating the heating system and window opening". However, the investigators did not elaborate further on these differences, and no monitoring of windows or radiator use was undertaken as part of the study.

In addition, Quigley's thesis also highlighted how improving a building's fabric does not guarantee good performance as the fabric cannot "ensure the heating is turned off in summer, or that the lights are turned off when not in use" (Quigley, 2016). The point being that it is equally important to give attention to the heating system, controls, and occupant behaviour. These POE studies reinforce the findings from the PBSA benchmarking workshop (see section 2.1.2.9), which also stressed the importance of a good controls strategy to PBSA performance (Hopkison and James, 2006).

2.5.4.2 Heating Controls

The only study to include monitoring of individual heating devices was Quigley's thesis (Quigley, 2016). In this study two PBSA buildings were monitored in London and Loughborough. In Loughborough 12 electric radiators were monitored for power use, whereas in London 16 individual bedrooms had their radiator surface temperature monitored (as it was a wet-heating system). The monitoring occurred from March to June in Loughborough and from March to August in London. As such, the monitoring did not occur during the coolest periods of the year.

In Loughborough the heating controls were designed such that the radiators should stay on for a maximum of two hours, unless the thermostat set-point is reached, at which point they should switch off. However, many occasions were observed in which the radiators were on for longer than two hours, and yet the set-point was never reached. Although, window use was not monitored, and as such it was not known whether or not windows were open during these events. Consequently, it could not be determined whether the capacity of the heating system was insufficient, or the occupant had left their window open on a cool day, or the set-point was very high.

Quigley also suggested that the heating patterns indicated that there were occasions in which the occupants wanted more heat but could not obtain it i.e. the controls were restricting space heating usage. Thus it is suggested that "care is needed in the control of restrictive radiators, so that they limit energy use but can be relied upon to meet comfort requirements". However, no interviews or surveys were conducted with the study participants. Thus it was not known whether the occupants were uncomfortable, or would have used more heating if they could.

In the London study Quigley suggested that the TRV type controls were not ideal because there was "no way to turn heating on for a fixed duration or to have it turn off automatically". As such, in many rooms radiators were left on for "weeks at a time". Whereas the controls in the Loughborough building prevented such behaviour.

Quigley also suggested that the mixture between Building Management System (BMS) and TRV control may have been confusing to occupants. For instance, there may have been times when they turn their heating on and it is not available, and so they leave it on and then get heating when it becomes available whether or not they want it. Quigley suggested that such a system is likely to lead to thermal discomfort and wasted energy.

Quigley also suggests that simplistic controls via TRVs may not be appropriate in PBSA, and should be avoided in new buildings. This is because heating patterns are typically variable (due to intermittent occupancy), while heating loads are relatively low (PBSA tend to have small rooms and be thermally lightweight). However, Quigley does acknowledge that determining the optimal control strategy that ensures comfort whilst limiting energy use is a difficult balance, and that more research is needed in this area (Quigley, 2016).

Quigley's research revealed several important insights around operating heating systems in PBSA. However, two important aspects were missed. Firstly, how does the use of the window affect both the use, and the adequacy of the heating system? For example, Quigley states how the lack of window opening data meant that it was "not possible to investigate relationship between window opening and internal temperature or the simultaneous use of window and space heating".

Secondly, what were the occupant's opinions on the thermal conditions in their rooms, or their ability to control the conditions? As Quigley's results are based on monitoring data alone phrases such as "may have been thermally uncomfortable", and "could have been why they operated their heating system in this manner" were used throughout. Thus feedback from the residents could have provided a richer analysis of the problem, and more definitive conclusions.

2.5.4.3 Indoor environmental quality

The over arching IEQ concern raised in the studies that included indoor environmental monitoring was overheating (RTA, 1995; Altan et al., 2013; Hernandez et al., 2014; Quigley, 2016). This will be covered in Section 2.5.4.5 below. No other major IEQ issues were reported in the POE studies.

However, only temperature and relative humidity were monitored.

Therefore including additional parameters, such as CO_2, could have been used to investigate other aspects of IEQ, such as IAQ. For instance, it is not possible to assess whether ventilation rates in modern UK PBSA are adequate from any of the studies conducted thus far.

2.5.4.4 Occupant feedback

In the studies that included occupant feedback (RTA, 1995; McGrath and Horton, 2011; Innovate UK, 2013) this was done via quantitative surveys only (see Table 2.9 below). These surveys were fairly wide ranging, and so this review will focus primarily on the aspects related to IEQ and energy usage.

References	**Response Rate**	**Survey Timing**
(RTA, 1995)	197 (50%)	April
(McGrath and Horton, 2011)	39 (8%)	Unknown
(Innovate UK, 2013)	71 (24%)	March

Table 2.9: Occupant Surveys

Rickaby Thompson Architects noted that on winter days, with the windows closed, the accommodation could become “stuffy” (RTA, 1995). Therefore a significant proportion of respondents reported using their windows in winter either “everyday” (25%) or “frequently” (21%). This was not the aim of the designers; the intention was for the windows to remain shut during the winter with fresh air supplied via the MVHR system.

In (McGrath and Horton, 2011) the response rate was very low (just 8% of the building’s occupants replied). This renders some of the statistical tests they used in their analysis questionable. Their main finding was that intrusive noise was the most pressing concern. Thus highlighting how the parameters that are routinely monitored in POE studies (e.g. temperature and relative humidity) are just one of many factors that residents will consider when evaluating the IEQ of their residences, and indeed may well not be the most important.

In Woodland Court (Innovate UK, 2013) the Building Use Studies (BUS) survey was applied. The BUS methodology uses a structured questionnaire that allows respondents to rate various aspects of building performance on a

1-7 scale, alongside providing space for qualitative feedback in the comments sections (see Section 3.4.6 for more details).

The investigators found the responses to the temperature in winter to be highly varied, with many positive comments, but also negative responses, such as “heating should be on during the day as well” and “heating turns off at night and is cold”. The investigators suggested that one of the main problems was the location of the temperature sensors used to control the heating; these were located on the ground and third floor corridors of each block (i.e. not in the habitable areas). Therefore, once a certain temperature was reached in the corridor the heating would turn off (regardless of the TRV setting in their rooms). This reinforces the need to provide thought-through and responsive control strategies in PBSA.

This review has identified two occupant feedback gaps in the existing UK PBSA POE literature. The first is that (with the possible exception of (McGrath and Horton, 2011) as it was not clear when this survey was undertaken) none of the feedback occurred after residents had experienced summer conditions. This is particularly pertinent for the residences that house post-graduate students, as they are likely to be in the accommodation for the entirety of summer. The second is the lack of any interviews to provide richer qualitative data. This would allow for follow up questions and more in-depth answers to questions on comfort, or why the occupants may have engaged in certain heating or ventilation practices.

2.5.4.5 Overheating in PBSA

Of the four studies (RTA, 1995; Altan et al., 2013; Quigley, 2016; Hernandez et al., 2014) that included temperature monitoring, three identified overheating as a significant issue (RTA, 1995; Altan et al., 2013; Quigley, 2016). The causal factors identified in the studies, and in other relevant POE studies are outlined below.

Limited Ventilation

PBSA rooms are often single-aspect, and typically have safety restrictors on the windows (these limit the opening width to 150mm). This means it is unlikely that purge ventilation rates of 4-5 ACH (which are required for effective passive cooling (HM Government, 2010a)) can be achieved. PBSA are also often in urban areas (due to the location of universities) where security, noise, light or pollution may affect the ability of occupants to use their windows, particularly at night (ZCH, 2013).

Thermally Lightweight Materials

PBSA are often thermally lightweight constructions in order to reduce material costs and increase the speed of construction. This can reduce the ability of the building to regulate temperature swings by absorbing the excess heat during the day, and then releasing it at night as the external temperature drops. However, it is worth noting that, increasing the thermal mass is only beneficial if there is an effective strategy to "purge" the heat at night.

Limited Shading

PBSA study bedrooms typically have relatively large glazing to exposed walls areas (particularly in relation to their floor area), which can result in high solar gains. Where such windows are used the shading strategy is often either not present, or not the most effective type (i.e. internal blinds and reflective coating on glass only).

Internal Gains

Insufficient insulation on pipework and valves, and large thermal stores used in the communal heating systems, can cause unwanted heat gains all year round.

Circulation Spaces

Internal corridors in PBSA often have limited ventilation and communal heating services running above them, which may also be poorly insulated. This can make them particularly susceptible to overheating (some of this heat is then inevitably transferred to adjoining apartments).

Overheating is not an inevitability

However, despite the overheating design risks that can be prevalent in PBSA one study did not observe any overheating problems. This was also the PBSA (Roebuck Hall) with the lowest heating demand (Hernandez et al., 2014). In this study the internal temperature was monitored inside 12 bedrooms over two years, and despite some increases in temperature during the daytime in summer, the CIBSE Guide A threshold criteria of 1% annual hours above 28°C was never exceeded (the paper did not comment on the 25°C - 5% criteria) (CIBSE, 2006).

However, there are important caveats. Compared with certain regions of the UK Dublin is both cooler, and less sunny (Weather-Guide, 2019). The investigators also did not monitor the kitchens areas, which were notably warmer in other studies (RTA, 1995; Altan et al., 2013). In addition, the occupants were not surveyed, and therefore it could not be determined whether they were satisfied with the thermal conditions. Nevertheless, these findings suggest that (with good design and construction) overheating, or at least higher temperatures, is not an inevitability in efficient, naturally-ventilated PBSA.

Occupant behaviour and overheating

At Constable Terrace the investigators monitored the temperature and relative humidity in four “typical” flats (RTA, 1995). They discuss the results purely qualitatively, noting that “on some occasions, particularly in the kitchen and lounge areas, internal temperatures reach the upper limit of acceptability” (RTA, 1995). The maximum temperatures were observed during the late afternoon / early evening periods. The investigator’s surmised that this was because the windows had been left closed in unoccupied flats, and therefore they suggest providing “secure, unattended, natural ventilation” to help alleviate the issue.

These findings also highlight the complexity of the relationship between occupancy and overheating. Typically overheating is only assessed during occupied hours (CIBSE, 2006), and occupants can exacerbate overheating by causing unwanted heat gains. However, in this case, it is the lack of occupancy that is actually causing the elevation of temperatures within the residences (assuming that had the residents been in they would have opened the windows). A similar point could also be made about the use of blinds to limit solar gains.

The Constable Terrace investigators also made two further interesting observations. The first being that, even when external temperatures reached 26°C in July, no corresponding peak in internal temperature was observed. This suggests that internal temperatures were more affected by internal and solar gains than the external temperature (as may be expected in a well-insulated airtight building). This is likely to have important implications for the likelihood of overheating outside of the summer months (see "Winter Overheating" below).

The second observation provides a vivid example of how the external environment can inhibit the ability of occupants to effectively regulate internal temperature. At Constable Terrace the designer's envisaged that the "summer mode" of ventilation would be extract only, whereby fresh air would be drawn in through open windows. However, during the summer examination period a nearby building site forced many residents to keep their windows closed to limit the acoustic disruption. Thus occupants were forced to choose between maintaining a comfortable internal temperature, or being disturbed while studying.

Winter overheating

The internal temperature and the relative humidity were monitored in an unreported number of bedrooms and kitchens at the Lancaster Eco-Residences between December 2008 and January 2009 (Altan et al., 2013). Despite the monitoring occurring over the winter period, incidences of overheating were observed. For example, during a day in which the average external temperature never exceeded 7.7°C, the internal temperature remained steady at between 25°C and 26°C for 7 hours.

The authors considered that the winter overheating issue was likely to be caused by high solar gains, and suggested that an improved shading strategy should be adopted. The fact that these residences were overheating during winter raises worrying questions about their likely performance during summer. These findings lead the authors to conclude that the "main problem of the residential complex may be overheating" (Altan et al., 2013).

Overheating assessment

Only one of the studies applied both the adaptive (Nicol, 2013) and static (CIBSE, 2006) overheating tests. In Quigley's thesis internal temperatures were monitored in an occupied PBSA in London between March to September.

The POE found evidence of "extreme overheating on floors seven to eleven, and very little overheating on floors one and two" (Quigley, 2016). They also found that the temperatures recorded within some rooms were "extremely high" (reaching a maximum of 34.8°C in one room) and "often long lasting". The author identified multiple causal factors (the majority of which were outlined above), including that the space heating was available for most of the summer (it would come on whenever the external temperature dipped below 15°C). The author concluded that this was "totally unnecessary", and no doubt contributed to the problem (Quigley, 2016). This study emphasises again the importance of an effective controls strategy for ensuring good thermal performance.

The investigation also indicated that overheating in the stairways and central corridors may have added to the problem. Both these areas lacked any ventilation and were likely to have high internal gains due to hot water service pipes. In particular the stairs may have exacerbated the problem on the upper floors because heat could easily rise up through the whole building as the "stairs were essentially one open space spanning the full height of the building" (Quigley, 2016). However, no monitoring was conducted in the stairways or corridors so these theories were not validated.

Due to the extent of overheating, heat stress was also considered (see

Section 3.5.5.2 for more details on heat stress). Humidity data was only collected for one room and so it was only possible to conduct this analysis in that room. In this room incidences of “caution” and “extreme caution” were observed on 14 occasions. However, the duration of the events was not recorded. Also due to the lack of humidity data from the other rooms it was not possible to assess whether such incidences were widespread throughout the buildings or isolated to this particular room.

2.5.4.6 Window Opening

Only one study was found examining window opening in UK PBSA (Li et al., 2017). The study had 21 participants, and occurred in a PBSA in Southampton during the summer of 2017. The research monitored window movement and indoor environmental variables (air temperature and relative humidity), alongside conducting weekly surveys for six weeks that were primarily focused on occupant comfort and window opening behaviour.

The results showed that a large percentage of participants were dissatisfied with the ventilation and thermal conditions in their room, and would prefer more air movement. It also showed that during the summer over 60% of occupants reported having their window constantly open, but that many were still uncomfortable despite this. The study also found that there was significant association between the use of a fan and the occupant’s thermal sensation vote i.e. those who reported using a fan were more likely to be satisfied with the indoor conditions in summer.

However, the study could be improved in a number of key areas. The lack of CO_2 data meant that the occupant’s reported dissatisfaction with ventilation and air movement could not be investigated further using IAQ data. The lack of qualitative feedback also meant that it was not possible to provide a more comprehensive understanding of the differences in window opening between participants, or their views on the adequacy of the windows. The wider population of the building was not also surveyed, and therefore it was not possible to assess how representative the participants were of the occupants more generally. Finally, the monitoring was conducted during summer only. Therefore it is not known how windows are used during the heating season in UK PBSA, and the effect this may have on space heating usage.

2.6 Summary

The literature review began by looking at the PBSA building type. It argued that this is an important building type to research due to the significant overall stock size, high development and construction rates, homogenisation of design, potential planning and regulatory issues, rapidly rising rental costs, and all inclusive fees (including utility bills).

The review then covered thermal comfort, and more specifically overheating. It suggested that adaptive thermal comfort is likely to be the most appropriate metric for assessing indoor conditions in PBSA. However, it also argued that in using adaptive thermal comfort theory it is important that continued POE is used to assess whether occupants are using the adaptive opportunities as expected, and that when they are used, they are delivering the intended effect. The section then reviewed overheating. It focused on the methods and challenges of assessing overheating in occupied buildings. It suggested that overheating is best assessed by combining both social (asking the occupants) and technical (monitoring the conditions) methods.

In the next section ventilation and IAQ were reviewed. It highlighted the importance of adequate IAQ, and explored the relationship between CO_2 and IAQ. It then covered the research methods that can be used to assess ventilation rates in occupied buildings, focusing on the challenges and limitations of the various approaches. The review found no evidence that ventilation assessments have been completed in occupied UK PBSA buildings to date.

The review then covered occupant behaviour, specifically heating usage and window opening. It outlined the key variables for monitoring heating behaviour, and presented findings from previous UK domestic studies on heating usage for context and comparison. It then covered window opening; outlining the types of windows common in PBSA, and also a brief review of previous window opening studies. The review found that there is a lack of understanding "of the dynamics of the relationship between indoor environment, occupant behaviour and energy consumption" (Fabi et al., 2012).

The section concluded by reviewing the PBSA POE studies that have occurred in the UK to date. These studies have highlighted how overheating was a particular issue for this building type. They also consistently raised poor heating controls as an issue, and suggested that this is likely to affect occupant satisfaction, and can also lead to overheating issues. They went on to suggest that this may cause occupants to use their windows during the heating season as a means of regulating the internal temperature (rather than simply turning the heating down or off). It was proposed that this could have a significant affect on the overall thermal performance of PBSA buildings.

However, a number of key gaps in the evidence were also identified. This meant that several of the suggestions and assertions that were made in this section could not be backed up with evidence. The key gaps in the understanding of this building type are listed below.

- None of the studies included any form of window monitoring during the heating season, and therefore suggestions about how occupants may have been regularly using windows throughout the winter months to prevent their rooms becoming overheated could not be validated.
- None of the studies included any other form of environmental monitoring beyond temperature and relative humidity, and therefore metrics such as whether the PBSA were effectively ventilated were not physically measured.
- None of the studies included any qualitative interviews with residents, and so it was not possible to gain a more in-depth understanding of

PBSA occupant's comfort, or practices. This was particularly concerning during summer. For instance, overheating was consistently raised as an issue yet not one of the studies confirmed whether or not this was a significant issue for the residents, or how they did (or could not) adapt to it.

Now that the literature review section has been completed and a number of clear gaps in our understanding of PBSA performance have been identified, the next section will outline the aims of this research, and the questions to be answered. It will also describe the research design that will be adopted to answer the research questions.

Chapter 3

Research Aims & Methodology

This chapter will begin by restating the aims and questions for this research. It will then propose the research design that can be used to achieve these aims, and answer the questions. This will be followed by a section outlining the case studies in detail. The final two sections of the chapter describe the data collection and analysis methods.

3.1 Research Aims and Questions

There are two primary aims for this research. The first aim is to investigate the interactions between occupants of PBSA, the indoor environment, and control of the heating and ventilation systems throughout the heating season. The second aim is to understand the various practices that occupants adopt to alleviate discomfort during warm weather periods. It will explore the actions taken by occupants, and whether these delivered the desired effect i.e. to restore comfort.

It should be noted that these two aims are not entirely independent. For instance, overheating is considered in the heating season. Indeed, defining the heating season in the UK is not straightforward (this area shall be covered in Section 3.5.3). Yet for the purposes of this thesis these two broad time-periods (i.e. when heating was mainly on, and when heating was mainly off) had sufficient important differences that it seemed both logical and beneficial to distinguish between them, and therefore to have slightly differing research aims and questions.

To achieve the research aims the following research questions will be answered in this thesis.

1. Can occupants of PBSA control indoor environmental conditions in the heating season, what are the influencing factors, and how does their behaviour affect energy demand?

2. To what extent do occupants of PBSA make use of the available adaptive opportunities to meet their thermal requirements during summer, and what affect do these actions have on the indoor environmental conditions?

3.2 Research Design

In this section a methodology is developed to enable the research questions to be addressed. Answering the above research questions requires an understanding of the interactions between the people, the buildings services (e.g. the ventilation and heating), the conditions inside the building, and the building itself. Critically, it also requires an understanding of how all these elements influence each other. Furthermore, as occupant behaviour is a key factor in this research, emphasis will be given to the occupant's perspective on the PBSA internal environment and how they interact with it. Occupant focus is something that has been lacking from previous PBSA POE studies to date (see Section 2.5.4).

It is proposed that the research questions can only be adequately addressed using an interdisciplinary approach. This will combine multiple data collection methods using in-depth case studies. Answering the research questions will involve both physical monitoring (technical) and self-reported (social) data from the occupants. The concepts and the rationale for using this approach are outlined in further detail below.

3.2.1 Interdisciplinary Approach

An inter-disciplinary approach has been described as the "process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline, and draws on the disciplines with the goal of integrating their insights to construct a more comprehensive understanding" (Burris et al., 2012). The issue of thermal control and IAQ in a domestic building necessitates the use of such an approach. This is because the efficient delivery of comfortable conditions in a building is not only a technical challenge, but a social one too. Understanding why the occupants adopted certain behaviours is equally important as the behaviours themselves.

This research will draw mainly upon the technical disciplines of environmental engineering (the author's background) and building physics. Yet it will also include aspects of social science in order to provide a more comprehensive understanding of the problem. The research does not aim to contribute to all the individual disciplines (as multi-disciplinary approaches might) but instead aims to integrate the findings in such a way as to provide a deeper understanding of a complex issue i.e. the control of thermal conditions within PBSA.

By considering just the technical aspects of the building and it services, other equally important factors may be overlooked. For example, through monitoring the building the researcher can form an understanding of window opening practices (e.g. the duration and frequency of window opening). Yet without incorporating aspects of social science (e.g. occupant interviews) it is not possible to ascertain the reasons or causes of window opening behaviour with certainty.

Therefore, gathering social data is a requirement for understanding how technical aspects of the building could be altered to encourage or discourage certain practices. Such approaches have been validated and encouraged by built environment researchers. For instance, Davies & Oreszcyn have previously expressed the “urgent need for the formation of multi and inter disciplinary teams” to address complex building performance problems (Davies and Oreszczyn, 2012).

3.2.2 Theoretical Research Perspective

The project is to be conducted within a pragmatist philosophical framework that orients itself towards solving practical problems in the “real world” i.e. how to design PBSA that are both low-energy, whilst remaining comfortable all year round (Robson, 2002; Feilzer, 2010; Creswell and Clark, 2007). It accepts that there are different elements of layers with the experiential world in buildings, some of which are objective (e.g. the internal air temperature), some subjective (e.g. an occupant’s thermal comfort), and some a mixture of the two (e.g. the overall assessment of overheating).

3.2.3 Mixed Methods

The way energy is used and the environmental conditions within PBSA are affected by a combination of physical elements (e.g. the efficiency of the heating systems and the building’s fabric) and social elements (e.g. comfort preferences, and the occupant’s understanding of how to operate the building). Therefore, the assessment of IEQ in PBSA is best achieved by collecting physical quantitative data in order to understand what occurred (e.g. the bedroom maintained an average of 26.5°C for five successive days), alongside qualitative data to investigate why this may have occurred (e.g. that was the occupant’s thermal comfort preference, or alternatively, there was a main hot water storage tank next to the bedroom and despite the occupant’s best efforts they could not lower the temperature). Hence the same quantitative results can have very different meanings once qualitative feedback is also considered.

This is essentially the theory of triangulation; that by combining methods to study a particular phenomenon one can compensate for the weaknesses in each single method by the counter balancing strength of the other (Dilanthi

Amaratunga et al., 2002). Therefore the aim of using mixed methods is to produce a final product which “can highlight the significant contributions of both methods” (Nau, 1995), and where “qualitative data can support explicitly the meaning of quantitative research” (Fossey et al., 2002).

3.2.4 Case Study Approach

This research will use case studies to achieve the research aims identified above. Yin defines a case study as “an empirical enquiry that investigates a contemporary phenomenon (the ‘case’) in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident”. (Yin, 2003).

3.2.4.1 Why Case Studies?

As highlighted above the IEQ conditions within a building depend upon (at least) the fabric, the HVAC systems, the location, the weather, the occupants, and critically, how all these factors interact. This can make it problematic to use conventional research methods from the physical sciences to study the internal conditions within occupied buildings. Investigations that attempt to control all the variables are likely to be impractical, and may overlook important factors that affect how the building is operating, such as the people within them (Oreszczyn and Lowe, 2010). Furthermore, the purpose of POE is to investigate real building performance, and thus it should be placed and understood within “real-life” context.

It is also important to acknowledge the potential weaknesses of using case studies. Firstly, it is very difficult to generalize from case studies i.e. issues found in one PBSA may not affect others. This limitation has been partly addressed through the literature review which has identified that new PBSA do tend to have relatively homogeneous designs. In addition, the primary motivation of the study is not to produce generalizable outcomes, but rather to generate “purely descriptive, phenomenological case studies” (Yin, 2003) that give an insight into thermal and IAQ control in new PBSA.

It has also been argued that case studies are particularly prone to bias, which may affect the form of data collection, or the way the data is interpreted. Yet, as argued previously by Flyvbjerg, providing that robust methods are employed there is nothing inherently biased about using case studies (Flyvbjerg, 2006).

While it may be possible to evaluate building performance using generalistic approaches, for example by surveying industry professionals, or investigating a few specific factors across a number of buildings, these approaches are likely to lack the depth, context and understanding possible in case studies (Turpin-Brooks and Viccars, 2006). Indeed, according to Leaman there is "nothing better than a vivid case study to communicate lessons learned and underwrite decision-making" in buildings (Leaman et al., 2010). Similarly many others have endorsed the approach as an effective tool for investigating building performance in practice, see for instance (Preiser and Vischer, 2005; Hadjri and Crozier, 2009; Hiromoto, 2015).

3.2.4.2 Case Study Selection

Ideally, the selection of case studies would be entirely strategic in order to obtain the "greatest possible amount of information on a given problem or phenomenon" (Flyvbjerg, 2006). Thus case studies may be selected either because they are typical or representative, or alternatively because they are atypical or extreme cases that can reveal "more information because they activate more actors and more basic mechanisms in the situation studied" (Flyvbjerg, 2006). However, practical research constraints are also somewhat inevitable, particularly in the study of occupied buildings in which ethical concerns, access and cost will restrict what is feasible. Furthermore, the depth of the investigation required to produce an effective case study limits the total number that can be pursued.

This research has incorporated two approaches to the selection of case studies for the monitoring over the 2017/18 academic year. One PBSA has been selected because it is an extreme case. It is a dense, high-rise PBSA, located in central London, with year-long lettings (see Section 3.3 for details). This was selected due to the likelihood of encountering overheating conditions, which presented the opportunity for feedback and observing the adaptive behaviours of PBSA occupants.

The other PBSA has been selected primarily because it has been built by the researcher's industrial sponsor; in return for research funding there is an agreement that the industrial sponsor's buildings will be evaluated. This set-up has many advantages, as it provides the researcher with unique access to the buildings, the necessary documentation to review, and critically, the personnel who are engaged in designing, constructing and operating the buildings. This is likely to make the feed-forward process of the POE more targeted and increase the impact of the research (see Section 7.3.1). This PBSA also has some interesting differences from the first case study in that it is medium-rise, and located in a lower-density suburban area.

Now that the research questions and methodology have been outlined the next section will describe the case studies in detail. Following this will be a section describing the data collection and analysis methods.

3.3 The Case Studies

This sections describes the case studies investigated in this thesis. It is focused on the thermal and ventilation control characteristics.

3.3.1 Case Study A

Case Study A (CSA) was completed in 2013, and is located in the London [redacted] The building has 12 storeys, spread across two main blocks, which are orientated around a central courtyard See Figure 3.3). The front of the building faces out onto [redacted] road, whilst the rear faces over the main train lines [redacted] It is primarily for post-graduate students and therefore offers year long tenancies.

[redacted]

Figure 3.1: External View

[redacted]

Figure 3.2: Satellite View

CONTENT REDACTED

[redacted]

Figure 3.3: Floor Plan

3.3.1.1 PBSA Layout

The building is subdivided into two main blocks, which are split into the spaces shown in Table 3.1. The PBSA has a maximum capacity of 378 residents, and is exclusively for post-graduate students studying at [redacted]

Area Use	**No. of Units**	**Area (m^2)**
Studio units	83	
Cluster units	295	
Retail		674
Common room		137
Offices		589

Table 3.1: CSA Schedule of Areas

3.3.1.2 Energy Efficiency Characteristics

The fabric details are displayed in Table 3.2. The air-permeability results from a selection of studio rooms that were tested are also included in Table 3.3. The building is also certified as Building Research Establishment Environmental Assessment Method (BREEAM)[1] "excellent".

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[1] BREEAM (Building Research Establishment Environmental Assessment Method) is a sustainability assessment method that is used to masterplan projects, infrastructure and buildings. Launched in 1990, by the Building Research Establishment (Building Research

Construction Type	Description	Area weighted average U-value (W/m^2K)
Ground floor	Insulated floor	0.22
Internal ceiling	Carpeted reinforced concrete ceiling	2.28
Internal partitions	Stud walls	1.99
External walls	Lightweight curtain walls	0.2
External glazing	Double glazed tophung	1.5

Table 3.2: CSA Construction Information

Room	Air Permeability at 50Pa ($m^3/h.m^2$)
[redacted]	4.4
[redacted]	3.6
[redacted]	4.3
[redacted]	4.2
[redacted]	3.7

Table 3.3: CSA Air Permeability Certificates

3.3.1.3 Building Services

Space Heating

The Low Temperature Hot Water (LTHW) is generated centrally using one gas fired CHP unit, connected in parallel with three gas fired condensing boilers, in conjunction with 1200 litres of thermal storage. The CHP and boiler flues rise all the way through the building and discharge at roof level.

The LTHW system serves the radiator heating system throughout the student accommodation areas and the associated common rooms and reception offices. The LTHW temperature to these radiators is controlled based on the external temperature (weather compensation) and the internal temperature sensors (overheat and fabric protection). Each radiator is

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Establishment (BRE)) it sets standards for the environmental performance of buildings through the design, specification, construction and operation phases and can be applied to new developments or refurbishment schemes individually controlled by use of a TRV to control the comfort level in each room. These are preset and locked at approximately 20°C. The occupant does have the ability to adjust the TRV by 3°C using a coin, but not to switch off the radiator entirely (the specifics of the control system is also covered in the Section 4.3.1.4 of the results.

Ventilation

The cluster block kitchens contain a MVHR unit, which provides supply air and extraction to each of the rooms and to the kitchen. The units run continuously at minimum ventilation rate and are switched into boost mode by the following actions; switching on the light switch in any of the shower rooms or switching on any cooker hob in the kitchen. The studios are ventilated by an individual MVHR unit which provides supply air to the bedroom, and extraction from both the shower room and bedroom. These run continuously at minimum ventilation rate, and boost when the shower room light is switched on, or by use of a boost switch in the kitchen area.

Each bedroom also has at least one operable window. All windows in CSA are top-hung, and the openings are restricted to 150mm (the reasons for the restricted openings are discussed in Section 2.4.3.1). The vast majority of the rooms in CSA are single-aspect. However, a few of the bedrooms on the upper floors of block A open out onto a corridor with operable windows (the rest of the corridors have no external openings). Thus in these rooms cross-ventilation can be achieved if the corridor and bedrooms windows are both open.

3.3.2 Case Study B

Case Study B (CSB) was completed in 2017, and is located on the outskirts of [redacted] The site consists of 6 new accommodation blocks (marked in blue in Figure 3.4a), spread out across a semi-urban campus. The accommodation offers 9-month tenancies from late September to late June. A photo of the accommodation blocks has also been included in Figure 3.4b.

The site also consists of 9 existing accommodation blocks (marked in pink in Figure 3.4a). The existing blocks were not investigated as part of the research. There is also a student services building on-site where students can access the customer services that include laundry, gym, faith space, refectory, bar, shop, study suite and a postal delivery point.

[redacted]

(a) CSB Site Plan

(b) CSB Cluster Block Photo

Figure 3.4

3.3.2.1 PBSA Layout

The new accommodation blocks have a maximum capacity of 530 rooms. These are split into the room types shown in Table 3.4.

Area Use	No. of Units
Studio units	60
Cluster units	290
Townhouse units	180

Table 3.4: CSB Room Types

3.3.2.2 Energy Efficiency Characteristics

The fabric details are displayed below in Table 3.2. The air-permeability results from a selection of studio rooms that were tested are also included in Table 3.6 below. The building is also certified as BREEAM “excellent”.

Construction Type (W/m^2K)	**Description**	**Area weighted average U-value (W/m^{2}K)**
Ground floor	Insulated floor	0.2
Internal ceiling	Carpeted reinforced concrete ceiling	1.3
Internal partitions	Stud walls	1.99
External walls	Medium weight curtain walls	0.19
Roof	Light weight	0.16
External glazing	Double glazed top-hung	1.7

Table 3.5: CSB Construction Information

Room	**Air Permeability at 50Pa (m^3/h.m^2)**
[redacted]	4
[redacted]	4

Table 3.6: CSB Air Permeability Certificates

3.3.2.3 Building Services

Space Heating

Space heating is provided by means of LTHW supplying a site wide district heating system. The LTHW is designed to be generated centrally using one gas fired CHP unit, connected in parallel with three gas fired condensing boilers. The CHP unit is configured as priority, with the boilers being a secondary source of heat. The system heats the water to charge thermal stores from which the LTHW is pumped to the residential blocks through flow and return pipework.

The primary heating circuits feed a calorifier on entry to the accommodation blocks (the calorifiers stores water to be used as Domestic Hot Water (DHW)) before connecting to the accommodation block heating circuit through a variable temperature valve. This hot water circuit is used to feed the radiators within the bedrooms, kitchens and general communal areas. Each radiator has been installed with a thermostatic valve that allow for settings from *frost mode* through to 5. In documentation provided to the residents it suggests that Setting 3 will give an internal room temperature between 19-23°C. A schematic of the heating system in the cluster blocks is shown in Figure 3.5.

[redacted]

Figure 3.5: CSB Cluster Block Heating Schematic

The heating was also timed by the BMS. It is on between 6am-8am, 12pm–2pm, and 4.30pm–11:30pm. Outside of these times the heating is off irrespective of the TRV setting unless the outdoor temperature falls below 4°C, then the heating is automatically triggered.

Ventilation

The cluster block bedrooms and studio rooms contain MEV systems that extract vitiated air from the bathroom pods within each cluster block. The twin fans are roof mounted with common duct work routed from the extract areas to the roof fans. However, the townhouse bedrooms are naturally ventilated only, with an MEV system serving the bathroom pods within the town houses. Each bedroom also has at least one operable window. All windows in CSB are top-hung, and the openings are restricted to 150mm. In contrast with CSA they have operable trickle vents.

Now the two case studies have been described the thesis will outline the methods used to answer the research questions.

3.4 Data Collection Methods

The next two sections provide an account of the methods used to achieve the project's aims, and answer the research questions. This section describes the data collection methods, while the second section covers how the collected data will be analysed.

The purpose of this research is to examine the control of the IEQ conditions in occupied PBSA buildings, including the occupant's perspectives on both of these. This requires forming an in-depth understanding of the building and its services, what the conditions were like, how the building was operated, and what the occupant's thought of it. Gaining such an understanding is only possible by using several different methods of data collection.

3.4.1 Document Review

As part of the evaluations it was necessary to undertake a thorough review of the design and as-built documentation. The complete list of documents that were collected for each case study are shown below in Table 3.7. These documents were selected in order to familiarize the researcher with the residences, and to understand the performance objectives for each building, as well as to review the information that was provided to the student occupants.

3.4.2 Study Bedroom Monitoring

This section explains how the indoor conditions and occupant behaviour was monitored in the study bedrooms. It was decided that the monitoring campaign would focus on bedrooms and the circulation areas only (i.e not communal spaces, such as kitchens). This was done for a range of reasons.

Design Stage Documents	Building Regulations UK Part L (BRUKL) Certificate Dynamic simulation modelling or SBEM report Overheating analysis Air permeability tests BREEAM reports
Drawings	BMS Control Strategy Heating schematic Ventilation schematic Mechanical services schematic Window designs Detailed site plan Metering plan Plant room layout
Operational Documents	Site maintenance reports Occupant handbooks Facilities management handbooks student welcome guide

Table 3.7: Review Documents

Firstly, it has been established in previous studies that when in the residences students reported spending the majority of the time in their study bedrooms (Innovate UK, 2013). Secondly, it is where they sleep, and night time temperatures have been highlighted previously as being particularly critical in overheating analysis due to the potential for sleep disruption. Finally, monitoring of the kitchen areas would have required all of the residents within a particular cluster block or townhouse to be willing to participate in the study. This would have made recruitment significantly more challenging.

3.4.2.1 Recruitment, Sensor Installation & Participant Information

The monitoring campaign required participants to be recruited, and the sensing equipment to be installed in their rooms. This section below outlines how this occurred.

Ethical Approval

The recruitment of participants for the investigation required the study to be approved by both the departmental ethics director and University College London (UCL)'s data protection team. The approvals can be found in Section A of the Appendices. Each of the participants was provided with an "participant information sheet", "sensor information sheet", and "consent form" (to be signed by the participants). Examples of all these are all included in Section B the Appendices.

Furthermore, when undertaking POE the researcher has a duty of care to the building occupants. This obligation may entail simply passing on grievances to management, or it could involve more direct interference e.g. making suggestions to occupants to try and help improve certain conditions. In the case of more direct measures, these may influence how occupants use the building, and consequently the researcher is having a direct affect on the investigation.

Nevertheless, if the conditions inside buildings are poor, and the researcher can offer recommendations to improve them, there is a moral imperative to act. Any advice given to the occupants should be clearly noted and considered when analysing the results (see for instance, Section 4.2.3.3 for details on an intervention made on ventilation in certain rooms in this thesis).

Recruitment

Participants were recruited via an email sent to all the residents. Those that were interested were visited and had the study explained in more detail to them. A financial reward of £20 was offered as an incentive for participating in the study.

There were 11 participants in CSA, and 9 at CSB. The number of participants was primarily limited by cost (both for the equipment and the incentives used for recruitment), and also the willingness of occupants to participate in the study. Ideally the monitored rooms would have been selected for the study such that they were both representative of the different areas of the buildings (e.g. room type, orientation and floor level), and of the occupants (e.g. different ages, genders, nationalities). In the end monitoring equipment was installed in every occupant's bedroom that agreed to participate.

Sensor Installation

The aim of the study was to monitor the conditions over a full year in order to gain a comprehensive understanding of how the PBSA performed, and were controlled, under a variety of seasonal conditions. There was also a particular emphasis on ensuring that monitoring occurred during warm weather conditions, due to the fact that overheating had been cited as a significant concern in these building types (see Section 2.5.4.5).

The new students moved into their respective residences in the middle of September 2017, and recruitment commenced two weeks after this date. Monitoring equipment was installed in CSA towards the end of October 2017, and removed at the end of August 2018. In CSB the monitoring occurred between the beginning of November 2017 and the end of June 2018. The monitoring period ended earlier in CSB as students are not in the residences over the summer period.

However, the participants left the accommodation at slightly different times towards the end of the monitoring period. After which, upon request of the FM team, the monitoring equipment was removed from their room. The exact dates and the duration of the monitoring period for each of the study bedrooms can be found in the Appendices in Sections C.1 (CSA) and C.2 (CSB).

Participants

Basic information was collected from each participant on their age, gender, nationality, and previous living arrangements. In CSA there were 6 female and 5 male participants, while in CSB the split was 6 females to 3 males. The study participants were all between the ages of 18-30. The participants in CSA were all international students bar one, whereas all but one of the CSB participants was a British national.

As discussed in Section 2.2, preferences for indoor environmental conditions can be affected by gender, nationality and multiple other factors. However, in this case the sample of participants was not large enough to investigate these factors or draw valid conclusions. Indeed, this is not the purpose of the participant feedback aspect to this research. This is done to allow more extensive perceptions to be gathered from a subset of the residents in both case studies regarding their thoughts on PBSA comfort and controls, which is an area that has been lacking from previous PBSA monitoring studies (see Section 2.5.4).

Furthermore, the qualitative data gathered from a small sample of participants forms only one part of the evidence to assess the PBSA conditions in practice. The other evidence sources include the monitoring of IEQ conditions and occupant behaviour (see Section 3.4.2.4), alongside the building wide surveys (see Section 3.4.4). All together these multiple sources of evidence aim to provide a comprehensive evaluation of both the conditions and the occupant's agency over the conditions in the respective case studies.

3.4.2.2 Monitored Rooms

The basic characteristics of each room are displayed below in Table 3.8. Diagrams of a sample of the rooms (including the location of the monitoring equipment) are shown below in Section 3.4.2.6. In Table 3.8 "CB" is an ensuite clusterblock bedroom and "TH" is a non-ensuite townhouse bedroom.

As Table 3.8 shows there is a mix of different room types in both case studies. CSB also has a reasonable range of different room orientations, including three rooms that are dual-aspect. However, the sample in CSA was heavily weighted towards rooms that faced NWW and NNW. As such, the majority of the rooms looked over the rail line that leads into [redacted] (see Section 3.3.1), while far fewer rooms faced either the courtyard or onto the [redacted]

Code	Floor	Room Type	Orientation
A1	5	CB	E
A2	5	CB	NWW
A3	1	STUDIO	NWW
A4	1	STUDIO	NWW
A5	2	STUDIO	SEE
A6	G	STUDIO	NWW
A7	3	CB	NWW
A8	3	CB	NWW
A9	6	CB	NWW
A10	7	CB	NNW
A11	4	CB	NWW
B1	1	TH	S & W
B2	2	TH	S & W
B3	2	TH	W
B4	3	TH	E
B5	3	TH	S & W
B6	1	CB	S
B7	1	CB	E
B8	2	STUDIO	W
B9	2	STUDIO	E

Table 3.8: Room Information

3.4.2.3 What Data to Collect?

There are two different sets of empirical data that had to be collected in order to address the research questions. Firstly, data must be collected to evaluate the indoor conditions within the bedrooms. This required collecting data to assess both the thermal conditions in the rooms, and also the IAQ (and hence investigate the adequacy of the ventilation).

The second set of data was to understand what actions the occupants took to effect the environmental conditions within their bedrooms. The primary means the occupants have in PBSA to control the indoor conditions within their rooms are how they operate their heating system, and their window. It is possible the occupants could also use other mechanisms to alter the internal conditions in their room, such as secondary heating systems, humidifiers, fans. It was not deemed feasible to monitor these practices and so these were covered during the interviews. Another method the occupants have for controlling the thermal conditions within their room is how they operate their blinds (i.e. control of solar gains). Again, it was not considered practically feasible to monitor blind use so this was also covered during the interviews.

3.4.2.4 IEQ Monitoring

Monitoring of the Thermal Conditions

As covered in the literature review in Section 2.2.1, an occupant's thermal comfort will depend upon several environmental parameters (e.g. air temperature ($\boldsymbol{T_a}$), radiant temperature ($\boldsymbol{T_r}$), humidity and air movement). It also depends on their clothing, activity levels and the degree of agency they have over the conditions (i.e. can they undertake effective adaptations).

However, it is practically very difficult to measure Mean Radiant Temperature (MRT), or air movement inside occupied buildings (Lomas et al., 2018a). Similarly, it was considered most practical to collect data on the occupant's typical activities and clothing during the interviews. Therefore (as is typical in monitoring studies) the thermal conditions within the room were monitored using wall-mounted HOBO temperature loggers (see device specification included in Table 3.9). These store the data internally, and need to be collected before the data can be downloaded.

The sampling frequency was set to 10-minute. This is higher than many other indoor temperature monitoring studies cited in this thesis e.g. (Pathan et al., 2017; Beizaee et al., 2013). A higher sampling frequency was chosen because, as well as assessing the long-term conditions experienced by the PBSA occupants throughout their stay, the study also wanted to focus on shorter time periods. This was done to analyse the effect that occupant actions had on the indoor conditions e.g. the change in internal temperature when a window is opened. As the sensor has a response time of 6 minutes (see Table 3.9 below) it was judged that the 10-minute resolution would be sufficient to monitor these affects.

The HOBOs were used to record air temperature ($\boldsymbol{T_a}$) and relative

Characteristics	**HOBO Temperature Sensor**
Measurement Range	Dry-bulb temperature: -20 ∼ 70°C
Measurement Accuracy	± 0.35°C
Resolution	0.03°C
Response Time	6 minutes

Table 3.9: HOBO Temperature Sensor Characteristics

humidity (RH). The characteristics of the RH sensor are listed below in Table 3.10. In reality, the sensors are likely to be recording some (undefined) mix of $\boldsymbol{T_a}$, radiant temperature ($\boldsymbol{T_r}$) and, potentially, a component of surface temperature ($\boldsymbol{T_s}$) i.e. from conduction through the mounting surface. How this temperature was converted into operative temperature ($\boldsymbol{T_{op}}$) (the parameter typically used in thermal comfort evaluations) is covered in Section 3.5.5.1 below.

Characteristics	**HOBO RH Sensor**
Measurement Range	1% to 90%, non-condensing
Measurement Accuracy	± 2.0% from 20% RH to 80% RH; below 20% RH and above 80% RH ± 6%
Resolution	0.01%
Response Time	6 minutes

Table 3.10: HOBO RH Sensor Characteristics

HOBOs were positioned on the wall in the centre of the bedroom, and also in the locations in which the occupants are likely to be spending the majority of their time when in their room (e.g. the bed and desk areas). As far as was practically possible, they were placed in positions away from direct sources of heat or sunlight. An example of the sensor placement for a typical room is shown in Section 3.4.2.6 below.

Multiple sensors were employed in order to better understand whether there was significant temperature variation within the studybedrooms (something which had not been considered in previous PBSA monitoring studies). The temperature in the corridors outside of the studybedrooms was also monitored to obtain an understanding of the thermal conditions in the circulation spaces, as well as investigating the potential heat flows paths within the accommodation. In addition the temperature in certain bathrooms, and some of the staircases was monitored. For a complete list of every sensor used in the study please refer to Tables C.3 (CSA) and C.4 (CSB) in the Appendices.

IAQ & Ventilation

As discussed in the literature review, the IAQ analysis in this study was limited to collection of CO_2 and RH data. The CO_2 concentration was monitored using an iBEM B3 device. This is an integrated environmental quality sensor developed by Tsinghua University. The iBEM B3 contains an "Senseair S8 Residential" Non-Dispersive Infrared (NDIR) CO_2 sensor (Senseair, 2019). The CO_2 sensor's specifications are included in Table 3.11.

Characteristics	**iBEM CO_2 Sensor**
Measurement Range	350 - 5000PPM
Operating Temperature	0 - 50°C
Measurement Accuracy	$\pm\,(70PPM \pm 5\%)$
Resolution	1PPM
Response Time	2 minutes

Table 3.11: iBEM CO_2 Sensor Parameters

The devices require mains power and need to be connected to a WiFi network. There is no on board storage, and so all the data was uploaded onto a server where it could be accessed via a password protected website. The sampling frequency was every 1-minute.

Where possible, the CO_2 sensor should be positioned so that it is representative of the average conditions in the room. This will depend upon how well-mixed the air in the room is, and also the ventilation pathways within the room. However, the placement of this sensor was also influenced by practical research constraints, such as the the location of plug sockets within the room, and the requirement to minimize disruption for the occupants. An example of the location of CO_2 sensors in typical rooms from each site can be found below in Section 3.4.2.6.

3.4.2.5 Occupant Control Monitoring

There were two occupancy control parameters that were measured through physical monitoring. This was the activity of the heat emitter (radiator), and window opening.

Radiator Surface Temperature Monitoring

HOBO temperature sensing devices (specification included in Table 3.9) were magnetically attached to radiators in the participant's bedrooms. These were used to infer space heating patterns. They could not quantify the actual radiator temperature, or the amount of energy used. This method was selected because it would have been disruptive and expensive to meter the flow of heat into the radiators in individual bedrooms. This method has also been shown to provide usable data in previous studies that have investigated occupants control of heating, see for instance (Love, 2014; Martin and Martin, 2006; Quigley, 2016).

All the devices were placed by the hot water inlet on the radiators, as shown in Figure 3.6a below. The devices were set to launch at the time of installation, and to log every 10-minutes. In three of the rooms in CSA the radiators were housed within additional casings (as shown below in Figure 3.6b). In this case the HOBO could not be placed directly on the radiator, which had an effect on the strength of the signal.

(a) Typical radiator **(b)** Radiator with casing

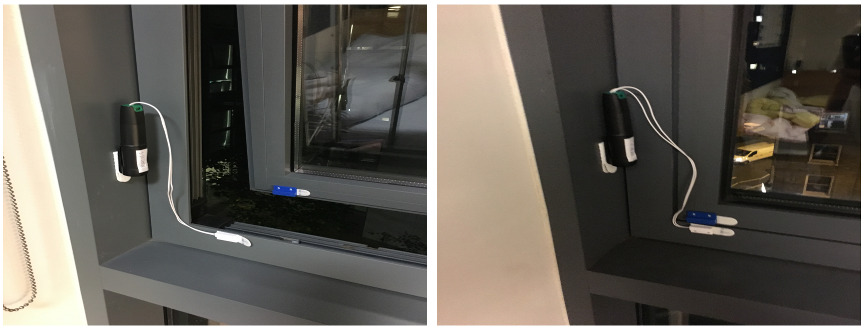
Figure 3.6: Monitoring of Radiators

Window Opening Monitoring

Window opening was monitored using state loggers (device specification included below in Table 3.12). Magnets were situated on the window and the frame as shown in Figure 3.7. These are binary devices, recording only the time at which the window is opened or closed, but not the degree to which the window is open.

Specifications	**Value**	**Units**
Time between events	200	ms
Time between state changes	500	ms
Time between event counts	50	ms
Timing accuracy	3	secs per 24hr
Operating temperature range	-35 to 80	°C
Typical Battery Life	1	year

Table 3.12: Window opening state logger parameters



(a) Open Window **(b)** Closed Window

Figure 3.7: Window opening monitoring device

From personal experience at CSA, it is difficult to part open the windows. The windows tend to revert to either being fully open or shut (i.e. they are bi-stable). At the CSB site, the windows could be placed on a partially open catch, which would record as open on the device. On this setting the window is only partially open (40mm), rather than the maximum opening width of 150mm. Thus it was not possible using this monitoring system to know whether the window was fully, or partially open. This is a clear limitation of the window monitoring. One of the methods of dealing with this limitation is the collection of qualitative data to ascertain how the occupant reported using their window.

3.4.2.6 Studybedroom Monitoring Diagram

The complete set-up in an example room from CSA and CSB are shown below in Figures 3.8 and 3.9 respectively.

[redacted]

Figure 3.8: CSA Example Sensor Placement - Room A2

[redacted]

Figure 3.9: CSB Example Sensor Placement - Room B5

3.4.3 Weather Data

Weather conditions have a significant impact upon the thermal conditions within buildings. In particular the external air temperature, but also solar radiation, wind speed and direction. These data sets were gathered by a combination of on-site measurements, and data collected from local met office stations.

3.4.3.1 Case Study A Weather Data

At CSA the external temperature was recorded using the site's temperature logging device which is connected to the BMS, and is situated in the courtyard. The data was checked against external temperature data downloaded from three additional weather stations. These were located at [redacted] (see Figure 3.10). These were selected as they were the three closest weather stations for which hourly temperature data could be accessed. As can be seen in Table 3.13, with the exception of [redacted] the amount of missing data was minimal.

Station Name	**Distance from Site (km)**	**Missing Data (%)**
[redacted]	4	0.04
[redacted]	5	0.07
[redacted]	0	0.32
[redacted]	2	12.47

Table 3.13: Case Study A Weather Station Information

3.4.3.2 Case Study B Weather Data

At CSB the plan was to make use of the BMS external temperature sensor. However, there was a logging issue with the BMS that was only shared with the researcher at the end of the study, meaning that only monthly statistical data was provided. Therefore at CSB the external temperature data is entirely reliant on weather stations. Nevertheless, the met office weather stations were still compared against the on-site monthly statistical data (see Section 3.5.3).

[redacted]

Figure 3.10: Case Study A Weather Station Map

Station Name	Distance from Site (km)	Missing Data (%)
[redacted]	21	0.07
[redacted]	36	0.24
[redacted]	8	0.05

Table 3.14: Case Study B Weather Station Information

[redacted]

Figure 3.11: Case Study B Weather Station Map

3.4.4 Occupant Interviews

Interviews were used to help understand the participant's perspective on the internal conditions and their behaviour. Semi-structured interview guides were drafted with the help of social scientists within UCL. These were produced to allow questions and prompts to be prepared ahead of time so that all the key content was covered.

A semi-structured approach was selected to provide "reliable, comparable qualitative data", whilst allowing the participants the freedom to "express their views in their own terms" (Barriball and While, 1994). They also allow for "probing", which can provide for "clarification of interesting and relevant issues raised by the respondents" (Barriball and While, 1994). It was felt that fully structured interviews would be too restrictive, and limit the richness of the interview data.

The occupants were interviewed three times during the study; at initial installation (Oct-Nov), in Winter (February) and in Summer (June-July). The interviews tended to last between 10-20 minutes (depending on how much detail the participant wanted to add). The date, time and duration of each interview is included in the Appendices in Table D.1 and D.2 for CSA and CSB respectively. A summary of the main points covered in each of the interviews is included below:

Interview 1

1. Basic personal details e.g. age, gender, nationality and previous living arrangements
2. General views on the accommodation
3. Thermal comfort perspectives
4. Air quality perspectives
5. Occupancy patterns

Interview 2

1. Completion of occupancy diaries
2. Winter thermal comfort perspectives
3. Winter air quality perspectives
4. Discussion of monitored data in winter
5. Winter occupant behaviour questions

Interview 3

1. Discussion of occupancy (has it changed from winter)
2. Summer thermal comfort perspectives
3. Summer air quality perspectives

4. Discussion of monitored data in summer
5. Summer occupant behaviour questions
6. Date at which occupant plans to move out

Each interview was recorded, and then the audio was transcribed, and documented using the NVivo qualitative analysis software package. The findings from each set of interviews were discussed with the supervisory team, and partly used to help inform the question guides for the next set of interviews.

3.4.4.1 Occupancy Diaries

As part of the second interview, participants were asked to complete occupant activity diaries. The participants were made aware that this would occur the week before the interview was scheduled to take place. This was done to prompt them to make a note of their activities, and also when they were in or out of their bedroom over the proceeding week.

The purpose of asking the occupants to fill out occupancy diaries was twofold. Firstly, to get a better understanding of the participants occupancy patterns. Secondly, to jog the participants memory so that when the discussion of internal conditions occurred (see Section 3.4.4.2) they would already be starting to think about the previous week. The occupancy diaries were completed in interviews 2 and 3. An example of the occupancy diaries from each case study is included in the Appendices in Section D.

3.4.4.2 Discussion of monitored data

In interviews 2 & 3 time series graphs of the temperature and CO_2 data over the proceeding week was discussed with the participants. This was done to better understand the opinions of the occupants towards the recorded conditions in their rooms, as well as the potential reasons certain conditions may have arisen. This was done to enhance the sociotechnical element of this research, and was partly informed by limitations identified in previous studies with regard to sociotechnical data collection and analysis; see for instance (Love and Cooper, 2015).

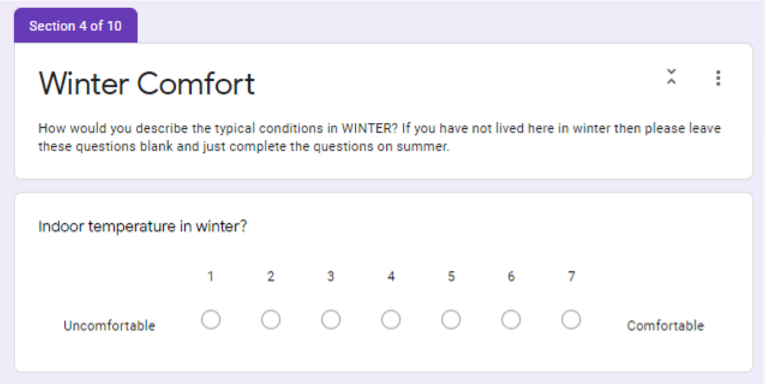
3.4.5 FM Interviews

After the monitoring was completed an interview was arranged with the FM personnel at each case study. Some of the preliminary results were discussed, and any clarifications regarding operation of the PBSA were sought (e.g. heater timing schedules). The FM personnel were also given the opportunity to opine on what they thought were the key performance issues in their respective PBSA. Unfortunately in CSA the lead FM had recently been replaced and therefore the interviewee was still relatively new to the site. This limited their ability to discuss operational issues noted over the previous year of monitoring.

3.4.6 Building Surveys

The building occupants were also surveyed using an adapted version of the Building Use Studies (BUS) survey (BUSMethodology, 2017). The BUS methodology is a well established, simple and standardised questionnaire to benchmark levels of occupant satisfaction within buildings.

The questionnaire focused on thermal comfort, IAQ, occupant control and adaptation. It consisted of 26 questions with 7-point Likert scale answers, and 6 spaces for comments on specific areas e.g. comments on personal control. An example question, along with possible answers is shown below in Figure 3.12. The complete set of summary statistics for the survey data is also available in the Appendices for CSA (Appendix E.1) and CSB (Appendix E.2).



Winter Comfort

How would you describe the typical conditions in WINTER? If you have not lived here in winter then please leave these questions blank and just complete the questions on summer.

Indoor temperature in winter?

	1	2	3	4	5	6	7	
Uncomfortable	○	○	○	○	○	○	○	Comfortable

Figure 3.12: Example BUS survey question for winter comfort

The surveys were administered by a link in an email a month before the end of the letting period, and were then left open until the end of the letting period. Participation was incentivised through a raffle draw to win vouchers. All the study participants also completed the surveys to help understand how representative the participants views were of the wider population. The details of the survey timing and response rates are displayed below in Table 3.15.

	Date Opened	Date Ended	Responses	Response Rate
CSA	15/08/18	31/08/18	74	20%
CSB	05/06/18	20/06/18	151	26%

Table 3.15: BUS Occupant Survey Details

3.4.7 Photography and Thermal Imaging

During each of the interviews photographs were used to record the positions of the monitoring equipment, along with the layouts of the participant's rooms. Additional photos were taken if something of interest was noted (e.g. an occupant positioning a fan by their bed). Thermal imaging was also used to better understand the location of heat sources, and heat flows within the buildings. This proved to be particularly valuable for understanding heat sources in the corridors.

3.5 Data Analysis Methods

The section below describes how the the collected data was analysed in order to answer the research questions.

3.5.1 Survey Data

The survey data was analysed by recording the percentage of response's for each score within a given question, and also by calculating the mean score for each question. The participant's responses were also separated from the wider building population. The comments on individual questions were grouped together into themes (e.g. positive or negative, too hot or too cold). The complete set of summary statistics for the survey data is also available in the Appendices for CSA (Appendix E.1) and CSB (Appendix E.2).

3.5.2 Interview Data

The qualitative data was analyzed in two ways. The first method was to use content analysis (Elo and Kyngas, 2008); whereby the frequency of concepts, behaviours and words were recorded, and collected into particular themes (or codes). This was done to provide a summary of the participant's views on particular factors.

The second method was sociotechnical analysis. In this case the qualitative data was examined alongside the physical monitored data. This checked for any similarities and differences between the data sets (e.g an occupant reporting rarely using their window, but the data suggesting it was frequently opened), and also investigated whether the qualitative data could explain certain physical findings (e.g the room was kept at 24°C because the occupant reported liking to wear light clothing when in residence). However, it was important to remain prescient to the risks of confirmation bias, and the potential for false positives when undertaking this type of analysis.

It is also important to acknowledge that it is simply not possible to eliminate subjectivity from the analysis of qualitative data. Thus demonstration of the processes for reaching conclusions must be suitably transparent. For example, it should be noted why certain quotes were selected regarding a particular point of interest (e.g. they were representative of many participants).

3.5.3 Weather Data

The different weather stations were compared against one another. This included visual comparison of the timeseries data, alongside statistical comparisons of daily averages, averages at particular times of day, as well as daily maximum and minimum temperatures. There were several important takeaways from the analysis.

The first is that the on-site sensor at CSA showed considerably less diurnal variation than the other [redacted] weather stations i.e. the night-time lows were warmer, whilst the day time peaks were cooler. This was considered to be likely due to the effect of the buildings thermal mass at night (retaining and releasing the daytime heat), alongside the permanently shaded courtyard reducing day time peaks.

However, the exact location and specification of the BMS temperature sensor at CSA was never provided despite repeated requests of the FM team. In the end it was decided that the closest weather station [redacted] would be the primary data source for the analysis, as the accuracy of the on-site temperature sensor could not be validated.

In the case of CSB the closest weather station was the most consistent with the monthly on site temperature measurements provided by CSB's FM team. Therefore this weather station [redacted] was used for the analysis.

3.5.3.1 Running Mean Temperature

The assessment of overheating using adaptive methods requires the use of the exponentially weighted running mean temperature ($\boldsymbol{T_{rm}}$). $\boldsymbol{T_{rm}}$ is calculated according to Equation 3.1 below.

$$T_{rm} = (1-\alpha)(T_{ed-1} + \alpha T_{ed-2} + \alpha^2 T^{ed-3}.....) \tag{3.1}$$

$\boldsymbol{T_{rm}}$ = exponentially weighted mean of the daily mean external temperature (°C); $\boldsymbol{\alpha}$ = a constant between 0 and 1 which governs how the running mean temperature responds to the daily mean external temperature (where 0.8 is the recommended value (CIBSE, 2008)); $\boldsymbol{T_{ed}}$ = mean daily external temperature (°C).

3.5.4 Data Quality

An initial check of the data to highlight any periods in which the devices were not monitoring was made. There were a number of important points to note.

There was no data loss from any of the HOBO temperature monitoring devices. There was occasional missing data for the iBEMs (CO_2 data). This was distributed randomly throughout the monitoring period, and was presumed to be the result of occupants switching off the monitoring devices and/or the wireless signal dropping out. In none of the rooms did this exceed 5% of the monitoring period. However, in one room (B9) the CO_2 sensor in the iBEM failed completely, and so no CO_2 data was recorded for this room. There was one room in CSB (B1) in which the one of window monitoring devices recorded no data for a 4-month period. All other devices appeared to function correctly.

Next a preliminary assessment of the monitored temperatures was completed to check for erroneous readings (e.g. unrealistically high or low temperature readings, or sudden rapid changes in temperature). This did not show any obviously erroneous temperature readings. Although readings were high at times, they were never exceptionally high. For instance, the maximum recorded bedroom temperature was 33°C, which was consistent with other PBSA monitoring studies (Quigley, 2016). Furthermore, no rapid spikes in temperature were observed.

In addition all the devices were calibrated against one another at the start and end of the monitoring process. During these investigations all devices were shown to be within the measurement accuracy range of each other. However, it is important to note that the devices were not calibrated using another additional "truth" device. Thus it is possible that all of the devices could have been "out" i.e. all reading too high or low.

3.5.5 Thermal Comfort

In this study three HOBOs were placed in each of the participants bedrooms (see Figures 3.8 and 3.9 above). Thus when using one indoor temperature or humidity value per room (e.g. for average daily temperatures), this was actually an average of the three sensors placed in each room. The average of the sensors was made at every time-step.

In this study air temperature ($\boldsymbol{T_a}$) and relative humidity (RH) were used to assess the thermal conditions within the PBSA case studies. However, the room operative temperature (**T_{op}**) is the typical metric used in thermal comfort standards (CEN, 2007). The equation for estimating **T_{op}** based on **T_a**, **T_r** and air velocity (**V_a**) is shown below.

$$T_{op} = T_r + \frac{(T_a\sqrt{10V_a})}{1 + \sqrt{10V_a}} \tag{3.2}$$

T_{op} = indoor operative temperature (°C); **T_a** = indoor air temperature (°C); **T_r** = mean radiant temperature (°C); **V_a** = is the indoor air velocity (m/s).

Both of the PBSA case studies under investigation in this thesis were well-insulated (see Sections 3.3.1.2 and 3.3.2.2). The monitoring devices were positioned away from direct radiation from the sun or from other high temperature radiant sources, and the window openings were restricted. Therefore a number of assumptions were made about the internal conditions. The same assumptions have been used in many previous overheating studies in occupied buildings e.g. (Lomas and Giridharan, 2012; Quigley, 2016).

1. The indoor air velocity is likely to be below 0.1 m/s
2. The difference between **T_a** and **T_r** is likely to be small

Under these assumptions it can be postulated that **T_a** is approximately equal to the **T_r**, and therefore that both are approximately equal to the room operative temperature **T_{op}** as shown in Equation 3.3 below.

$$T_a \approx T_r \approx T_{op} \tag{3.3}$$

3.5.5.1 Analysis of Indoor Temperatures

There are several different parameters that should be assessed to obtain a comprehensive understanding of the thermal conditions within the participant's bedrooms. These are shown below:

1. What were the average conditions like in the room over differing periods (e.g. the whole monitoring period, seasons, weeks, months and days)?
2. What was the distribution of temperatures in the room i.e. what proportion of time did the room spend within difference temperature bands?
3. How stable was the temperature in the room?
4. How much did the temperature vary within different areas of individual rooms?
5. How much does temperature vary between different areas of the building e.g. study bedrooms, circulation areas and bathrooms?
6. What is the “feels like” temperature?

The first five of these require minimal pre-processing of the data, and rely solely on statistical analysis techniques. However, the calculation of the “feels like” temperature, and its representation on a pyschometric chart, does require some pre-processing of the data to be undertaken. This is described below.

The “feels like” Temperature

The “feels like” temperature includes humidity to better assess how the human body actually experiences or “feels” temperature. It has been calculated to examine whether the conditions within the rooms are falling with the “comfort zone” (as covered in Section 2.2.1.1).

In order plot psychometric charts the specific humidity ($\boldsymbol{q}$) must be calculated from the relative humidity (RH). The first step in doing this is to calculate the dew point temperature ($\boldsymbol{T_{dp}}$) using Equation 3.4 (Lawrence, 2005).

$$T_{dp} = \frac{B_1[ln(\frac{RH}{100}) + \frac{A_1 T_a}{B_1+T_a}]}{A_1 - ln(\frac{RH}{100}) - \frac{A_1 T_a}{B_1+T_a}} \tag{3.4}$$

A_1 and B_1 = constants with the recommended values of 7.625 and 243.04°C respectively (Alduchov and Eskridge, 1996); RH = relative humidity (%); $\boldsymbol{T_{dp}}$ = The dew point temperature (°C); $\boldsymbol{T_a}$ = The air temperature (°C).

Once $\boldsymbol{T_{dp}}$ is calculated, the vapour pressure $\boldsymbol{e}$ can be calculated using Equation 3.5 (Bolton, 1980).

$$e = 6.112 \times \frac{17.67 \times T_{dp}}{T_{dp} + 243.5}; \tag{3.5}$$

$\boldsymbol{e}$ = vapour pressure (Pa); $\boldsymbol{T_{dp}}$ = the dew-point temperature (°C).

Once $\boldsymbol{e}$ is calculated, the specific humidity ($\boldsymbol{q}$) - also sometimes referred to as the humidity ratio or moisture content - is then calculated using Equation 3.6.

$$q = \frac{0.622 \times e}{p - (0.0378 \times e)} \tag{3.6}$$

$\boldsymbol{q}$ = specific humidity (g/kg); $\boldsymbol{e}$ = vapour pressure (Pa); $\boldsymbol{p}$ = surface pressure (Pa).

The specific humidity (or moisture content) can then be plotted on the vertical axis, with dry bulb or air temperature on the horizontal axis (see example pyschometric chart below in Figure 3.13). The final component to add is the relative humidity saturation curves. To plot these the saturation pressure of water was obtained from *Lange's Handbook of Chemistry* (Dean and Lange, 1934).

3.5.5.2 Overheating

Overheating was assessed in the buildings using the CIBSE Guide A Static criteria (CIBSE, 2006), alongside the British Standard (BS) and European Standard (EN) 15251 adaptive criteria CEN (2007). The strength and drawbacks of each approach were explored in the literature review in Section 2.2.2.3. The decision to apply both techniques was done for comparative

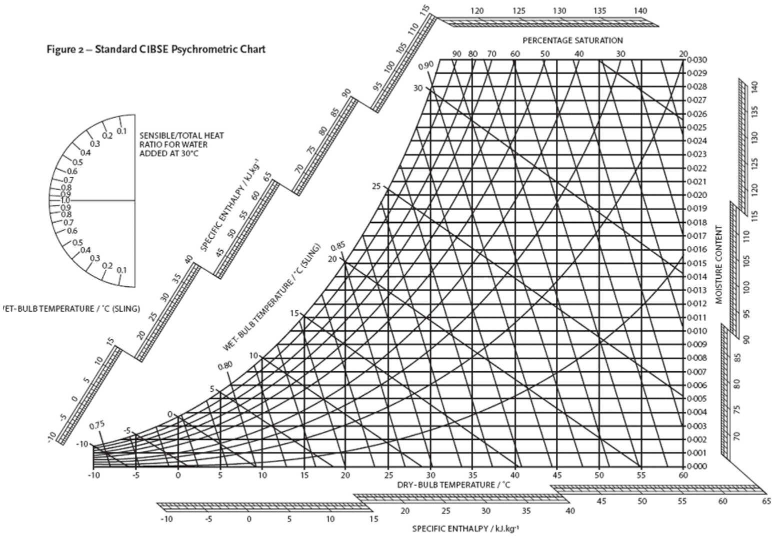


Figure 3.13: Example Standard CIBSE Pyschometric Chart (Legg, 2009)

purposes with other studies, and to allow for the strengths of each analysis technique in the overall evaluation of overheating.

Static criteria

The mean hourly internal temperature data was used to calculate the number of exceedances using the criteria shown below in Table 3.16. Bedrooms in PBSA could be (and were) occupied at any point in the day, and therefore it seems reasonable to suggest that overheating should also be avoided at all times of day. However, night time temperatures were also of particular interest in this study. Therefore the assessment was undertaken assuming both standard occupancy hours (see Table 3.16 below), and that the rooms were occupied continuously.

	Standard Occupancy Hours	Overheating criteria
Bedroom	23:00 - 07:00	1% of occupied hours above 26°C 5% of occupied hours above 24°C

Table 3.16: CIBSE Guide A Static Overheating Criteria

Adaptive criteria

Overheating was also assessed using adaptive methods. These purport that the comfort temperature inside buildings is related to the outdoor air temperature. These methods use the exponentially weighted running mean ($\boldsymbol{T_{rm}}$) of the external temperature (as calculated above in Equation 3.1).

The comfort temperature $\boldsymbol{T_{comf}}$ is calculated from the $\boldsymbol{T_{rm}}$ using Equation 3.7. The suggested acceptable range is based on the type of building being assessed, and the sensitivity of the occupants. This study will use Category II, as the buildings are relatively new and the occupants are unlikely to be “frail or sensitive persons” (Nicol and Humphreys, 2010).

$$T_{comf} = 0.33T_{rm} + 18.8 \pm 3 \tag{3.7}$$

$\boldsymbol{T_{comf}}$ = comfort temperature (°C); $\boldsymbol{T_{rm}}$ = exponentially weighted running mean of the external temperature (°C).

Equation 3.7 was used to calculate the absolute time, and the percentage of time that the internal conditions fall within the $\boldsymbol{T_{comf}}$ boundaries.

Adaptive Overheating Metrics

Different criteria were then applied to determine if the building is overheating. The most widely used to date has been TM52 (Nicol, 2013). The CIBSE TM52 three criterion system is shown below. If a room fails any two of the three criteria then it is classed as overheating (Nicol, 2013).

1. To allow for the duration of overheating the number of hours during which the temperature is greater than or equal to one degree above the threshold comfort temperature during the period May to September inclusive shall not be more than 3% of occupied hours
2. To allow for the severity of overheating the weighted exceedence ($\mathrm{W_e}$) shall be less than or equal to 6 in any one day
3. To set an absolute maximum value for the indoor operative temperature

the value of ΔT shall not exceed 4K

To apply TM52 correctly, Criterion I should be assessed between May and September, whereas Criterion's II and III should be assessed over the entire year (Nicol, 2013). In this study Criterion I was assessed from May until the end of the monitoring period, whereas Criterion's II and III were assessed over the entire monitoring period.

Heat stress

The metric of heat stress is normally reserved for work place environments. However, buildings that are affected by incidences of extreme overheating can cross a point at which heat stress becomes a serious concern (Quigley, 2016). In this thesis the *humidex* methodology was used to estimate heat stress, and provide an additional analysis tool to explore overheating. This is calculated according to Equation 3.8 below, in which $\boldsymbol{T_{dp}}$ is calculated using Equation 3.4 above. The humidex number was then used to assess the risk based on Table 3.17 (Masterton and Richardson, 1979).

$$HUM = T_a + 0.5555 \times (6.11 \times e^{(5417.7530 \times (\frac{1}{273.16} - \frac{1}{T_{dp}}))} - 10) \qquad (3.8)$$

$\boldsymbol{HUM}$ = HUMIDEX number; $\boldsymbol{T_a}$ = air temperature (°C); $\boldsymbol{T_{dp}}$ = the dew point temperature (°C).

Humidex Range	Degree of Comfort
20-29	Comfortable
30-39	Some discomfort
40-45	Great discomfort; avoid exertion
45+	Dangerous; heat stroke possible

Table 3.17: HUMIDEX Scale

3.5.6 Occupant Behaviour Monitoring

Achieving the research aims required forming an understanding of when and why the occupants were using their windows and heating systems. For window opening practices this was relatively straightforward. The data shows the timestamp when the window is opened and closed, and so from this various practices could be shown (e.g. average daily opening length, typical opening times, diurnal opening profiles). The data could also be analysed alongside external or internal conditions (e.g. the likelihood of a window being open at certain external temperatures).

However, the heating system is not so straightforward as the data showed only the surface temperature of the radiator. Therefore an algorithm was used to determine whether the heating is on or off.

3.5.6.1 Radiator surface temperature algorithm

The radiator surface temperature algorithm is based on studies that have also used a similar monitoring method to determine heating usage (Love, 2014; Martin and Martin, 2006). The way the algorithm works is explained below, and is also shown in its algorithmic form in Table 3.18.

The algorithm "uses a state variable to keep track of whether the heating is currently believed to be on or off" (Martin and Martin, 2006). If the heating is off, then a temperature rise of more than a fixed amount (e.g. 1°C), or an observed temperature greater than a fixed amount (e.g. 35°C) triggers the assumption that the heating system has been turned on. Conversely, if the system is believed to be on, then a temperature fall of more than a fixed amount (e.g. 1°C), or an absolute temperature of less than a fixed amount (e.g. 18°C) triggers the assumption that it has been turned off. Finally, if none of these criteria are fulfilled then the state of the system is assumed to be unchanged.

The algorithm was modified to improve its reliability at predicting heating usage from the radiator surface temperature profiles generated in this study (as shown below in Table 3.18). The principal change was to use air temperature ($\boldsymbol{T_a}$), alongside the radiator surface temperature ($\boldsymbol{T_r}$) to predict whether the radiator was on or off.

This was done because there were times in which $\boldsymbol{T_r}$ was above 25°C but the heating was off (i.e. $\boldsymbol{T_a}$ was above 25°C even when the heating was off and therefore $\boldsymbol{T_r}$ was not reducing in temperature). There were also times in which 35°C was not exceeded, but the radiator appeared to be on. Whilst in terms of determining when the heating was off, the PBSA rooms rarely ever dropped below 18°C. This was the case even when the heating had been switched off for extended periods. Therefore in this scenario $\boldsymbol{T_r}$ was neither below 18°C nor declining, and yet the heating was off.

These two issues were overcome by using $\boldsymbol{T_a}$ plus a small buffer to determine whether the radiator was providing heat or not. The value of the buffer was selected by a process of sensitivity analysis alongside visual inspection of the data at different times of the year. An example of the algorithm predicting heating usage is shown below in Figure 3.14 for CSB in the first two days of February 2018. This period has been shown because a range of different radiator profiles are occurring.

The determination of an appropriate buffer value required it to be small enough to capture periods in which the TRV was on a low setting, but large enough to avoid capturing those periods in which hot water is circulating around the pipework but the TRV is closed. Through inspection of the $\boldsymbol{T_r}$ and $\boldsymbol{T_a}$ data throughout the monitoring period it was satisfied that the algorithm was functioning adequately for estimating heating usage. However, there are methodological improvements regarding how the radiators could have been monitored; these are discussed in Section 7.2.2.

3.5.7 IAQ & Ventilation

3.5.7.1 IAQ

Initially IAQ was gauged based on the concentration of CO_2 in the participant's rooms. A static limit of 1000PPM was used to provide a metric against which to judge the "stuffiness" of the conditions, as has been used in several previous domestic studies (Sharpe et al., 2015; Offermann, 2010; Sundersingh and Bearg, 2003). This was assessed during the whole monitoring period, and overnight only (i.e. 23:00 - 07:00).

Original Algorithm (Martin and Martin, 2006)

```
if Radstate = 0
    if $T_r(t) - T(t-1) \geq 2$
        Radstate = 1
    else if $T_r(t) \geq 35$
        Radstate = 1
else if Radstate = 1
    else if $T_r(t) - T_r(t-1) \leq -2$
        Radstate = 0
    else if $T_r(t) < 18$
        Radstate = 0
```

Love Algorithm (Love, 2014)

```
if $Radstate = 0$
    if $T_r(t) - T_r(t-1) \geq 2$
        Radstate = 1
    else if $T_r(t) \geq 25$
        Radstate = 1
else if Radstate = 1
    else if $T_r(t) - T_r(t-1) \leq -1.5$
        Radstate = 0
    else if $T(t) < 18$
        $Radstate = 0$
```

Algorithm Adapted for this Research

```
if $Radstate = 0$
    if $T_r(t) - T_r(t-1) \geq 2$
        Radstate = 1
    else if $T_r(t) \geq (T_a + 5)$
        Radstate = 1
else if Radstate = 1
    else if $T_r(t) - T_r(t-1) \leq -1.5$
        Radstate = 0
    else if $T_r(t) < (T_a + 1)$
        Radstate = 0
```

Table 3.18: Radiator temperature algorithms for determining whether the heating was on or off. The modifications made for this study are highlighted in yellow.

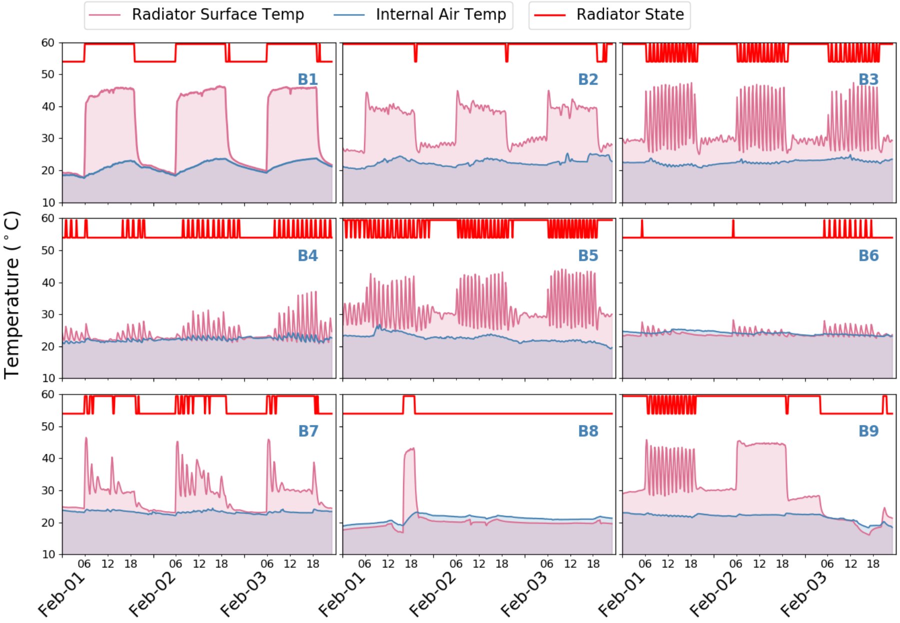


Figure 3.14: Heating usage prediction in CSB in winter 2018

3.5.7.2 Ventilation

The CO_2 concentration was also used to estimate the ventilation rate. The equilibrium method was not used due to the fact that the rooms rarely reached equilibrium. CO_2 levels tended to be rising during periods the rooms were occupied, or falling as the occupant either took adaptive action (i.e. opened a window) or left the room. The only rooms in which this was not always the case were the larger rooms in CSA that had their own mechanical ventilation systems. The fact that equilibrium conditions were rarely reached is in itself an indication that the ventilation rates in the other rooms were likely to be low.

The constant injection method was not used because this method could only be used when the window was shut (i.e. when CO_2 levels were rising). This study was interested in the ventilation rate when the window was both open and closed. As such, the CO_2 decay method was selected; this is described below.

3.5.7.3 CO_2 Decay Locator

As discussed in Section 2.3.4 the decay periods must be of sufficient time-span and range to match the sensors response-time and sensitivity respectively (the details of the CO_2 sensors used in this study are provided above in Table 3.11). The data must also be smoothed first because there is significant noise in the CO_2 data, and this can disrupt the automatic CO_2 data locator. The basic algorithmic rules that were used to locate the CO_2 decay curves within the time-series data are provided below:

- The CO_2 concentration must be above 600PPM at the start of the decay
- The CO_2 concentration must fall by more than 100PPM during the decay
- The CO_2 concentration must come within 200PPM of the outdoor CO_2 concentration
- The CO_2 decay duration should exceed 5 minutes
- The CO_2 decay ends when for 3 consecutive minutes the concentration is either constant or rising

An example of the automatic CO_2 decay locator is shown in Figure 3.15 for room A9 during a period in early May. The CO_2 time series data is in green with the decay periods shown in red.

In CSA a total of 2844 decays were located (2234 window open, and 650 window closed), while in CSB the figure was 2245 (1444 window open, and 801 window closed). The total count of the decays is provided to illustrate

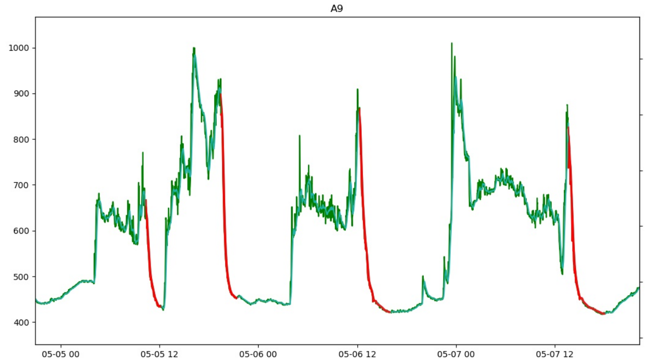


Figure 3.15: Example of CO_2 decay locator with time series data in green and decay periods shown in red

why this had to be done automatically. The alternative method would have been to manually find the decays. This would have substantially reduced the number of decay events that could have been analysed, and as such far fewer estimates of the ventilation rate would have been calculated.

3.5.7.4 CO_2 Decay Method

All the techniques suggested to relate CO_2 concentration to building air exchange rates are based on the same premise; a mass balance of CO_2 in the building. The mass balance for a single zone building is expressed below in Equation 3.9.

$$\frac{VdC}{dt} = G + QC_R - QC \tag{3.9}$$

$\boldsymbol{V}$ = room (or zone) volume (m^3); $\boldsymbol{C}$ = CO_2 concentration in the room ($mg \cdot m^{-3}$); $\boldsymbol{C_R}$ = CO_2 concentration in the outdoor air ($mg \cdot m^{-3}$); $\boldsymbol{Q}$ = flow rate of outdoor or replacement air ($m^3 \cdot m^{-1}$); $\boldsymbol{G}$ = CO_2 emission rate of indoor sources ($mg \cdot h^{-1}$).

If the indoor generation rate is zero (i.e. the building is unoccupied, and there are no internal sources of CO_2 generation) then the concentration relative to the outdoors will decay from its initial value to the outdoor concentration according to Equation 3.10.

$$C_t - C_R = (C_0 - C_R)e^{-\frac{tQ}{V}} \tag{3.10}$$

$\boldsymbol{V}$ = room (or zone) volume (m^3); $C_t = CO_2$ concentration in the room ($mg \cdot m^{-3}$) at Time ($t = t$); $C_0 = CO_2$ concentration in the room ($mg \cdot m^{-3}$) at Time ($t = 0$); $\boldsymbol{Q}$ = flow rate of outdoor or replacement air ($m^3 \cdot m^{-1}$); $\boldsymbol{V}$ = room (or zone) volume (m^3).

3.5.7.5 Outdoor CO_2 Concentration

As shown above in Equation 3.10 the estimation of the ventilation rate is dependent upon the outdoor CO_2 concentration ($\boldsymbol{C_R}$) during the measurement period (i.e. the period of time in which the decay occurs). $\boldsymbol{C_R}$ can be variable. However, no external CO_2 monitoring was conducted at the case study locations. Therefore the only outdoor data available was CO_2 data recorded at [redacted] over the monitoring period.

This data was used unless any of the indoor CO_2 sensors in the case studies were reading below the [redacted] during the period of the decay. In this case the lowest indoor measurement was used instead. This occurred rarely, but there were CO_2 sensors installed in the circulation spaces in both case studies where it did happen on occasions.

3.5.7.6 Ventilation Flow Rate

Then Equation 3.10 can be re-arranged to find the volumetric flow rate at which external air is entering the zone. This is shown below in Equation 3.11.

$$Q = V\frac{ln\frac{C_t1(t_1)}{C_t2(t_2)}}{(t_2 - t_1)} \tag{3.11}$$

$\boldsymbol{Q}$ = flow rate of outdoor or replacement air ($m^3 \cdot m^{-1}$); $C_t = CO_2$ concentration in the room ($mg \cdot m^{-3}$) at Time ($t = t$).

Finally, the air change rate (ACH) for the single zone can be calculated according to Equation 3.12 below.

$$ACH^{-1} = \frac{Q \times 3600}{V} \tag{3.12}$$

ACH = air changes per hour; $\boldsymbol{Q}$ = flow rate of outdoor or replacement air ($m^3 \cdot m^{-1}$); $\boldsymbol{V}$ = room (or zone) volume (m^3).

3.5.7.7 Ventilation, Window State & Occupancy

If the window state was closed during the decay it was assumed that the rooms were unoccupied. This seemed reasonable as in the vast majority of bedrooms whenever they were occupied the CO_2 level tended to consistently increase, whilst the bedroom doors were fire doors that should remain shut or the occupant risked receiving a fine. The majority of participants reported adhering to this rule (although it is possible they may have felt obliged to respond accordingly due to fear of self-incrimination).

However, when the window state was open it is possible that the participant was either still in their room (exhaling CO_2) while the decay occurred, or that they had left. The inability to accurately assess occupancy was a limitation of the study (see Section 7.2). This was overcome by analysing the CO_2 decay curves during periods in which the window was open assuming that the room could be either occupied or not.

In the end the assumption was made that when the window was open the room was occupied. This was based on the interview data showing that many participant's reported opening their windows when entering their room, or whilst in their room, but rarely did any of participants suggest that they opened their window and then immediately left their room. Therefore, despite the uncertainties noted in Section 2.3.4 with regard to the CO_2 generation rate of people, the decision was made to include it for the decays that occurred whilst the window was open. Thus Equation 3.11 was solved with the addition of $\boldsymbol{G}$ (the CO_2 generation rate for an occupant) when the window was open at the time of the decay.

The value of $\boldsymbol{G}$ was based on Table 2.4 in Section 2.3.4. It was assumed that when in their room the occupants were likely to be either sitting or lying down (how the occupants used their rooms and what activities they undertook was covered in the interviews; see Section 3.4.4). As such, a value at 1 MET was selected, and therefore a CO_2 generation rate (***G***) of $0.0038L/s$ and $0.003L/s$ was assumed for males and females respectively.

3.5.8 Heat Loss Model

One of the aims of this research was to assess the energy demand implications of how the thermal conditions were being controlled. To do this a simplified model of the heat transfer processes occurring in each of the monitored bedrooms was developed. Hourly internal and external temperatures were used to estimate the heat losses from each bedroom. The following technical details were collected for each room:

- Hourly internal temperature over the monitoring period (°C)
- Volume of the room (m^3)
- The area of external walls (and ceiling if top floor room) and windows (m^2)
- The thermal transmittance ($U - value$) of external walls, ceiling and windows (W/m^2K)
- The ventilation rate with the window closed and open, as calculated above in Section 3.5.7.7 (m^3/s). The window was assumed to be open for the entire hour long period if it was open for more than 80% of the hour (otherwise it was assumed to be closed)

One major simplification was made in this model. This was the assumption that no heat is lost to adjacent rooms or corridors (i.e. all conduction losses are via the external walls, ceilings or windows). As shall be shown in Section 5.2.3.6 of the results this assumption is defensible due to the fact that the majority of corridors are warmer than the bedrooms, and the difference in temperature between neighbouring rooms was found to be relatively negligible. There are four primary heat loss mechanisms for the

PBSA study bedrooms. These are listed below.

1. Heat loss via conduction through the external walls and windows
2. Heat loss through infiltration and via controlled ventilation (e.g. MVHR) i.e. the ventilation rate with the window closed
3. Heat loss through an open window i.e. the difference in ventilation rate between when the window is closed and open

3.5.8.1 Conductive Heat Losses

Conductive heat losses were calculated according to Equation 3.13 below.

$$H_k = \sum (U \times A \times (T_i - T_o)) \tag{3.13}$$

$\boldsymbol{H_k}$ = rate of conductive heat loss (Js^-1); $\boldsymbol{U}$ = thermal transmittance of surface (W/m^2K); $\boldsymbol{A}$ = area of surface (m^2); $\boldsymbol{T_i}$ = internal temperature (°C); $\boldsymbol{T_o}$ = outdoor temperature (°C).

3.5.8.2 Ventilation Heat Losses

In the case of the remaining three heat loss mechanisms these can be estimated using Equation 3.14 for ventilation heat losses below. The values for the constants can be found in *Building Services & Equipment* (Hall, 1994).

$$H_v = Q_v \times C_p \times \rho \times (T_i - T_o) \tag{3.14}$$

$\boldsymbol{H_v}$ = rate of ventilation heat loss (Js^-1); $\boldsymbol{Q_v}$ = volumetric flow rate of air out of space (m^3s^{-1}); $\boldsymbol{C_p}$ = specific heat capacity of air (J/kgK); $\boldsymbol{\rho}$ = density of air (kg/m^3) - assumed to be 1.2 at 20°C; $\boldsymbol{T_i}$ = internal temperature (°C); $\boldsymbol{T_o}$ = outdoor temperature (°C).

In the case of heat losses for when the window is open this is estimated by subtracting the ventilation rate with the window closed, from the ventilation rate with the window open i.e. it is the difference between the two. This method is based on that used in (Jack et al., 2016).

Equation 3.14 must be adjusted slightly for the MVHR system. The manufacturers product information sheet had a stated efficiency ($\boldsymbol{MVHR_{eff}}$) of 90% for the MVHR system. However, as the building is five years old there is likely to be some fouling on the heat exchanger plates. Also, the monitored efficiencies in other domestic MVHR systems tend to be lower e.g. (Lowe and Johnston, 1997), and therefore an efficiency of 80% was assumed.

$$H_{MVHR} = \frac{1 - MVHR_{eff}}{1} \times C_p \times \rho \times q_v \times (T_i - T_o) \tag{3.15}$$

This monitoring set-up did not allow for distinguishing between planned ventilation and infiltration. In CSB this does not have an impact on the heat loss equations as they will remain unchanged whether ventilation is occurring via infiltration or planned ventilation (e.g. through trickle vents).

However, as covered in Section 3.3.1.3, CSA does not have trickle vents but an MVHR system. In this case, with the window closed, some ventilation will be occurring via the MVHR unit (and thus be heated by the exiting warm internal air) while some will be via infiltration (and not preheated). In this case all window closed ventilation (including infiltration) was assumed to be via the MVHR system in CSA. Therefore Equation 3.15 was used for the ventilation losses in CSA when the windows were closed.

3.6 Summary

The chapter began by restating the research questions and aims. This was followed by the research design. This section outlined how an interdisciplinary approach (combining both social and technical methods) would be applied to study PBSA performance in operation using two in-depth case studies.

The second section described the key characteristics of the case studies, focusing on heating and ventilation design. It has shown how the case studies have a number of similarities including high fabric efficiency standards, wet heating systems and top-hung (restricted opening) windows. However, it also outlined a number of key differences. These include the location (urban compared with suburban), the fact that one is a high-rise single building design whilst the other is medium-rise separated blocks, and also annual versus 9-month tenancies. Other differences in terms of building design include the ventilation strategies and heating controls.

The third section described how the different data sets for this study were collected, this included:

1. The collection of the design and as-built documentation for each case study
2. The collection of weather data
3. The IEQ and occupant behaviour physical monitoring data
4. The semi-structured interviews with the study participants, and facilities management staff
5. The building surveys

The final section of this chapter outlined how the data would be analysed in this thesis. This included discussion and justification for how the external air temperature data was selected, and how the survey and qualitative data would be analysed. It concluded by showing the range of different methods and metrics that would be used to analyse the quantitative data. The thesis is now at the stage where the results can be presented.

Chapter 4

Controls in the Heating Season

The results have been split into two chapters. This chapter will cover the control of the conditions during the winter and shoulder seasons. The second results chapter focuses on the late spring and summer periods (justification for why these two periods have been split into separate chapters is provided in Section 3.1). The results sections are then be followed by the discussion. The discussion will interpret the findings and describe their significance in terms of what was already known about the research problem under investigation.

The first results chapter is split into the following sections. The first two sections provides context by summarising the weather and indoor conditions respectively. These sections are not the main focus of the results chapter. They are necessary to provide the reader with an overview of the conditions experienced by the occupants so that they can understand and contextualise the participant's responses and behaviours.

The remaining sections of the chapter uses multi-variable analysis to address the first research question. The first part looks at how the participants controlled the indoor conditions, while the second part assesses the adequacy of those controls. The third section investigates the causal factors for the participant's control strategies. The fourth and final section looks at the likely impact on the thermal performance of the PBSA due to the participant's behaviour.

4.1 Weather Conditions

Weather conditions have a significant impact upon the internal conditions within buildings. In particular air temperature, solar radiation, wind speed and direction. For context, the daily minimum and maximum external air temperatures at the case study locations over the heating season period are shown below in Figures 4.1 and 4.2.

The daily temperature ranges are compared against the Met Office monthly average minimum and maximum temperatures at the same locations (Royal Meteorological Society, 2018). These values represent the average daily minimum or maximum air temperatures for each month between 1981-2010.

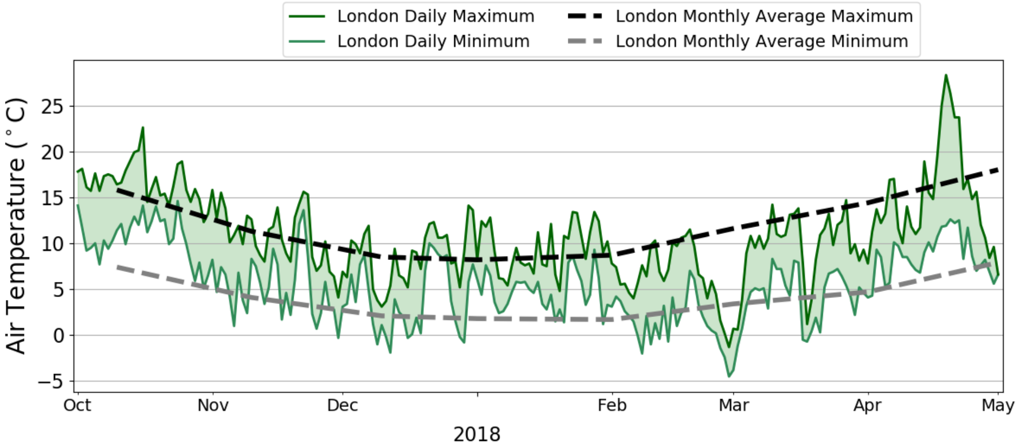


Figure 4.1: Daily minimum and maximum external air temperatures in London over the heating season monitoring period compared against Met Office historical monthly minimum and maximum temperatures for the same location (Royal Meteorological Society, 2018).

The 2017/18 winter was generally rather unsettled. The temperatures fluctuated either side of the long-term average, with some mild spells (especially in southern areas), but also periods with widespread frosts. The mean temperature over the winter period (December - February) was 0.2°C below the 1981-2010 average, however the total sunshine hours were 21% above the 1981-2010 average (Royal Meteorological Society, 2018).

The most notable event was the "beast from the east", which occurred

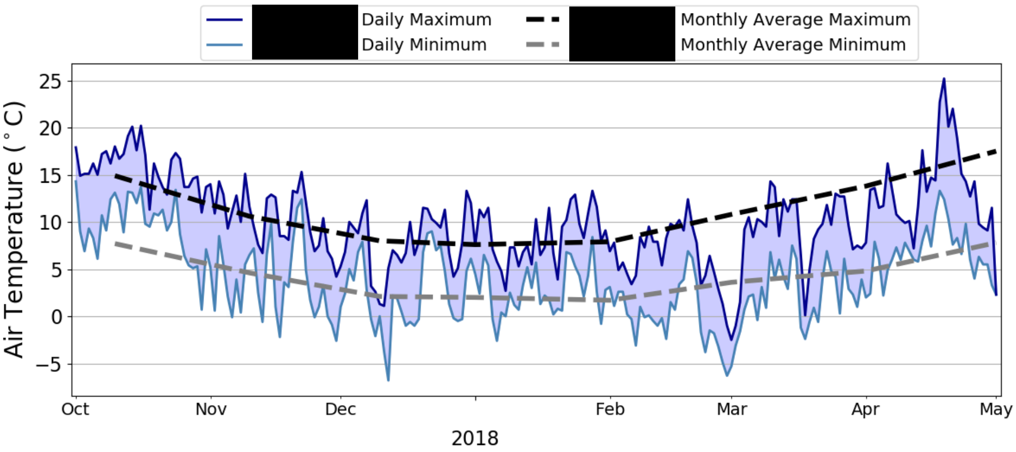


Figure 4.2: Daily minimum and maximum external air temperatures in [redacted] over the heating season monitoring period compared against Met Office historical monthly minimum and maximum temperatures for the same location (Royal Meteorological Society, 2018).

between the 22nd February and the 5th of March. This brought widespread unusually low temperatures, and heavy snowfall to large areas of UK (including both [redacted] and London). This can be seen in Figures 4.1 and 4.2 around the March 2018 period when the recorded daily maximum temperatures fall below the monthly average minimum temperatures. The cold snap also brought strong winds that delivered bitterly cold wind chill factors. These were estimated to be as low as -15°C at times in London (Royal Meteorological Society, 2018).

One other point to note is the period in late April 2018, which was unseasonably warm for the time of year. As shown in Figures 4.1 and 4.2 during this period daily temperatures were as much as 10°C above the long term averages.

4.2 Indoor Conditions during the Heating Season

The section below examines the internal conditions over the October to May period. Firstly, by evaluating the thermal conditions, then by looking at IAQ, and finally covering occupant feedback on the conditions. The aim of this section is to provide the reader with an overview of the conditions experienced by the inhabitants so that they can contextualise the participant's behaviour.

4.2.1 Thermal Conditions

The thermal conditions over the heating season are summarised below. The weekly average internal temperature across all the monitored bedrooms is shown below in Figure 4.3.

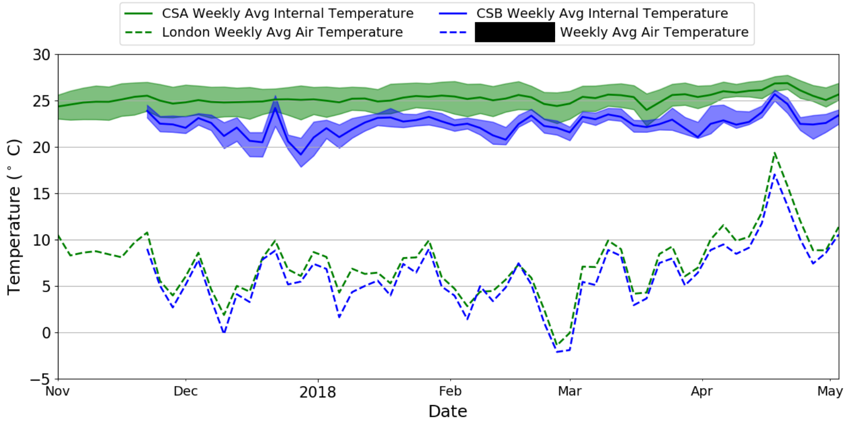
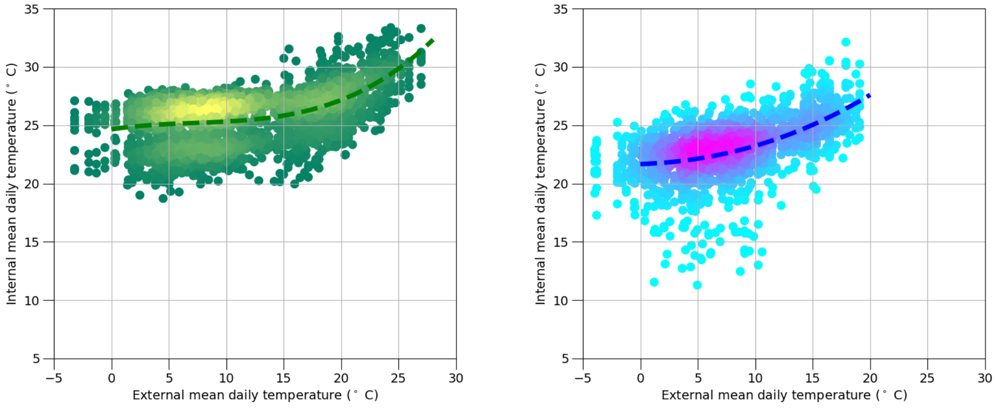


Figure 4.3: Weekly average internal and external temperatures at the case study locations. The faded band represents the inter-quartile range of indoor temperatures.



(a) CSA **(b)** CSB

Figure 4.4: Mean daily internal temperature plotted against external temperature for all rooms in both case studies across the entire monitoring period. The yellow (CSA) and pink (CSB) represent a concentration of observations i.e. a higher density of points.

Figure 4.3 and 4.4a show that the average weekly temperature across all the rooms in CSA is approximately 25°C over the heating season. The average internal temperatures tended to be both stable, and relatively unaffected by the external air temperature. For instance, during the "beast from the east" in late February when the weekly average temperature in London fell to -2°C, the average weekly internal temperature remained at 24.8°C.

Figure 4.3 and 4.4b show that the average weekly temperature across all the rooms in CSB varied between approximately 20°C to 25°C. The average weekly internal temperature in CSB showed greater fluctuations, and was more responsive to external air temperature.

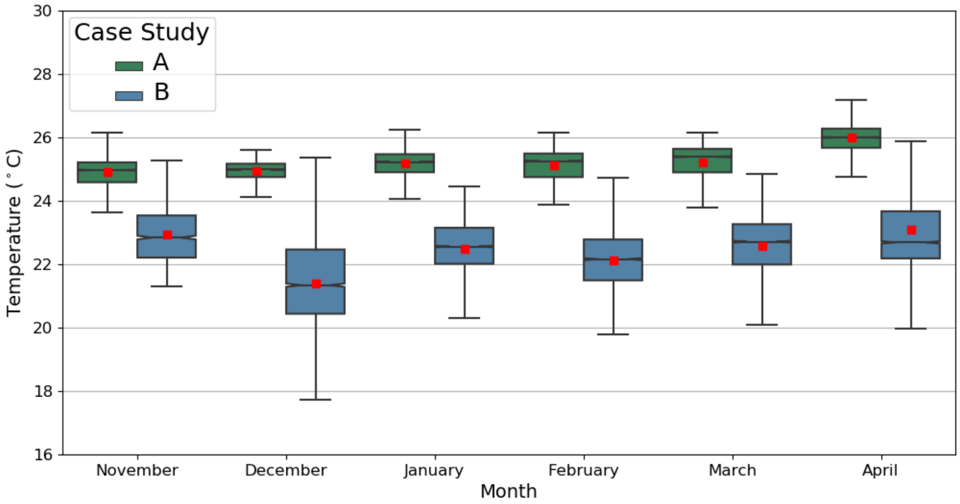


Figure 4.5: Monthly internal temperature boxplots for CSA and CSB. The monthly mean is represented by the red square dot.

Figure 4.5 shows how during the heating season CSB is both cooler, and has a greater range of internal temperatures between the participant's bedrooms. However, although CSB was cooler than CSA, the average internal temperatures at both sites is still relatively warm when compared against other UK domestic internal temperature monitoring studies (this is discussed further in Section 6.2.1).

4.2.1.1 Inter Room Variability

Figures 4.6 & 4.7 show the distribution of hourly average temperatures in all of the monitored rooms over the heating season. The results are ordered by the mean temperature in each room over the entire heating season (i.e. October - May), with coolest at the top, and warmest at the bottom.

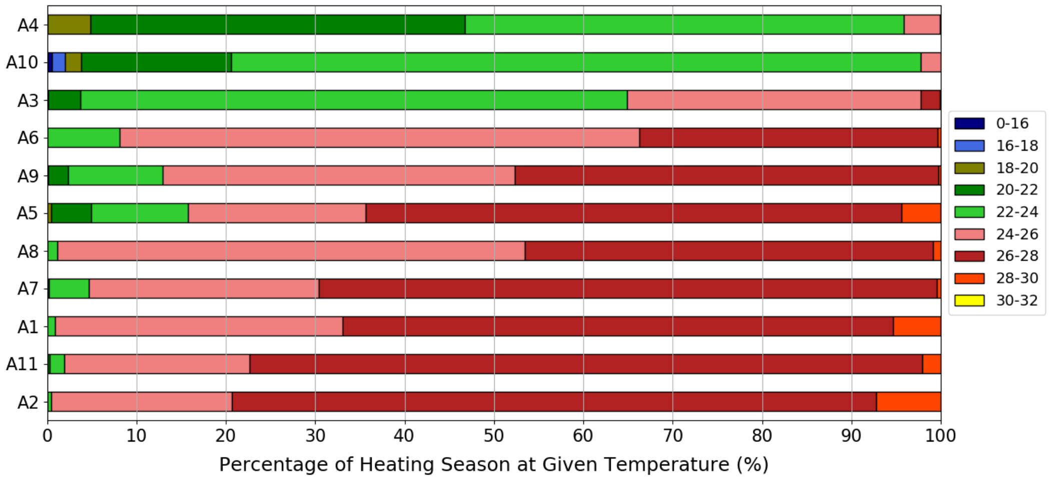


Figure 4.6: The distribution of temperatures in the monitored bedrooms in CSA over the heating season.

In CSA (Figure 4.6) many of the rooms remained warm for the majority of the heating season; for instance, 8 of the rooms in CSA are above 24°C for 80% of the heating season, whilst 7 of the rooms are above 26°C for 40% of the period. In general, the rooms on the lower floors (and in particular the basement rooms) were noticeably cooler.

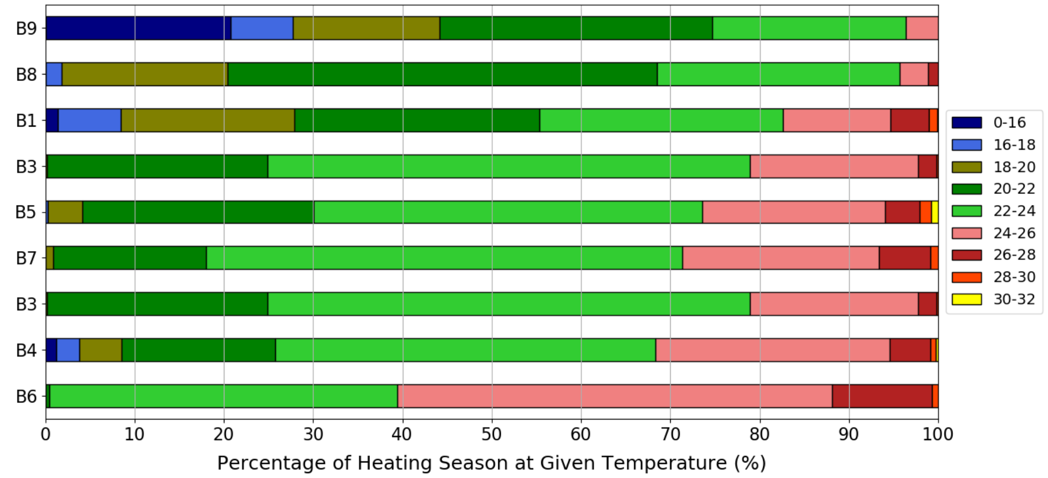


Figure 4.7: The distribution of temperatures in the monitored bedrooms in CSB over the heating season.

In comparison in CSB (Figure 4.6) many of the rooms were notably cooler, staying within 18°C to 24°C for the majority of the period. One room (B9) also fell below 16°C for approximately 20% of the period. This was due to the occupant leaving their window open and the heating off whilst they vacated their accommodation over the Christmas break. As such, this did not impact on the occupant's thermal comfort, as shall be covered below in Section 4.2.3 below on occupant feedback.

4.2.1.2 Further Observations

There are two further observations to note from the internal temperature monitoring. Firstly, there was relatively minimal diurnal variation in temperature within rooms i.e. the temperatures tended to be relatively stable throughout the heating season, and also during the night and day. Secondly, the corridors were also generally warmer than the bedrooms (on average by 2-3°C), whilst the CSB townhouse bathrooms were particularly warm. For example, the average temperature in the first floor bathroom in the CSB townhouses exceeded 30°C over the heating season (see Section 5.2.3.6).

4.2.2 Indoor Air Quality

The IAQ analysis was limited to CO_2 and RH. These are covered below.

4.2.2.1 Indoor CO_2 Concentration

As described in Section 3.4.2.4 CO_2 levels were used as a proxy for stuffiness. The weekly average and maximum CO_2 levels for each of the case studies is shown in Figure 4.8 below.

As shown in Figure 4.8 the weekly average CO_2 concentration in CSB regularly exceeded the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) recommended CO_2 limit of 1000PPM (American Society of Heating and Engineers, 1986). The exceedances generally occurred in B1-B5. These were the townhouse rooms that lacked mechanical ventilation (see Section 3.3.2.3 for details). The high CO_2 concentrations were most pronounced at night. An example of the CO_2 profiles for a 3-day period in January 2018 is shown in Figure 4.9 for all the

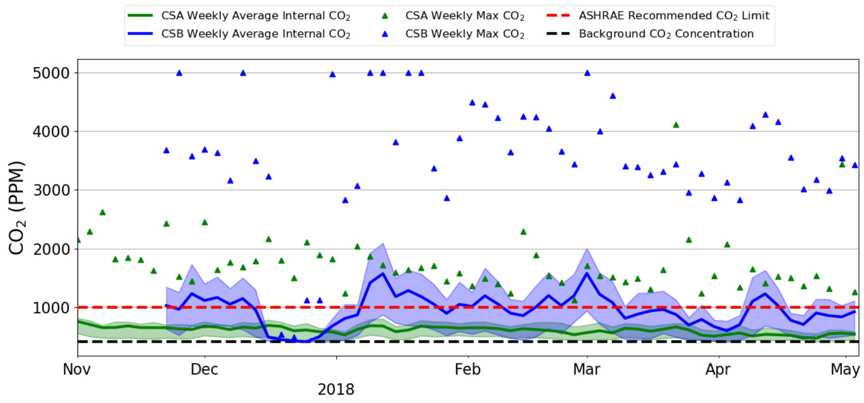


Figure 4.8: Average and maximum CO_2 levels across all rooms inside CSA and CSB over the heating season. The faded band represents the inter-quartile range of values. The background CO_2 level (black dashed line) and ASHRAE recommended limit (red dashed line) are included for reference (American Society of Heating and Engineers, 1986).

rooms in CSB.

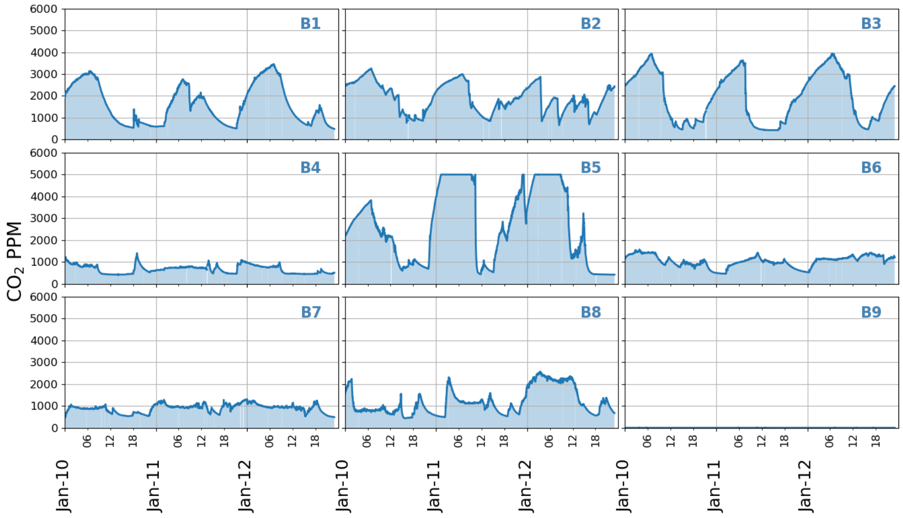


Figure 4.9: The CO_2 concentrations (PPM) in CSB rooms over a 3-day period in January.

Figure 4.9 shows how the CO_2 concentration tended to rise during the night, and then falls away in the morning as the participant's either opened their windows, or left their rooms. The relationship between CO_2 concentration and window opening is shown below in Section 4.3.3.2. Also note that the CO_2 sensor in B9 had failed (see Section 3.5.4). There are two further important points to note from Figure 4.9.

The first is that B4 managed to maintain significantly lower CO_2 concentrations than the other townhouse rooms. This is likely due to the fact that the participant in B4 left their window open almost continuously throughout the entire heating season (see Figure 4.19 in Section 4.3.1.2 below). The second observation is that all of the townhouse rooms reached the maximum sensor limit of 5000PPM on occasions (for example, see B5 in Figure 4.9, and also the weekly maximum values in Figure 4.8). Therefore the actual maximum CO_2 concentration in these rooms over the monitoring period is unknown.

Over the heating season the maximum CO_2 concentration of 5000PPM was either met or exceeded for between a total of 0.7 hours (B4) to a maximum of 35 hours (B5). This included periods in which the CO_2 concentration was 5000PPM or above for over 8 hours. For instance, in room B5 a consistent CO_2 concentration reading of 5000PPM was recorded between 01:10 - 09:30 on the 1st November 2018. Three further occasions were recorded in B5 where the CO_2 concentration was recorded as 5000PPM for 6 hours or more, while there was also one occasion in which it reached 5000PPM for 8 hours in B1. The significance of this in terms of HSE legislation is covered in Section 6.3.

As well as reaching very high CO_2 concentrations at times, the overnight concentrations in certain rooms in CSB was also consistently high throughout the heating season. This is shown below in a distribution plot (Figure 4.10). This shows the percentage of nighttime hours (23:00-07:00) that each room in CSB spent at a given CO_2 concentration over the heating season.

Figure 4.10 shows that 5 of the rooms were above 1000PPM for over 50% of the nighttime hours, while 4 of the rooms are above 2000PPM for 30% of the nighttime hours. These results indicate that the overnight environment in these rooms is likely to have been excessively stuffy, and therefore that ventilation in the townhouse rooms was an issue. The occupant feedback on this topic is covered below in Section 4.2.3.2, while the issue is discussed in

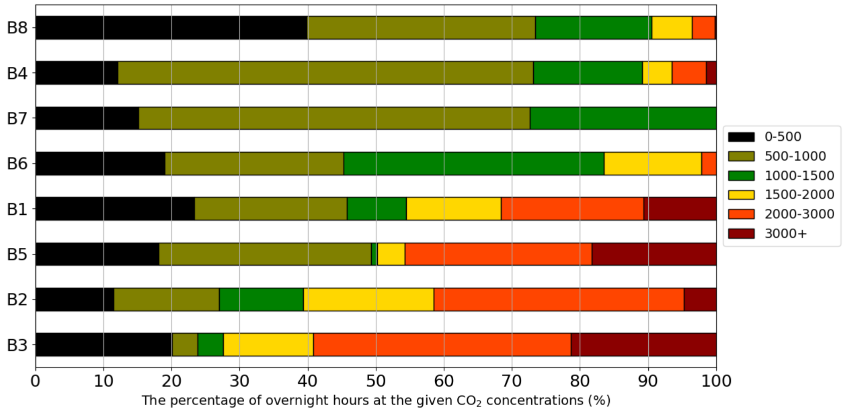


Figure 4.10: The percentage of overnight hours (23:00-07:00) at a given CO$_2$ concentration (PPM) in CSB rooms over the heating season.

greater detail in Section 6.3.

4.2.2.2 Indoor Relative Humidity

The weekly average internal and external RH is shown in Figure 4.11. Figure 4.11 shows that the monitored rooms generally stayed within acceptable RH conditions (i.e. 40-70% RH) throughout the heating season (CIBSE, 2003). However, the average RH level in CSA does dip below 40% on several occasions when the external temperatures drop e.g. in February during the "beast from the east" cold snap. As an example, the conditions in the driest room are shown for the late February period in Figure 4.12.

Figure 4.12 shows how the internal RH in room A7 is consistently below 40% over this period, and at time drops below 20%. It is to be expected that internal RH will drop in winter. This is because the cold winter air does not contain much water vapour i.e. it has a low absolute humidity content. Therefore as this air warms up it inevitably leads to low RH (despite the absolute humidity content remaining the same). This process is outlined in Section 2.3.5.

However, the high internal temperatures over the winter period inside the monitored rooms in CSA (see Section 4.2.1.1) amplified this affect. As such, the dry conditions were more pronounced in the warmest rooms in CSA. The

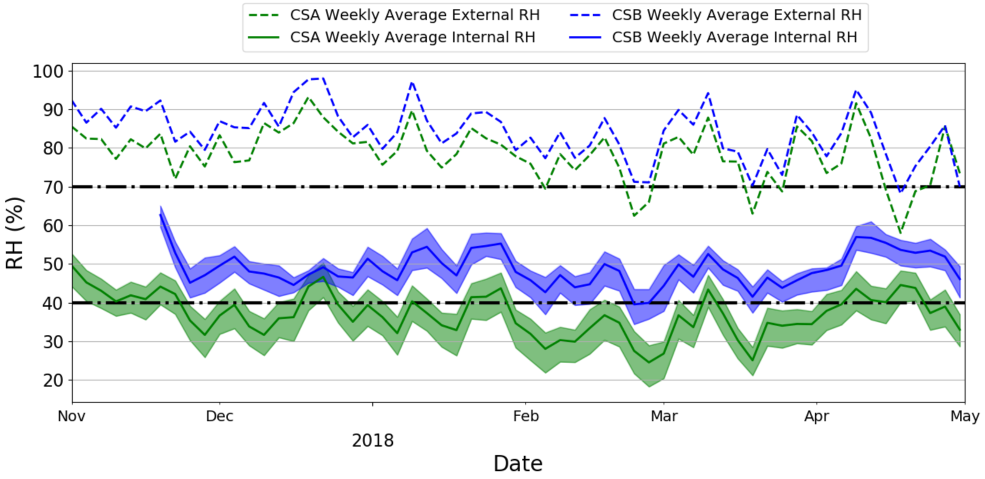


Figure 4.11: Weekly average internal and external RH over the heating season. The faded band represents the inter-quartile range of indoor RH. The CIBSE recommended limits for dwellings of 40% to 70% RH are also highlighted by the black dashed lines (CIBSE, 2003).

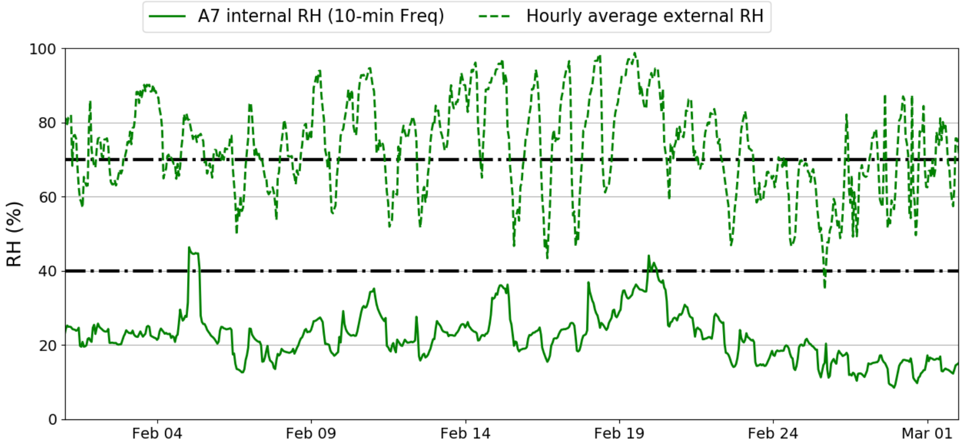


Figure 4.12: The RH levels in the driest room in CSA during late February 2018. The CIBSE recommended limits for dwellings of 40% to 70% RH are also highlighted by the black dashed lines (CIBSE, 2003).

dry conditions were also a serious issue for the participant's, as discussed in Section 4.2.3.3 below.

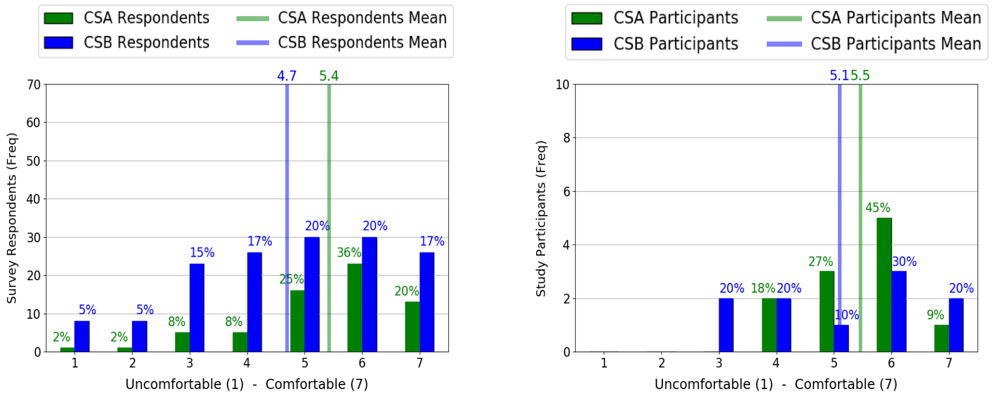
4.2.3 Occupant Feedback

The occupant feedback on the winter conditions is presented next. This is separated into two sections; the survey results, followed by the interview analysis.

4.2.3.1 Thermal Comfort Survey Results

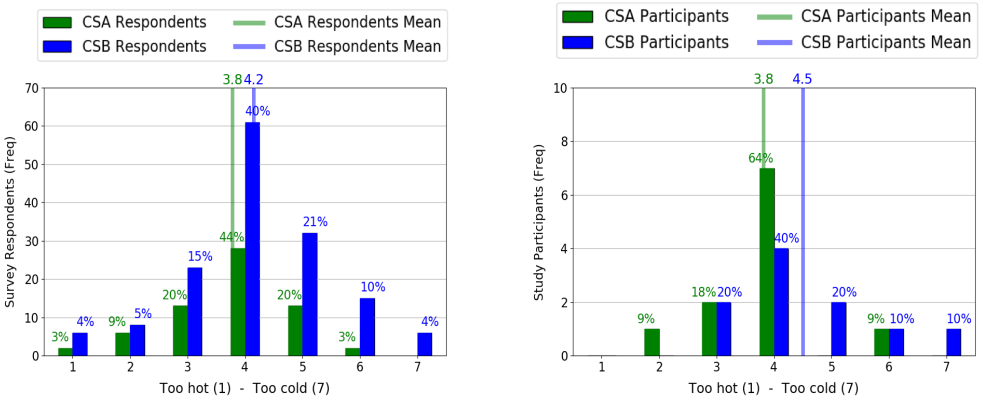
The survey results for thermal comfort in winter are shown below for each case study. The results are separated into the "participants" i.e. those occupants who participated in the monitoring study (Figure 4.13b), and the "respondents" i.e. those who responded to the survey (Figure 4.13a), but did not participate in the monitoring study. The mean scores for both sets of results are shown by the dashed lines. These have been added to allow for comparison between the participants and the respondents. The complete set of summary statistics for the survey data is also available in the Appendices for CSA (Appendix E.1) and CSB (Appendix E.2).

In this section Figure 4.13 shows the results for the question "how would you describe the conditions in winter?", whereby 1 is uncomfortable, and 7 is comfortable. Below which Figure 4.14 shows the results for "how would you describe the temperature in winter?", whereby 1 is too hot, 7 is too cold and 4 is neutral.



(a) Survey Respondents **(b)** Study Participants

Figure 4.13: Survey results for "how would you describe the typical conditions in winter?"



(a) Survey Respondents **(b)** Study Participants

Figure 4.14: Survey results for "how would you describe the indoor temperature in winter?"

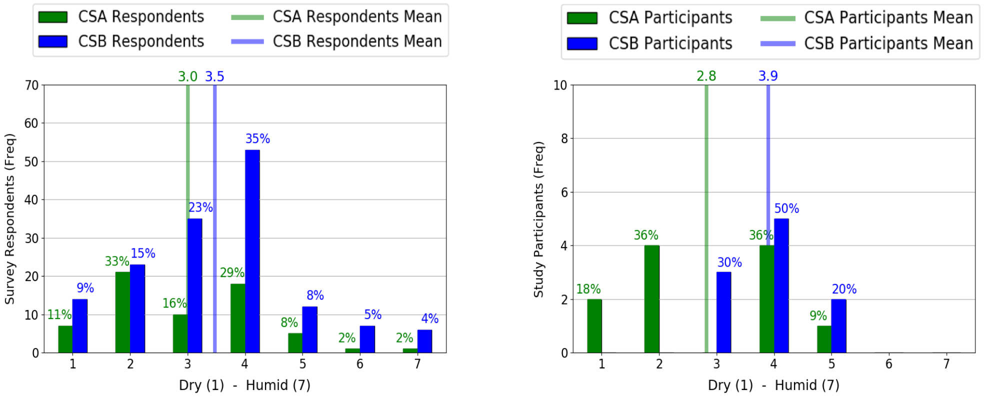
Figure 4.13 shows that the survey respondents in CSA were generally comfortable during the winter; with over 80% answering 4 or above. The winter comfort findings for CSB were slightly more mixed. Figure 4.14 shows that in both cases the largest proportion of responses was 4 i.e. neither too hot nor too cold. In both cases the participant's responses were broadly similar to the general respondents (with a notable exclusion of the lowest scores for the participants).

4.2.3.2 Indoor Air Quality Survey Results

The survey results for the questions "how would you describe the typical indoor air in winter - dry (1) or humid (7)" and "how would you describe the typical indoor air in winter - fresh (1) or stuffy (7)" are displayed below in Figure 4.15 and 4.16 respectively.

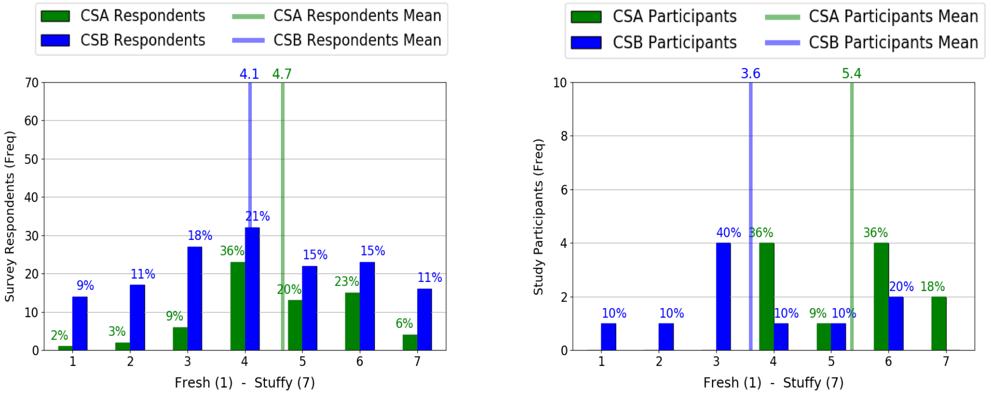
Figure 4.15 shows that many of the respondents found the indoor air to be dry in winter, although a large number in both PBSA answered 4 (i.e. neither dry nor humid). The chart also shows how CSA occupants reported the winter air to be drier, which correlates with the monitoring showing drier conditions in CSA (see Section 4.2.2.2 above).

Figure 4.16 shows that the occupants in CSB were relatively split regarding whether the conditions were fresh or stuffy, with a significant



(a) Survey Respondents **(b)** Study Participants

Figure 4.15: Survey results for "how would you describe the indoor air in winter (dry-humid)?"



(a) Survey Respondents **(b)** Study Participants

Figure 4.16: Survey results for "how would you describe the indoor air in winter (fresh-stuffy)?"

minority answering both 1 and 7. However, in CSA the results for both the respondents and participants are skewed towards the "stuffy" side. This is somewhat surprising given the CO_2 concentrations in the monitored rooms in CSB were significantly higher than in CSA (see Section 4.2.2.1 above). It also contrasts with the findings from the interviews in Section 4.2.3.3 below.

4.2.3.3 Interview Results

The participants were interviewed twice about the indoor conditions during the heating season (see Section 3.4.4 for the interview details). This section of the results chapter will cover the participants responses regarding the conditions only. It will not cover the participants views on the controls, or how they used them (this is covered in Section 4.3 below). However, it is worth noting that, as discussed in Section 2.4 of the literature review, these two issues are interconnected and cannot be separated entirely i.e. the participant's responses to questions of indoor comfort will be partly informed by their views on the adequacy of the controls.

CSA Overview

In CSA the main response from the participants was that they were generally comfortable during the heating season. Comments such as "Yeah... it's been fine... it's pretty comfortable" [A4 - 31-10-17] were common. Indeed, 10 out of the 11 participants at CSA expressed such views. However, several participants did opine that the temperatures were often fairly warm "yeah I do think sometimes in the morning when I wake up it can be a bit hot" [A1 - 05-02-18], and that this tended to occur during the night; "Yeh well it can get a bit hot at night, because if you close the window if you want to sleep it's too hot" [A11 - 30-10-17].

Many of the participants acknowledged that the conditions were generally warm, but that they liked this, for example "It's very warm. That's what I feel. But I like to be warm" [A6 - 07-02-18]. There was only one participant who felt very uncomfortable during the heating season, e.g. "It's hot pretty much all the time. Then at night time it gets quite unbearable" [A10 - 02-11-17]. This participant felt that to have comfortable internal conditions then the external temperature needed to be very cold, for example "well at least in these past few weeks it has been pretty cold outside, so it has been more bearable inside" [A10 - 05-02-18].

CSB Overview

In CSB the participants also reported being generally comfortable. However there were notably more complaints about the conditions than in CSA. In this case 6 out of the 9 participants had some negative opinions about the conditions. These complaints tended to be focused on the stability of the temperature throughout the day.

There were complaints that the conditions were on occasion too cold "usually 90% of the time I'm okay in this room but sometimes that other time I can wake up and I think my blanket has fallen off because I'm that cold" [B1 - 22-11-17]. Although, interestingly the monitoring in this room showed the temperature not to fall below 20°C over the heating season (see Figure 4.7 above). It seems likely that this particular occupant was affected by drafts due to leaving their window open overnight (see Section 4.3.2.2).

However, more of the participants reported being too warm on occasions, e.g. "it's often suddenly too hot in the mornings. Yeah I have to like rush and open my windows and stand by my windows for a bit" [B2 - 22-11-17]. This is borne out in the monitored data, which shows that 6 out of the 9 rooms spent 20% or more of the heating season above 24°C.

Overall though, as with CSA, it would be fair to surmise that the participants were generally satisfied with the conditions in their bedrooms. However, in both case studies there were specific issues that were raised by multiple occupants. These are covered below.

Dry Air in CSA

Five of the CSA participants complained that the air was too dry. These complaints tended to be voiced early in the interview, and without prompting. For instance, "the air is very, very dry in here, it has been really bad, especially during colder times" [A7 - 01-11-17]. The participants then went on to list some of the ways this affected them "sometimes it makes my throat hurt, especially in the morning when I wake up" [A4 - 31-10-17], and "it makes my skin bad so I will get pimples" [A1 - 05-02-18].

Indeed, one participant complained of frequent static shocks because the conditions were so dry, e.g. "I have been using this [points to a humidifier]... although we're not supposed to, but I have to so my throat doesn't hurt and I have less electric shocks" [A7 - 01-11-17]. This final comment also highlights a further issue for the residents; they were not allowed to use humidifiers in order to improve the conditions. The regulation of the ability to control the conditions inside the rooms is explored in greater detail in Section 4.3 below.

Overheating in CSB Townhouse Bathrooms

All participants located in the townhouses in CSB complained of very uncomfortable conditions in the bathrooms. In the townhouses the bedrooms do not have en-suites, and so the bathrooms are located in the central corridor (see Section 3.3.2.1 for details). A chart showing the conditions inside the townhouse bathrooms can be found in Section 5.2.3.6 that provides examples of acute overheating conditions.

The comments on the bathroom conditions were fairly extreme, e.g."the bathroom is boiling. Oh my god. It's so warm, it's just ridiculous really" [B2 - 21-02-18] and "like because the showers are quite small as well, so if I'm in the show, and it is steamy and it's hot, it can be quite kind of claustrophobic it just feels a bit... well yeah very uncomfortable and it's just like get me out" [B4 - 21-02-18]. The uncomfortably warm conditions in the bathrooms was a unanimous view amongst the participants in the townhouses. Although one participant did comment that there was at least one upside to this situation "I mean it's just so hot in there that you can't have a long shower, so at least you're never waiting long for the shower" [B5 - 21-11-17].

Stuffiness in CSB Bedrooms

Similarly all residents in the CSB townhouses complained vociferously of stuffy conditions in their bedrooms. The comments included "well basically if I ever close my window it will get stuffy again" [B3 - 21-11-17], "so stuffy, just so, so stuffy" [B2 - 21-02-18] and "it can get very stuffy in here, yeah, like really bad" [B5 - 21-02-18]. Many residents then went on to highlight how this made them feel, for example "it gets so stuffy overnight that I wake up and I feel really tired, and there have been a few times when I have woken up with a headache and I feel a bit nauseous and things" [B3 - 21-02-18], and "I got like headaches, feeling quite nauseous, just... well kind of like being on your period again. Like almost ill like you can't really face the world. Quite bad if you're a student and then you have to go to university" [B2 - 21-02-18].

Several of them (those that tended to work in their rooms) also commented on how they felt these conditions affected their ability to study "yeah well the air isn't fresh enough so you get a bit agitated, and then I find it kind of hard to concentrate and study in my room, which is kind of frustrating" [B3 - 21-02-18]. Indeed, stuffiness was raised repeatedly by the participants. Furthermore, many indicated how counteracting stuffiness was also the primary driver of window opening (see Section 4.3.1.2 below), which also likely affected their space heating usage (see Section 4.3.4 below).

The participants in the CSB townhouses were then asked if they opened their trickle vents (details of CSB ventilation can be found in Section 3.3.2.3). Firstly, the majority of participants did not know they had trickle vents, or what their purpose was. For instance, when they were pointed out, one participant responded "I didn't know that was there or what it was for. I've never heard of them. I don't think we have them on the windows at home." [B2 - 22-11-17]

Due to the extremely stuffy conditions observed in the townhouses it was suggested by the author to the participants that leaving their trickle ventilators open may help. However, when returning in February, the CSB townhouse participants still responded that they left them shut. The reason was surprising. "I can't have them open it's too noisy. It's like a really loud whistling noise. It's horrible if you're trying to sleep" [B5 - 21-02-18]. Indeed, one participant even confessed to taping up their trickle vent, as even when it was closed it was problematic, for example "then again I have been naughty because I have taped up my little vent thing.... Yeh, because the wind howls through it when it is very windy and its very loud. Like so loud that you can't sleep" [B3 - 21-02-18].

4.2.4 Summary

The above section on indoor conditions shows two clear trends. Firstly, indoor temperatures were generally warm, and that secondly, most of the occupants and the study participants reported being comfortable. However, there were three specific complaints. These were overly dry conditions in several CSA rooms, stuffy conditions in CSB townhouse bedrooms, and overheating conditions in CSB townhouse bathrooms. Now that the conditions (and the occupants views on the conditions) have been summarised, the rest of the chapter will focus on the control of the conditions.

4.3 Thermal Control in the Heating Season

The remainder of this results chapter is split into four sections. They all combine qualitative and quantitative analysis (from several data sources) to answer the first research question.

The first deals with how the participants controlled the conditions in their rooms (i.e. their thermal control strategies). The second considers the adequacy of the controls from the occupant's perspective. The third section looks at the causal factors that affected how they controlled the conditions i.e. why they adopted particular control strategies. The fourth and final section investigates how the adopted control strategies were likely to have affected the thermal efficiency of the buildings.

4.3.1 Thermal Control Strategies

Across both case studies a consistent theme emerged on how the majority of participants controlled the conditions in their rooms. The strategy was to use the window to control the temperature i.e. they closed the window to heat their room, and opened it to cool it down (often cycling frequently between the two).

In the case of CSA (in which occupants had extremely limited control over the heating) opening the window was the only real means of moderating the temperature. Therefore comments such as, “sometimes it gets quite warm, but I just open the window” [A11 - 05-02-18], and “I have to have my window open in order to cool my room, or you know, it just gets far too hot” [A10 - 02-11-17] were common.

In CSB, with the notable exception of two participants, the dominant controls strategy was also to leave the heating on high, and then use the window to control the temperature. For example, a typical comment was “yeah well I keep my radiator on 4 pretty much all the time, and then just open the window if it gets too hot” [B5 - 21-11-17].

4.3.1.1 Radiator Use

The quantitative evidence for this control strategy can be found from observing heater usage, and window opening in the participant’s bedrooms. The radiator surface temperature was monitored from the beginning to the end of the study, as was the internal air temperature. As an example, these two parameters are displayed below in Figure 4.17 for all the bedrooms in CSB.

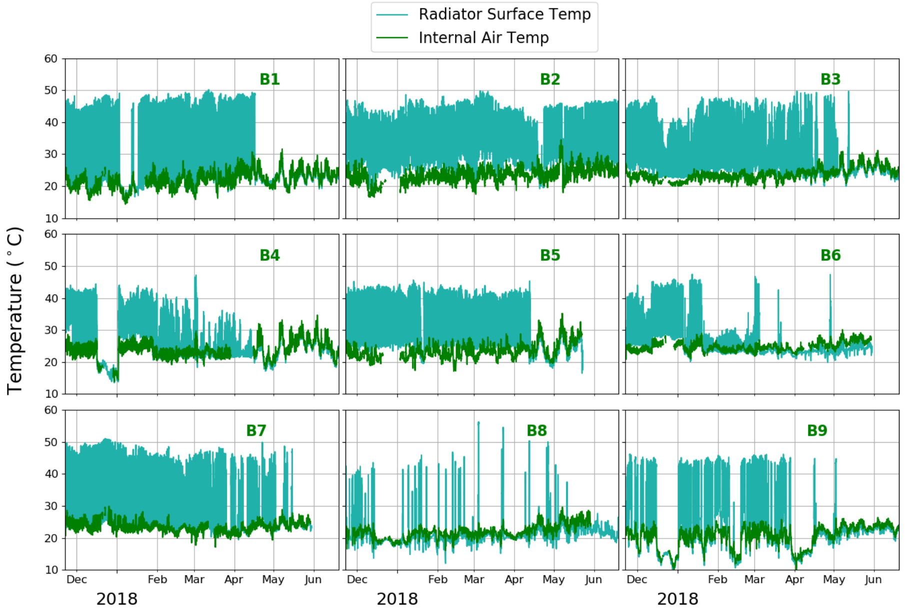


Figure 4.17: Radiator surface temperature and internal air temperature in CSB rooms over the heating season.

This data was used alongside the algorithm developed in Section 3.5.6.1

Room	CSA (%)	CSB (%)
1	82	35
2	84	67
3	88	51
4	91	29
5	84	49
6	75	21
7	86	25
8	95	3
9	96	35
10	96	
11	94	

Table 4.1: The percentage of time the radiators were on in each of the monitored rooms over the heating season.

to determine whether the heating was on or off in each bedroom. These results are displayed below in Table 4.1.

As covered in Section 3.3.2.3, according to the FM in CSB the heating was available between 6am-8am, then 12pm–2pm, then 4.30pm–11:30pm. Outside of these times the heating is off irrespective of the TRV setting, unless the outside temperature falls below 4°C then the heating is automatically triggered. Hence the theoretical maximum amount the heating could be on in CSB (excluding the times when the heating is automatically triggered) is 46%.

However, from analysis of the radiator surface temperature profiles this heating pattern appeared to only occur in the CSB clusterblocks. Therefore in B1-B5 the heating appeared to be available at all times. It is not clear from the configuration of heating system in CSB why this would be the case. The FM team could also not suggest why this occurred, stating simply "that shouldn't have happened" [CSB FM - 01-09-19].

There are three main observations that can be drawn from Table 4.1. Firstly, in this case, providing greater control appears to reduce total heating hours. For instance, even when allowing for the periods in which the heating was centrally switched off in certain rooms in CSB, the average percentage of time in which the heating was in CSA was greater than in CSB. Indeed, it was suggested by several participants in CSA that had they had more control over heating they would have used less heat, e.g. "I'd definitely use less heating, because if I went out for a long time then I would turn the heating down, or even off actually" [A1 - 05-02-18].

Secondly, where occupants do have control, heating usage varied dramatically. This is easily shown by examining two extreme cases from CSB. While B8 had their heating on just 3% of the heating season, B2 used it for 67%. This is equivalent to having the heating on continuously for approximately 5 or 107 days respectively.

Finally, the TRV design strategy in CSA does not appear to have worked. The design strategy was that the TRV would be "preset and locked at approximately 20°C", although the "occupant does have the ability to adjust the TRV by 3°C using a coin". Yet 8 out of the 11 monitored rooms exceeded 24°C for more than 80% of the heating season (see Figure 4.6 in Section 4.2.1 above). Furthermore, the data shows how even when these rooms were overheating, the radiators were still providing more heat.

4.3.1.2 Window Use

In contrast to heating, the opening of windows tends to have two main IEQ drivers; thermal control, and for ventilation. Although, as covered in Section 2.4.3 there are a multitude of potential reasons an occupant may choose to open their window. This section will examine how the participant's used their window. The causal factors relating to window use are explored in Section 4.3.3 below.

Total Window Opening Time

The percentage of time the windows were open or closed over the heating season is shown in Figure 4.18 for CSA and Figure 4.19 for CSB. The charts also show the total amount of time (in days) that this percentage equates to over the heating season for a sample of rooms.

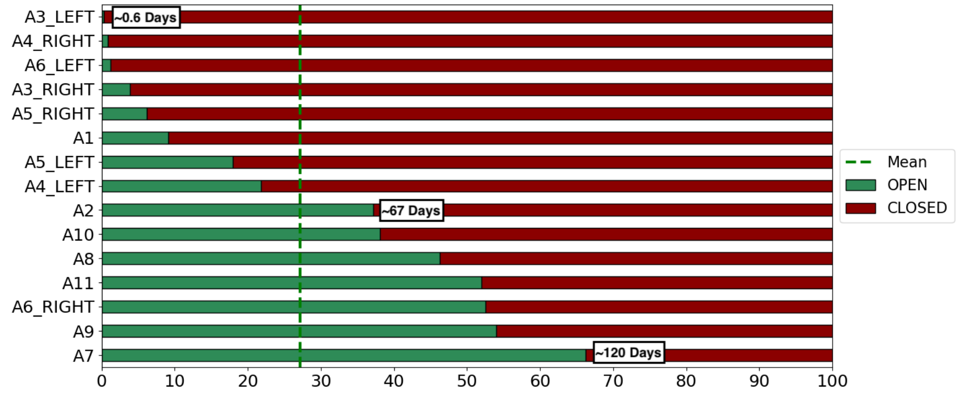


Figure 4.18: The percentage of the heating season in which the windows were open in the monitored rooms in CSA. The total amount of time in days this percentage equates to is added for a sample of the rooms.

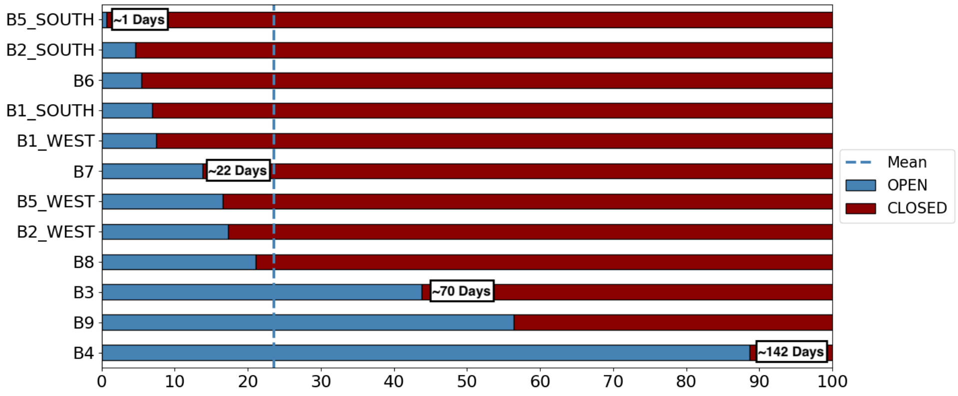


Figure 4.19: The percentage of the heating season in which the windows were open in the monitored rooms in CSB. The total amount of time in days this percentage equates to is added for a sample of the rooms.

Figures 4.18 and 4.19 show that in both case studies windows were often open for substantial periods of the heating season. Indeed, in a quarter of the rooms (across both case studies) the windows were open more than they were closed. Yet, as with heating, the results showed dramatic variation in window opening habits. For instance, in CSA the window opening varied from just 4% of the heating season (A3) to 66% (A7).

Diurnal Variation

The opening of windows occurred throughout the heating season i.e. it was not just limited to warmer periods. For example the diurnal patterns of window opening are shown below in Figure 4.20. This chart shows the average percentage of windows open in each case study over a day in the heating season.

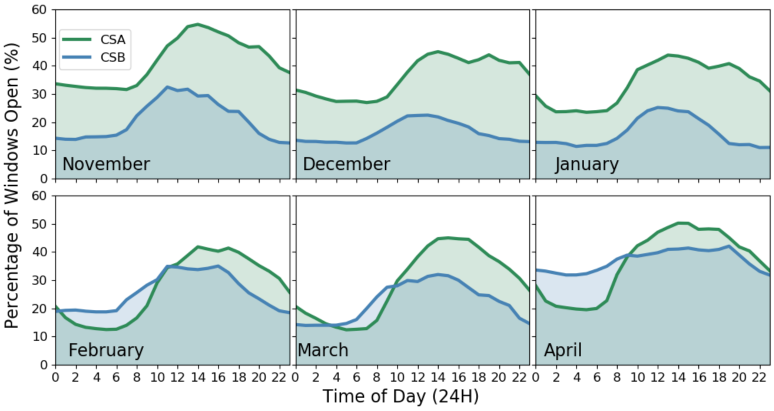


Figure 4.20: Monthly diurnal window opening profiles. The chart shows the average percentage of windows open in each case throughout the day from November to April.

Figure 4.20 shows that there is a clear diurnal pattern to window opening i.e. the likelihood of windows being open increases during the daytime. However, there is limited variation between the different months. Indeed, in CSA between 2-6PM on average 40% of windows were open throughout the heating season. This suggests that regular window opening occurred irrespective of the external conditions.

Frequency & Duration of Openings

Alongside determining the total amount of time the window is open it is important to understand both the frequency (i.e. how often are windows opened or closed) and the duration of the opening events. Figure 4.21 shows the number of opening events that fall within particular time bands, while Figure 4.22 shows the total cumulative time in hours that the window is open within those same time bands.

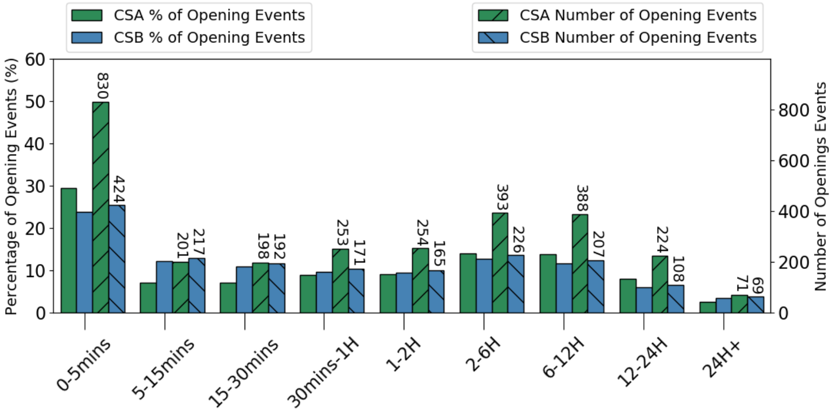


Figure 4.21: The frequency of window opening events for different time periods. The left hand axis shows the percentage of all opening events that fall within that time band. The right hand axis counts the total number of events within that time band.

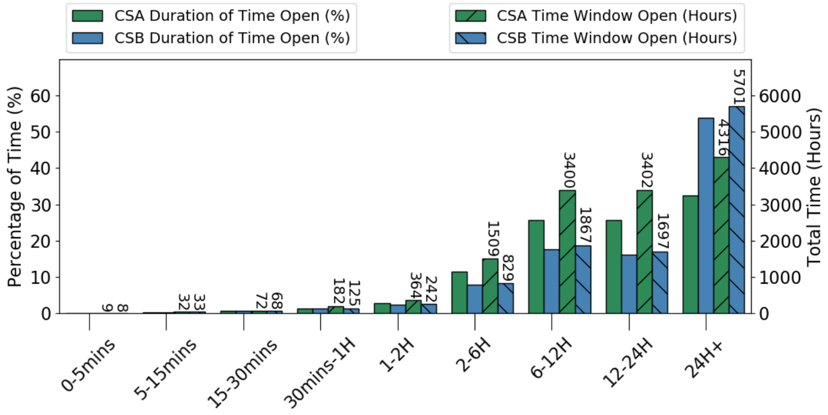


Figure 4.22: The cumulative duration of the time the window is open for different time periods, calculated by adding up window opening events within the same time bands. The left hand axis shows the cumulative percentage of time for opening events within that time band. The right hand axis counts the total time in hours for opening events within that time band.

Figure 4.21 show that a significant proportion of all window opening events occur for relatively short periods. For instance, in both case studies approximately 50% of all window opening events occur for an hour or less.

However, as shown in Figure 4.21, it is the relatively infrequent longer duration events that cumulatively amount to a large proportion of the total time the window is open. For instance, although events longer than 24 hours make up just 3.6% of all window opening events in CSB, they are responsible for 56% of the cumulative time the windows are open. In other words, while most window openings are short, it is the longer duration events that make up a large proportion of the total time the window is open. The importance of this finding is discussed in Section 6.2.2.

4.3.1.3 Heating On and Window Open

Another piece of evidence showing that occupants tended to use their windows for thermal control is the amount of time in the heating season in which the heating was on, and the windows were open. This is shown in Table 4.2 for CSA and CSB. For the rooms with two windows the percentage of time that the heating was on and at least one window was open has been calculated.

Room	Htg & Win (Days)	Htg & Win (%)
A1	11.4	4.5
A2	92.0	36.0
A3	4.7	1.8
A4	41.5	16.3
A5	27.0	10.6
A6	123.9	48.5
A7	183.9	72.0
A8	99.7	39.0
A9	105.4	41.3
A10	71.2	27.9
A11	123.3	48.3

(a) CSA

Room	Htg & Win (Days)	Htg & Win (%)
B1	2.5	1.6
B2	22.3	14.0
B3	23.8	15.0
B4	39.8	25.1
B5	16.9	10.6
B6	1.1	0.7
B7	7.3	4.6
B8	0.4	0.2
B9	14.5	9.1

(b) CSB

Table 4.2: The total time the window was open and the heating was on at the same time in the participant's bedrooms over the heating season.

If the windows were only used as a last resort for thermal control then you would have expected to see the heating switched off before the windows were opened. Yet many rooms spent significant periods of the heating season with the heating on and their windows open. The behaviour observed in the monitored rooms in CSB was (according to the FM at CSB) representative of the majority of occupants at that PBSA. During the interview with the FM he commented “because the number of times I walk around the site in the midst of winter and a large proportion of the windows are open, and you know I just think... what a waste” [CSB FM - 01-09-19].

4.3.1.4 Summary

The above section has suggested that a common control strategy in these case studies was to use the window as the primary means of thermal control. This was first made clear during the interviews in which the participants explained how they controlled the conditions in the room. The monitoring of environmental conditions and occupant behaviour was then shown to provide further evidence for the strategy. This was evidenced by the fact that for many rooms in both case studies the heating was mainly on, while the windows were opened frequently, often for sustained periods, and also while the heating was on.

4.3.2 The Adequacy of the Controls

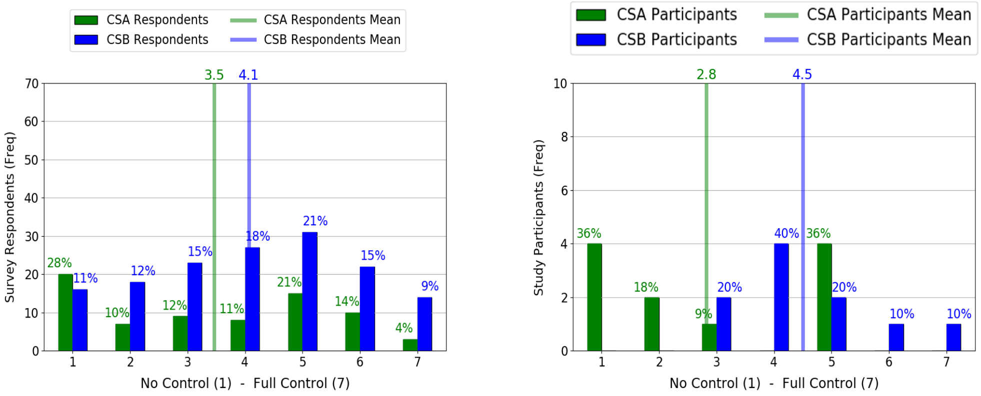
The section above identified a common control strategy that was widely adopted in both case studies. However, it did not comment on whether the participants thought this was an acceptable (or preferable) controls strategy, or indeed their views (or the rest of the occupants views) on the controls more generally. This is be covered in the section below.

4.3.2.1 Heating Control Survey Responses

In the survey the occupants were asked “how much control do you personally have over the heating?”. The results are displayed below in Figure 4.23.

Figure 4.23 shows that in CSA the respondents generally felt there was a lack of personal control over the heating, with the highest percentage of respondents answering 1. In CSB the results were far more mixed. The responses were distributed between “no control” and “full control”.

These responses broadly reflect the control the respective building occupants had. Yet on their own they provide relatively limited insight. Hence the majority of the evidence in this section comes from analysis of the



(a) Survey Respondents

(b) Study Participants

Figure 4.23: Survey results for the question "how much control do you personally have over the heating?"

interviews. These are used to provide a richer understanding of the participant's perspective on the controls.

4.3.2.2 Controls at Night

In general the participants suggested that, purely from a comfort perspective, the control strategy was broadly acceptable during the daytime. However, several did suggest that using such a strategy meant that they were frequently choosing between being too warm (with the window closed), or too cool (with the window open). The evidence for this is presented in Section 4.3.3.1 below.

However, the main problem with this strategy (excluding space heating implications for now) was that it did not work for the participants overnight. This is for two reasons. The first is that the majority of occupants felt that they could not open their windows overnight. This was primarily because of noise, for example "although I find the train is noisy if I open the window. So I have to choose between being hot or having the train noise" [A8 - 30-10-17] or "unfortunately I have to keep them closed at night, because it's just too noisy" [A6 - 07-02-18]. However, there were also other issues raised regarding window opening at night, including insects, pigeons and security concerns.

The other problem with this strategy was that the windows could not be adjusted whilst they are sleeping. Therefore many felt that they had to choose between being too hot, or too cold whilst they slept. For example, “well I’m either too warm with it shut or too cold with it open, so like I said my strategy has been to leave the window open for the longest time before you go to bed, and then shutting it just before you go to sleep and hope you fall asleep before it gets too hot” [A11 - 05-02-18]. Or alternatively “it gets too hot and stuffy if I don’t open it, but then there’s a draught if I do, and obviously I’m sleeping right by the window so the draught is really not nice” [B3 - 21-02-18]. A diagram showing how the participants in certain rooms in CSB were affected by the draft is shown in Figure 4.24.

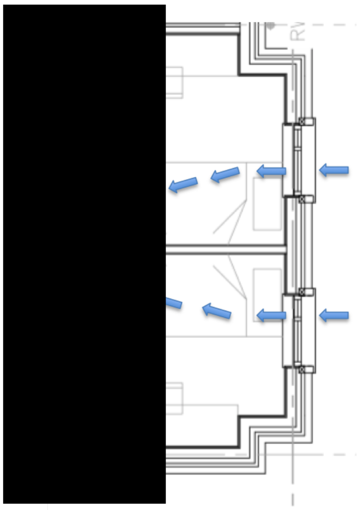

[redacted]

Figure 4.24: Diagram showing how the draught would cross directly over the bed in the CSB townhouse bedrooms.

4.3.2.3 Confusion

In CSA there was confusion over whether the heating system was adjustable or not. According to the FM the radiator could be adjusted by between 1-3°C using a coin, but not be switched off altogether (see Section 3.3.1.3 for details of the system).

The responses varied from certainty in its adjust-ability “yeh well I just use a coin for the radiator if I want to change it” [A6 - 30-10-17], to adamant that it cannot be changed “you can’t change the heating... it’s just on all the time” [A10 - 02-11-17], to everything in between “hmm I’m not sure whether you can change it or not... I heard from someone that you need to call the maintenance guys if you want to change it" [A11 - 30-10-17]. Thus depending on whether the occupants knew whether they had the ability to adjust the radiator or not may have influenced how they answered the survey question on heating control, which is shown in Figure 4.23 above.

In CSB the confusion was over the availability of heating at different times of day. In general it was known that there were periods during which heating was not available (although this was not universal). For instance, while one participant professed they were clueless "I don't know how it works and I don't know what it does" [B1 - 22-11-17], another expressed scepticism at the distributed information "we have a little book that says that there should be timings but I don't know if they're really quite accurate" [B2 - 22-11-17], while another suggested that heating was available at all times "yeah the heating is always on night and day... that's why it is always so hot" [B8 - 13-02-18].

4.3.2.4 Centrally Controlled System

Despite the differing accounts about the timing of the system in CSB what united the participants was the view that restricting the heating to between certain times was generally unfair e.g. "yeah sometimes during the day it does get cold, and the radiator's not working, which doesn't seem right.. you know considering how much we're paying" [B2 - 21-02-18]. This also fed into the general feeling that the occupants wanted greater control, which is covered in Section 4.3.2.5 below.

4.3.2.5 More Control Please

There was near unanimous consensus across both buildings that the participants wanted greater control over the heating system in their rooms. Indeed, only two participants professed that they were satisfied with the controls. One in CSA was happy for the conditions to be controlled centrally as they thought their window was sufficient "yeah I think it works fine. As long as I keep the window open it feels pretty good" [A9 - 06-02-18], while the other in CSB (the participant who rarely ever used their heating) thought it was very responsive "the radiator is really really good actually. It heats the room up really quickly" [B8 - 21-02-18].

In CSA the complaints were primarily focused on gaining even limited control over the heating system "firstly I would just like to control the temperature a bit. You know when to switch it on and when to switch it off. Particularly when to switch if off" [A11 - 05-02-18], and "I really haven't had a need to use it so far so why is it switched on? I don't get why I can't turn it off if I want to" [A10 - 02-11-17]. While in CSB the complaints were primarily focused on the heating schedule and getting too much heat at certain times, whilst receiving insufficient heat at others, e.g. "you are always worrying about what time it turns on and off and then timing it correctly to heat up your room at the right time" [B6 - 13-02-18].

In addition, when asked how greater control would affect their heating usage, the majority of the participants suggested they thought they would use less heating. For instance, "I would definitely turn it off during the day, so then I wouldn't have to leave my window open to not return to a sauna" [A10 - 05-02-18], and "I would use less heating because if I went out for a long time then I would turn the heating down, or even off" [A2 - 05-02-18]. However, it should be noted that two occupants did suggest that they may use more heating if they had complete control, for instance "I think I would tend to turn up the heat if I was using it, so I think it's a better thing that I'm not controlling it" [A9 - 06-02-18].

4.3.2.6 Summary

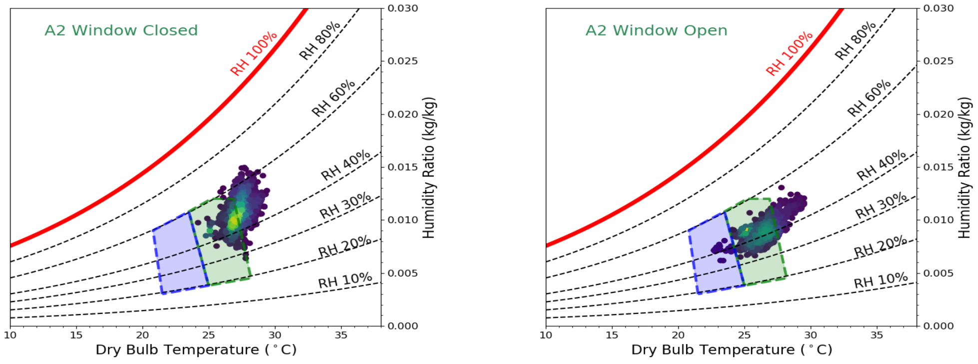
The above section has shown that in CSA the respondents generally felt there was a lack of personal control over the heating, whereas in CSB the results were distributed more equally between "no control" and "full control". Meanwhile analysis of the interviews highlighted several clear themes, such as the preference for more control, confusion at how the controls work, the unfairness of centrally controlled systems, and that using the window for thermal control was an ineffective strategy overnight.

4.3.3 Thermal Control Causal Factors

Thus far this results section has described the indoor environmental conditions, how those conditions were brought about (i.e. how were the conditions controlled in the participant's rooms), and what were the participant's views on the controls. This next section will explore the reasons why the participants controlled their rooms in this particular manner.

4.3.3.1 Preventing Overheating

In CSA, in which occupants could not control the heating, windows were used in order to prevent their rooms from becoming overheated. This can be clearly shown using psychometric charts by separating the times during which the window was open, and when it was closed. This is shown in Figure 4.25 for room A2.

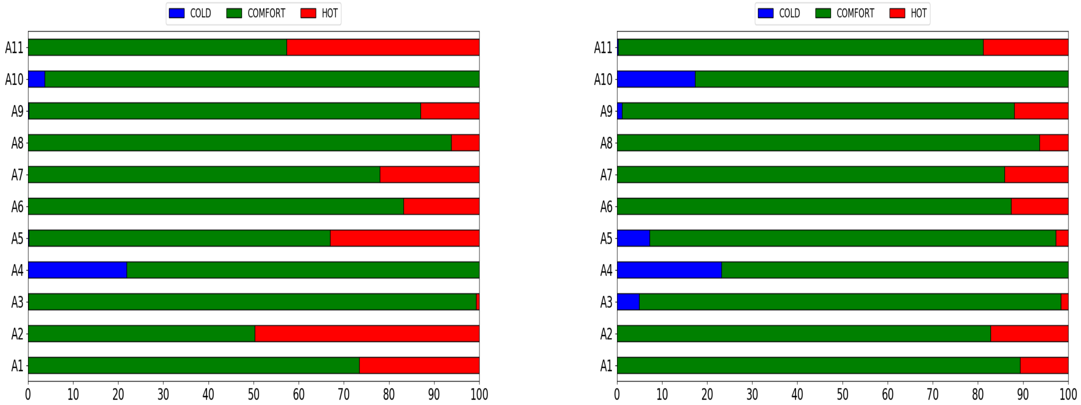


(a) Window Closed **(b)** Window Open

Figure 4.25: Psychometric charts showing the conditions inside room A2 over the heating season for different window states. The green area represents the 0.5 ***clo*** comfort band, while the blue box represents the 1 ***clo*** comfort band.

Figure 4.25 shows that the amount of time the room temperatures are within the comfort bands is greater for when the window is open, than when the window is closed. According to the participants, clothing levels equating to roughly 0.5 ***clo*** were common nearly all year round. Figure 4.25 helps to explain why this may have been the case.

These psychometric charts have been used to calculate the percentage of time in which the conditions are within the 0.5 to 1 ***clo*** comfort bands for when the windows are either open or closed. The results and are shown below in Figure 4.26.



(a) Window Closed

(b) Window Open

Figure 4.26: Charts showing the percentage of time over the heating season in which the internal conditions inside the CSA study bedrooms were within the 0.5 to 1 ***clo*** comfort bands for different window states i.e. open or closed.

The majority of the monitored rooms in CSA spend a greater percentage of their time within the comfort band area when the window is open, rather than closed. Thus Figure 4.26 shows that for many participants the pursuit of keeping their rooms comfortably cool during the heating season depended upon opening their window regularly.

In addition to the monitored empirical conditions there is also a large amount of supporting qualitative evidence from the interviews. In fact, the majority of participants in CSA expressed how they had to open their windows regularly to prevent overheating. For instance, “I have to have my window open or it gets far too hot” [A2 - 30-10-17], and “I mean, if I close my window then it does get hot and it gets hot fast” [A11 - 05-02-18], and “if I shut the window then it gets hot... like really hot” [A8 - 30-10-17].

4.3.3.2 Inadequate Ventilation

The second causal factor, which affected the townhouse rooms in CSB most acutely, was inadequate ventilation. In this case, participants felt that they had to open their windows in order to prevent their rooms becoming stuffy. On some occasions, this was despite the thermal discomfort that it caused them. In other words, they prioritised fresh air over some thermal discomfort. The stuffy conditions in the CSB townhouse rooms have been shown above in Section 4.2.2.1.

The need to open windows to prevent stuffiness, and the corresponding effect on the environmental conditions in the room (and the radiator's response) can be seen by combining multiple variables onto one chart. This is shown below in Figure 4.27 for room B3 during a period in mid February 2018.

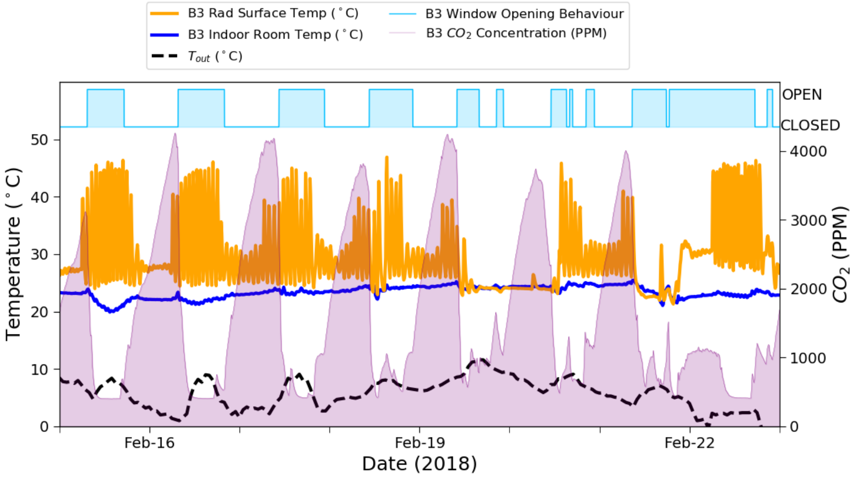


Figure 4.27: Chart showing frequent window opening, heating usage and stuffy overnight conditions in room B3 during a cold period in February 2018.
KEY DESCRIPTION:
Window opening is shown at the top. The window is open if the area is shaded. CO_2 levels are the shaded area at the bottom of the chart, and are shown on the right y-axis. Internal temperature, radiator surface room temperature, and external temperature are shown on the left y-axis.

Figure 4.27 shows that during the night (when the window is shut) the CO_2 concentration rises to approximately 4000PPM. Therefore during the day, when this occupant liked to study in their room, they opened the window to provide more fresh air. The opening of the window then causes a response from the radiator (as the air temperature in the rooms drops the TRV valve opens up to provide heat to the radiator).

In some cases (e.g. February 15th), despite the radiator turning on it is still not sufficient (for a time) to prevent the internal room temperature from dropping. Thus Figure 4.27 shows how inadequate ventilation is leading to window opening, which in turn necessitates the need for heating to maintain the internal room temperature.

The events in Figure 4.27 were also described by the participant directly. The following extract is provided verbatim from the second interview conducted with the participant in room B3 on the 21st February 2018. The entire extract of the interview has been provided here as it provides an illuminating explanation of Figure 4.27, and an illustration of the insight that can gained from combining qualitative and quantitative data.

So generally how comfortable have you found your room?

Hmm well if I don't have my window open then it gets very stuffy, so I try and have my window open to get fresh air in when I'm in here, but then this can get a bit chilly when I'm working because of the draft, but it's not too bad.

So if you have your window shut how does it feel?

Stuffy. Yes, definitely stuffy. And I'd rather be a bit cold when I'm trying to work than find it really stuffy, because then like I can't concentrate and I get tired.

And so you think that can affect your studying?

Yeahhh the air isn't fresh enough so you get a bit like agitated.

So that makes you open your window regularly?

Yes.

And then are there any particular times of the day you notice it being stuffy?

Mornings. And I think generally if I am just in my room working and I don't have the window open.

So how do you notice the stuffiness in the morning?

Well I can wake up and I feel really tired, and there have been a few times when I *have woken up with a headache and I feel a bit nauseous and things. Yeah that type of thing. So basically you wake up and think "I shouldn't wake up feeling like that".*

So what stops you leaving your window open at night?

Well it is just too cold. Because the draft goes right over my bed. And if I open the trickle vents then it really howls. But yeah if I wasn't right next to the window I probably would have it open a bit more.

There's also a clear counter example to the behaviour above. In bedroom B8, in which the participant reported that the air is "fine, yeah I haven't had any problems with it" [B8 - 21-02-18], the window was used infrequently, and therefore so was the heating. Despite the lack of heating the room was shown to remain relatively warm. This participant also reported staying in their room during the day as they "had to do lots of reading for uni, so I prefer to do this in my room" [B8 - 21-02-18]. The exact same chart as shown above in Figure 4.27 for B3, is shown in Figure 4.28 for room B8.

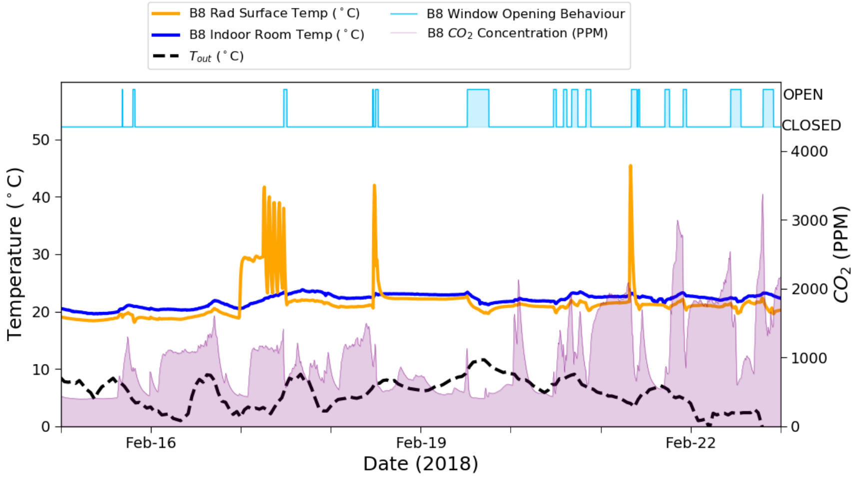


Figure 4.28: Chart showing infrequent window opening and minimal heating usage in room B8 during a cold period in February 2018.
KEY DESCRIPTION:
Window opening is shown at the top. The window is open if the area is shaded. CO_2 levels are the shaded area at the bottom of the chart, and are shown on the right y-axis. Internal temperature, radiator surface room temperature, and external temperature are shown on the left y-axis.

Two fairly extreme examples were selected to highlight how IAQ issues can affect occupant behaviour, and therefore the demand for heat. The charts show that where ventilation is adequate, window opening can be reduced, which can also minimise heating use. Moreover this can occur without significantly lowering the internal temperature in the room, as should be expected in buildings that adhere to modern standards for energy efficiency (see Section 3.3.2.2 for details on the energy efficiency characteristics of the PBSA).

4.3.3.3 Poor Understanding

There is evidence from the interviews that occupants did not properly understand the heating system. This has been covered above in Section 4.3.2.3. In short, in CSA occupants did not know whether they could adjust their heating, whereas in CSB occupants did not know the heating timing schedules, or how their TRVs worked. Thus comments such as “I don’t know how the control works and I don’t know what it does” [B1 - 22-11-17] were common.

Another factor that seemed important to residents in CSB was to make sure they received heat while it was available. Hence “well I keep my radiator on all the time because I don’t know when the heat system comes on and off here so I just leave it on because I don’t know... and I don’t want to miss out on the heat in case my room gets too cold” [B5 - 21-02-18]. It seemed that for many participants leaving the heating permanently on felt like the no-lose option; it was the best option for ensuring your room was sufficiently warm, and if it became too warm, then you could just use the window to adjust the temperature. These ideas are further explored in the discussion in Section 6.2.

4.3.3.4 Responsiveness

Many participants expressed how they wanted instantaneous thermal change within their bedrooms when they took adaptive actions, and that it was opening the window that provided this. The most telling comment was the following; “I use the window to control the temperature because it is just so instant, whereas I turn the knob on the radiator and nothing really seems to happen” [B2 - 21-02-18]. In this response the participant highlights the allure of using the window for thermal control.

Figure 4.29 below shows the window being used to adjust the temperature in A2 in early February 2018. It can be clearly seen how the temperature tracks down when the window is open, but also how quickly it returns to the residual temperature of approximately 27°C once the window is closed again.

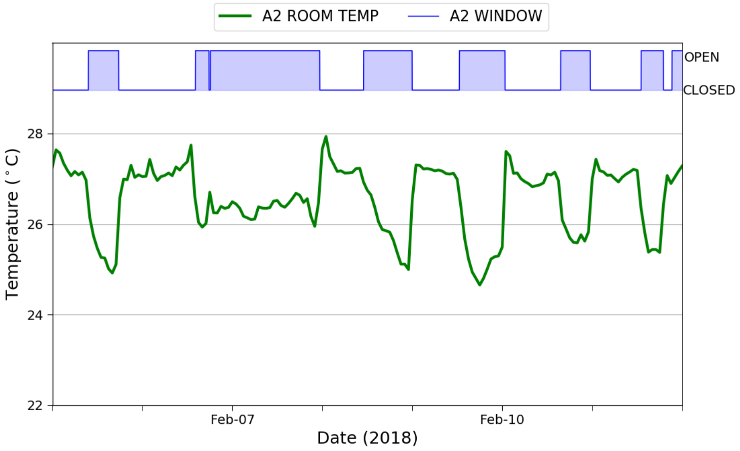
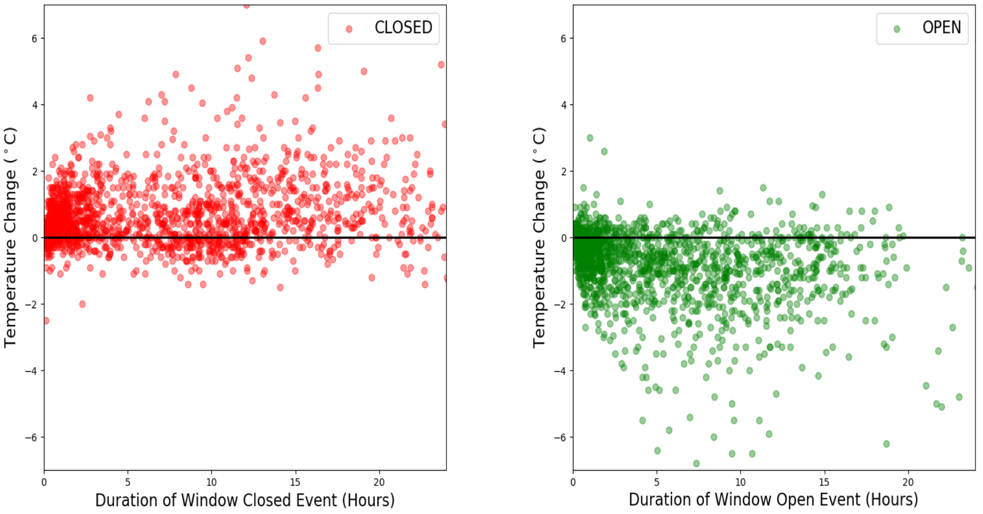


Figure 4.29: Chart showing the reduction or increase in internal temperature in room A2 during window opening or closing events respectively.
KEY DESCRIPTION:
In this chart window opening is shown at the top. The window is open if the area is shaded. The internal temperature is shown on the left y-axis.

This trend can also be shown across all rooms in CSA. To do this the change in temperature can be calculated for window events i.e. periods in which the window is either open or closed, but does not change state. This is shown below in Figure 4.30a (for open window events) and in Figure 4.30b (for closed window events).

Figure 4.30a shows how when the window is closed the internal temperature is generally increasing, whilst Figure 4.30b shows when the window is open the internal temperature is generally decreasing. Indeed, Figure 4.30b also shows that it tended to be the longer opening events that lead to the more significant reductions in internal temperature (e.g. a reduction 3°C or more). As such, targeting these longer opening events could represent an effective energy conservation measure. This will be discussed further in Section 6.3.



(a) Window Closed

(b) Window Open

Figure 4.30: The internal temperature change in rooms in CSA during periods when the window was either closed or open. The duration of the window event is also shown.

4.3.3.5 Financial Implications

An additional factor that appeared to influence behaviour is the fact that, compared with other rental properties, there is no financial incentives (or penalties) for different heating practices. In these particular case studies (as is common in PBSA; see Section 2.1) the occupants rental costs are fixed regardless of their energy usage. The majority of residents were clear that they thought their behaviour would change if they were paying for their heat directly (rather than it be included in the rental fee). For example, “I think if I was paying for my heating that would change my behaviour. Definitely, yeah. Because I would think about it more whereas at the moment it is kind of like ahhh I don’t pay for it. Well I do pay for it I guess but in a lump sum so I’m like ahh it’s fine” [B1 - 21-02-18].

This can be clearly shown during the occasions at which participants left their rooms unoccupied for extended periods with the window open, and the heating on. An example is shown below in Figure 4.31 for room B5.

In Figure 4.31 the room was unoccupied between the 15th February to

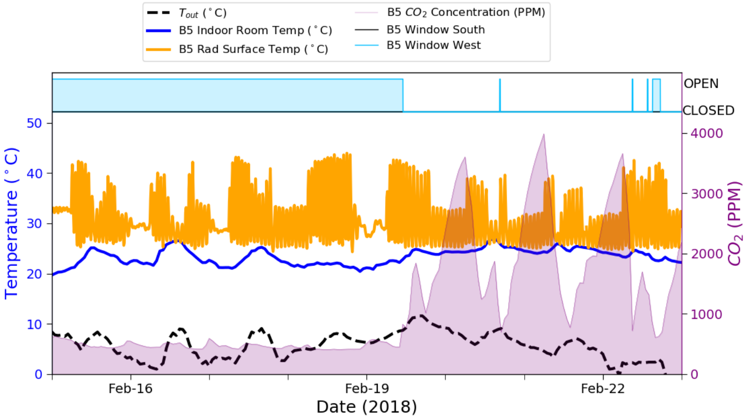


Figure 4.31: Chart showing the heating on and window open in room B5 while it is unoccupied during the heating season.
KEY DESCRIPTION:
Window opening is shown at the top. The window is open if the area is shaded. CO_2 levels are the shaded area at the bottom of the chart, and are shown on the right y-axis. Internal temperature, radiator surface room temperature, and external temperature are shown on the left y-axis.

midday on the 19th February. This can be seen from the CO_2 concentration, but was also confirmed during the interviews. Over this period the occupant had left their heating on and one of their windows open, yet there is no financial impact for this behaviour. Similarly, Table 4.2 in Section 4.3.1.3 shows how frequently the participants left their windows open and had their heating on.

4.3.3.6 Summary

The section above has argued that there were five interacting factors that were the main drivers of the window opening thermal control strategy identified previously in Section 4.3.1. These were to prevent overheating, inadequate ventilation, poor understanding, the desire for responsiveness, and a lack of financial implications. Thus far this chapter has only considered the comfort implications of how the rooms were controlled. Yet there is also energy usage implications of frequent, and long lasting window opening during the heating season. This will be explored below.

4.3.4 Window Heat Losses

The opening of windows throughout the heating season has inevitable consequences for heating usage (and therefore overall energy demand). This study aims to estimate the amount of heat loss via window opening to examine the relative importance of window opening to overall thermal performance. This is done in this thesis by constructing a simplified model of the heat transfer processes occurring in individual rooms (see Section 3.5.8 for details).

4.3.4.1 Ventilation Rates

The first step in understanding heat losses in the PBSA bedrooms was to assess the ventilation rates in each bedroom with the windows closed, and open. This was done using CO_2 decay curves (see Section 3.5.7.2 for a description of the methods). The estimated air change rates for CSA are plotted below in Figure 4.32. Below which Figure 4.33 shows the distribution of air change rates in the CSA monitored rooms for both window states.

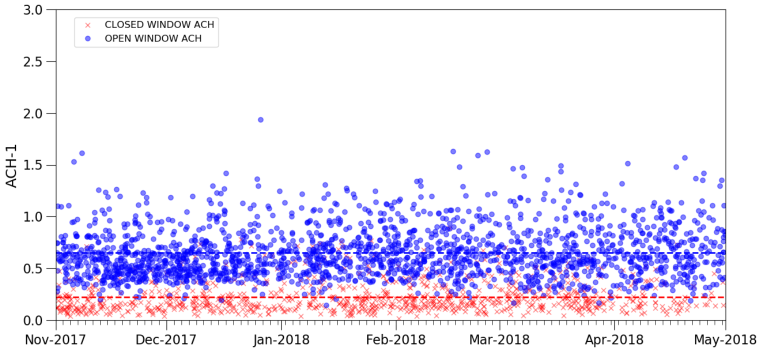


Figure 4.32: Estimated air change rates in CSA when the window was open or closed.

The first observation from Figure 4.33 is that many rooms were under ventilated without their windows open. The only rooms that come close to the advised 0.5 ACH (HM Government, 2010a), are the three rooms with larger individual mechanical ventilation systems.

Another observation from Figure 4.33 is that even with the windows open, air change rates still averaged around 0.5-0.6 ACH. This is significantly below purge ventilation rates, which are defined as 4 ACH (NHBC, 2012). This has important implications for summer thermal comfort (see Chapter 5). Indeed, summer ventilation rates may be lower still due to reduced ventilation driving

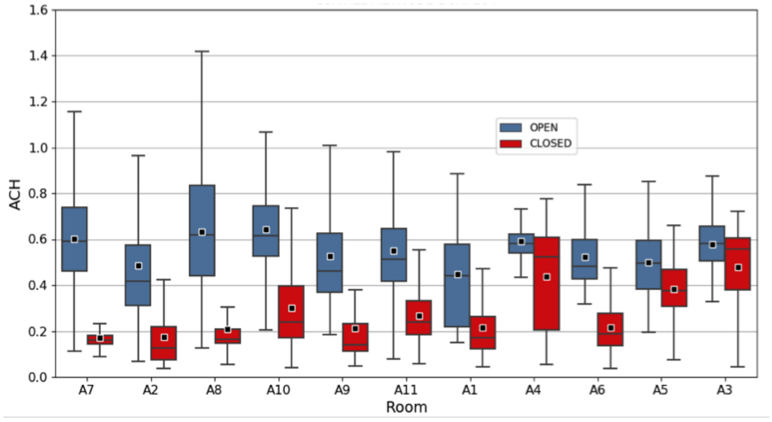


Figure 4.33: Distribution of estimated air change rates in CSA when the window was open or closed. The mean value is shown by the black square dot.

forces i.e. smaller internal and external temperature differentials, and reduced average wind velocities (MetOffice, 2018).

The ventilation rates were also estimated for the bedrooms in CSB (CO_2 levels were not recorded in room B9 so the ventilation rate could not be plotted for this room). These are shown below in Figures 4.34 and 4.35.

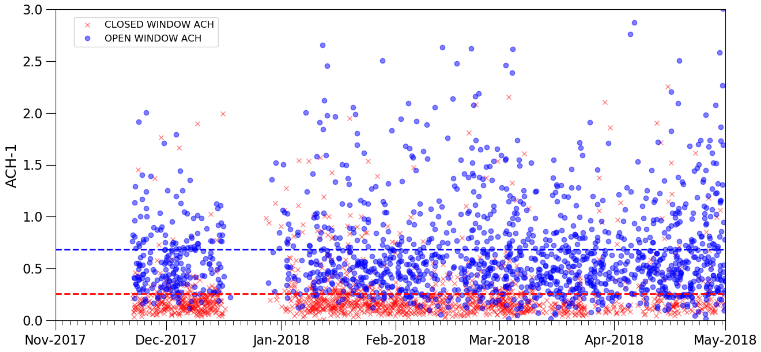


Figure 4.34: Estimated air change rates in CSB when the window was open or closed.

Similarly to CSA the ventilation rates with the windows closed are low; this correlates with the CO_2 concentration IAQ issues identified above in Section 4.2.2.1. Figure 4.35 also shows how the ventilation rate with the window open was highly variable between rooms. The rooms with two windows at differing angles all had higher ventilation rates. The effect was

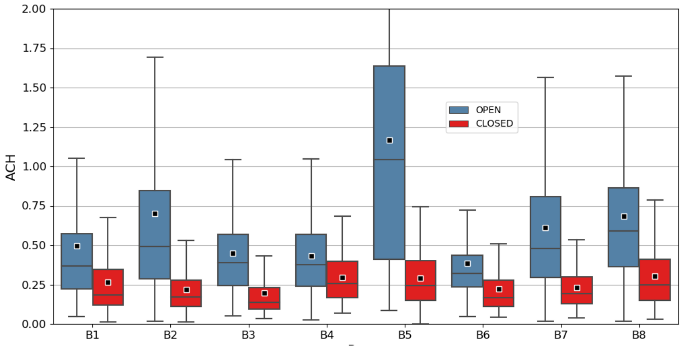


Figure 4.35: Distribution of estimated air change rates in CSB when the window was open or closed. The mean value is shown by the black square dot.

most pronounced in rooms with windows facing south and west.

4.3.4.2 Heat Losses

The ventilation rates, alongside hourly internal and external temperatures, were used to estimate the heat losses throughout the heating season for each of the rooms. The methods used to estimate heat losses are outlined in Section 3.5.8. However, it is worth repeating three particular assumptions again.

1. No heat is lost to external rooms, or corridors (i.e. all losses are via conduction through the external wall, or ventilation).

2. The window closed ventilation rate is a combination of infiltration and planned ventilation. In CSA it was assumed that all ventilation with the window closed was via the MVHR, as it was not possible to disaggregate between the two.

3. The heat losses attributable to the window being open is estimated by subtracting the ventilation rate with the window closed from the ventilation rate with the window open.

4. The window is considered to be open for the entire hour when it is open for more than 80% of that hour (otherwise it is assumed to be shut for the entire hour).

Under these assumptions the daily heat losses can be calculated for each room. An example is shown below in Figure 4.36 for room A6.

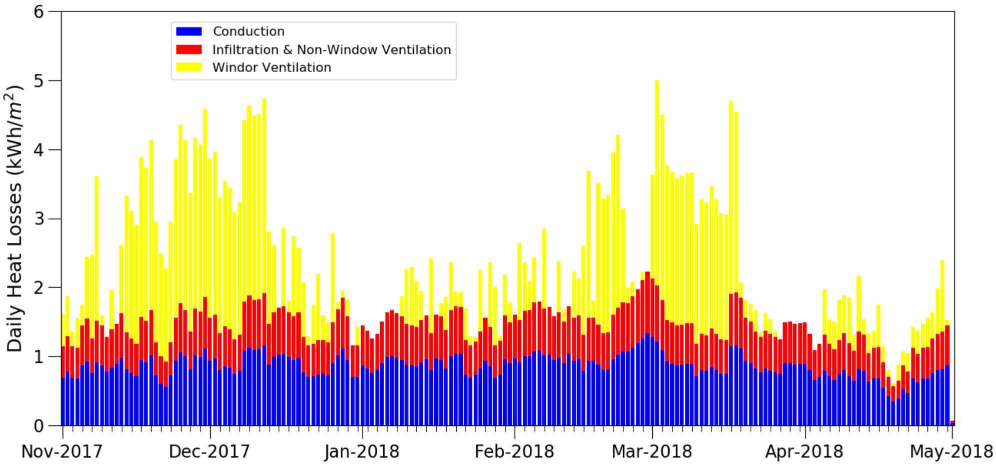


Figure 4.36: Chart showing the daily estimated heat losses in room A6 over the heating season

Figure 4.36 shows how the modelling indicates that the total amount of heat lost through the window can be significant. The losses are highest on days in which the window is left open for extended periods, and the difference between the internal and external temperature is high.

The heat losses were estimated for each room, after which the total heat losses via the different mechanisms were summed over the whole heating season. This is shown below in Figure 4.37. The heat losses have been divided by the floor area in each room to calculate the amount of heat lost per Usable Floor Area (UFA).

Figure 4.37 shows that the heat lost via windows was estimated to be as high as 44% of the total heat losses in certain rooms. Thus if window opening could be reduced (as long as adequate IAQ could be maintained) the modelling suggest that there are sizeable thermal savings available. Figure 4.37 also shows how in the rooms with bigger, more powerful MVHR units (e.g. A3, A4, A5; see Section 3.3.1.3 for details) window opening during the heating season was reduced, and therefore so were thermal losses via the windows. Although

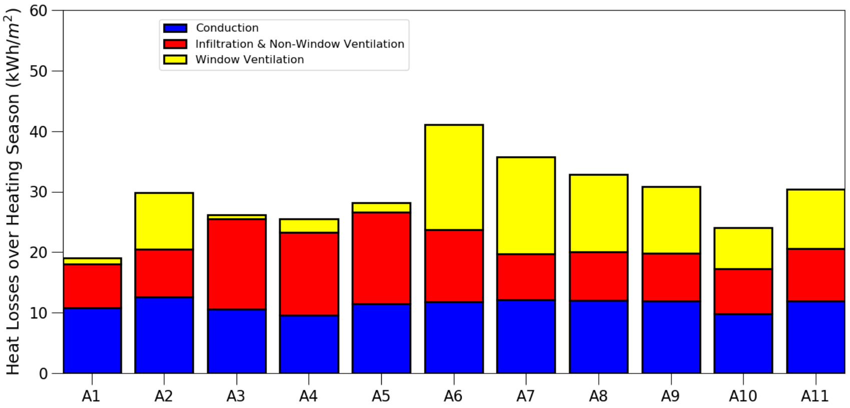


Figure 4.37: Estimated heat losses for the monitored rooms in CSA over the heating season.

the higher ventilation rate delivered through the MVHR system increased the thermal losses via “infiltration and non-window ventilation”.

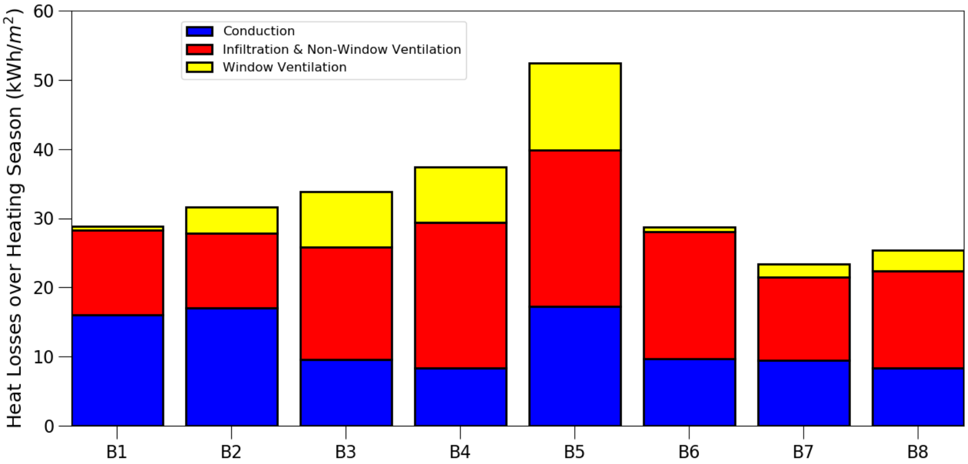


Figure 4.38: Estimated heat losses for the monitored rooms in CSB over the heating season.

Figure 4.38 also shows that the heat lost via the windows was estimated to be significant in the rooms in which the windows were used regularly. Although in the dual-aspect rooms the losses were proportionally lower due to the increased conduction losses from having two externally facing walls. Nevertheless, the modelling suggests that tackling prolonged window opening during the heating season could lead to relatively significant thermal savings.

However, it is important to note that many of the rooms were under ventilated with their windows closed. This can be evidenced by the low estimated air change rates with windows closed (see Figures 4.33 and 4.35) and also the high CO_2 concentrations in the bedrooms, particularly in CSB (see Section 4.2.2.1). As such, window opening was required in these rooms to maintain adequate IAQ. This view was supported by interviews from the occupants (see Section 4.2.3.2).

Hence a proportion of the losses estimated from window opening would still occur if the bedrooms delivered higher background ventilation rates (e.g. through trickle vents with greater opening areas), as appears necessary to provide adequate IAQ. Although the extra losses from planned ventilation could be significantly reduced if an MVHR system were used. This topic will be discussed further in Section 6.3.

4.4 Summary

This chapter began by showing how the internal conditions were generally warm and stable, and that the CSB townhouses suffered from stuffy conditions. It then went on to show that the occupants and participants reported being generally comfortable during the heating season, although there were a few specific areas of complaint.

The chapter then described how many of the participants used their window as the primary means of thermal control. This was generally viewed as an acceptable (if not optimal) strategy. The most problematic time being at night when the continuous adaptive control required was not possible, and so occupants had to chose between being uncomfortably hot and stuffy, or cold with a draught.

The section argued that there were five interacting factors that drove this behaviour; preventing overheating, inadequate ventilation, poor understanding, the desire for responsiveness, and a lack of financial implications. Finally, a model was used to show that the regular opening of windows was likely to be responsible for a significant proportion of the total heat losses in certain rooms i.e. those that left their windows open for extended periods.

In summary, the conditions were warm (and in certain rooms stuffy), but the occupants generally felt comfortable. This was because they knew they could take adaptive action (opening the window) that lead to a rapid thermal change in the internal environment of the room i.e. they had control of the conditions. However, this control strategy was ineffectual at night, and likely contributed to considerable thermal losses.

Chapter 5

Overheating Adaptation

This chapter will cover the assessment of the thermal conditions in the case studies over the late spring and summer period. The first sections will provide an overview of the conditions. This includes a section on the weather conditions, and an evaluation of the indoor conditions (including an assessment of overheating). Again, these sections are not the focus of this chapter, but are considered necessary in order for the reader to contextualise the participant's adaptive responses to the conditions. Hence the second section will assess occupant behaviour over the period. It will explore the adaptive actions taken by the occupants to alleviate overheating, and whether these were successful.

5.1 Summer Weather Conditions

Figures 5.1 and 5.2 show the daily minimum and maximum external air temperature at the case study locations over the 2018 summer monitoring period. As in Section 4.1, the external temperatures have been compared the Met Office monthly average minimum and maximum temperatures at the same locations (MetOffice, 2018). These values represent the average daily minimum or maximum air temperatures for each month between 1981-2010

The Summer of 2018 was a record breaking year for England; officially becoming the hottest on record since 1976 (MetOffice, 2018). An official heatwave was declared between the 22nd June and 7th August 2018. This

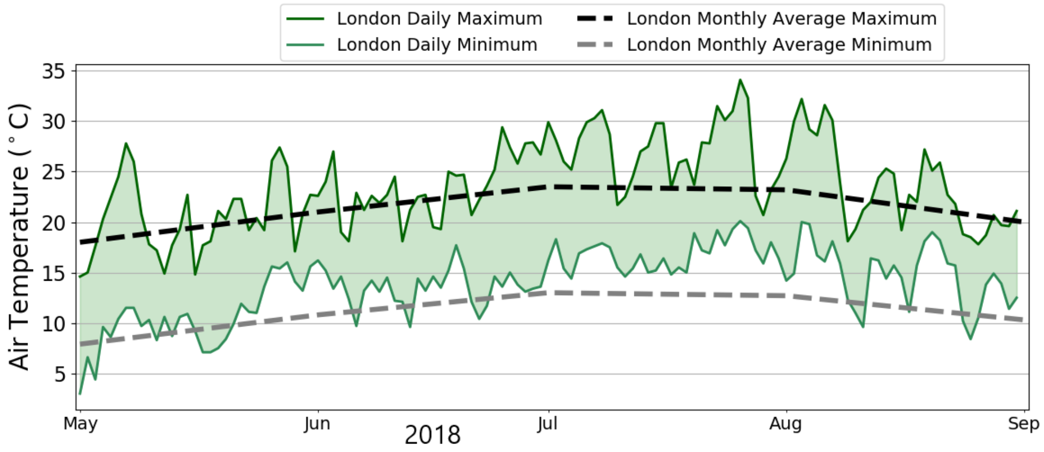


Figure 5.1: Daily minimum and maximum external air temperatures in London over the summer monitoring period compared against Met Office historical monthly minimum and maximum temperatures for the same location (MetOffice, 2018)

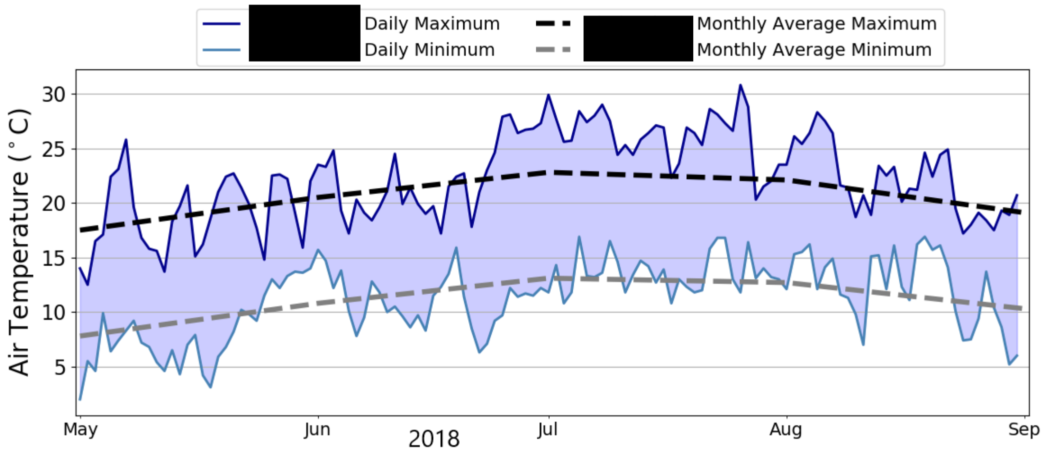


Figure 5.2: Daily minimum and maximum external air temperatures in [redacted] over the summer monitoring period compared against Met Office historical monthly minimum and maximum temperatures for the same location (MetOffice, 2018)

can be seen in Figures 5.1 and 5.2, as the daily maximum temperatures were consistently warmer than the long term averages. One particular point to note is the fact that the daily minimum temperatures were also consistently high in London (Figure 5.1). Thus even at night the temperatures often remained elevated, something which is particularly unusual for the UK (MetOffice, 2018).

Therefore the evaluation of the conditions (particularly for CSA, which was occupied throughout the summer) have been undertaken during a period of unusually warm weather. However, as noted in Section 1, due to global warming the conditions experienced during the 2018 Summer are likely to occur more frequently in the future (CCC, 2017). As such, it seems prescient, and indeed necessary for the future well-being of occupants, that newly built dwellings should be able to remain within broadly acceptable comfort ranges under such conditions. Indeed, if they cannot, then retrofitting such buildings to limit overheating will surely become necessary in the years ahead.

5.2 Summer Indoor Conditions

The section below will outline the thermal conditions experienced during the late spring and summer periods. In the case of CSA this is from May to late August. In CSA this is from May to mid June (the exact dates at which the different participants left the study can be found in the Appendices Sections C.1 and C.2). The section begins by covering the monitored internal conditions, and is followed by occupant feedback on the conditions.

5.2.1 Thermal Conditions

This section shows the monitored thermal conditions over the "summer" period i.e. from May on wards. The average conditions across all the monitored rooms in each case study are shown in Figure 5.3.

Figure 5.3 shows how the weekly average temperature across all rooms in both case studies regularly exceeded 25°C from May on wards. It also shows how when the external temperature rises the average conditions in CSB more closely reflect those experienced in CSA. Yet when the external temperature drops, the internal temperature in CSB also drops, whereas CSA stays relatively stable (thus increasing the average temperature difference between the two case studies). In addition, the inter-quartile range in CSA is slightly larger than in CSB i.e. in CSA there is slightly greater variation in temperatures between the rooms.

The other key observation is that in CSB the residents were not in their

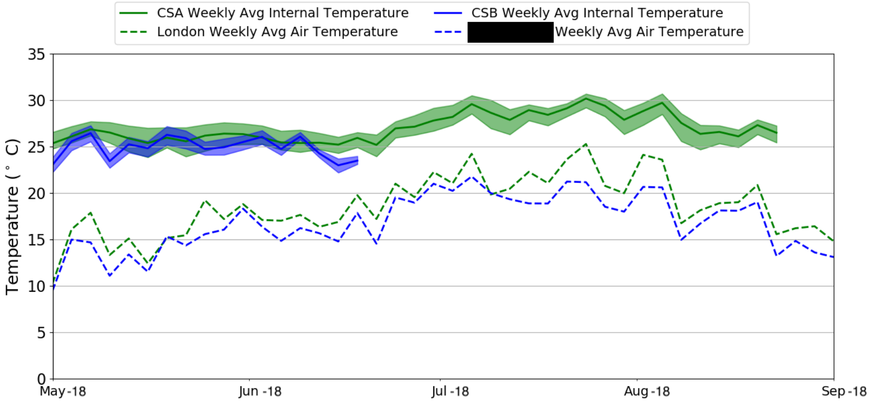


Figure 5.3: Weekly average internal and external temperatures at the case study locations. The faded band represents the inter-quartile range of indoor temperatures.

accommodation during the official 2018 heatwave (this occurred between the 22 June to the 7 August 2018). It can be clearly seen how during this heatwave the conditions inside CSA became markedly warmer. Indeed, towards the end of July the weekly average temperature in CSA exceeded 30°C.

5.2.1.1 Inter-Room Variability

Figure 5.3 masks the significant variations in internal temperatures that existed between the rooms. Therefore the distribution of internal temperatures for each of the rooms is shown below in Figures 5.4 and 5.5. These are ordered by mean temperature over the whole summer monitoring period, with coolest at the top, and warmest at the bottom.

Figure 5.4 shows that many of the rooms in CSA were consistently warm throughout the entire summer (e.g. 8 of the rooms were above 26°C for approximately 70% of the summer). However, there was significant differences between the rooms. For instance, the warmest room (A2) was above 30°C for approximately 30% of the summer period, while three rooms (A4, A5, and A6) almost never surpassed 30°C.

The distribution of temperatures in CSB (whilst the participants were in residence) was markedly cooler than CSA. Nevertheless, Figure 5.5 shows that many of the bedrooms still experienced warm temperatures for significant

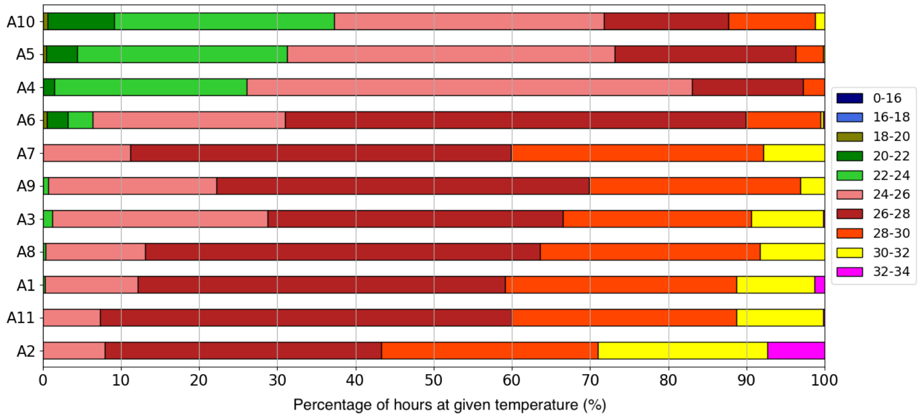


Figure 5.4: The distribution of internal temperatures in the monitored CSA rooms over the summer monitoring period (May - September)

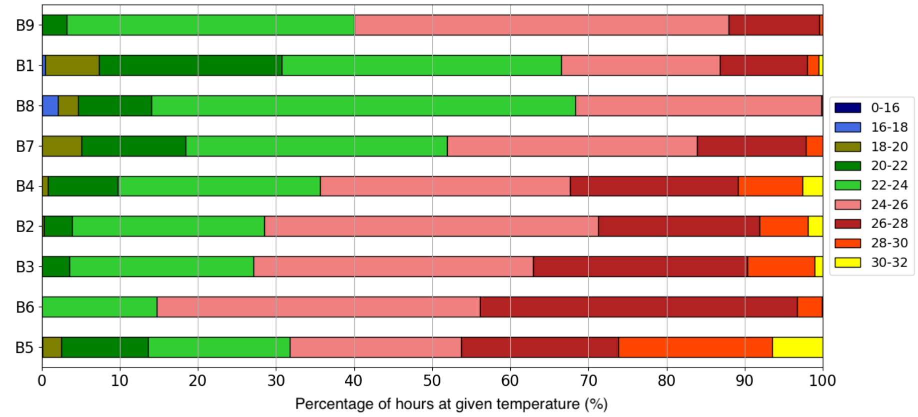


Figure 5.5: The distribution of internal temperatures in the monitored CSB rooms over the summer monitoring period (May - July)

periods. For instance, all rooms were above 24°C for over 30% of the period, whilst all rooms (with the exception of B8) were above 26°C for at least 10% of the time.

Again, there was significant discrepancies between rooms. This was partly attributable to the differences between rooms, and their propensity to overheat (see Section 5.4 below). It was also party due the date at which the participant left their room, with the participants who stayed longer tending to be in the PBSA during warmer weather conditions (see Sections C.1 and C.2 of the Appendices for the dates at which each participant left the study).

5.2.2 Indoor Air Quality

As in Section 4, IAQ analysis was limited to analysis of RH and CO_2 concentration. However, during the summer period, these two metrics did not represent the IAQ issues reported by the study participants (see Section 5.2.4.3 for occupant feedback on summer IAQ) as closely as they did for the heating season in Section 4.

5.2.2.1 Indoor CO_2 Concentration

The weekly average and maximum CO_2 concentration for each of the case studies is shown in Figure 5.6 below.

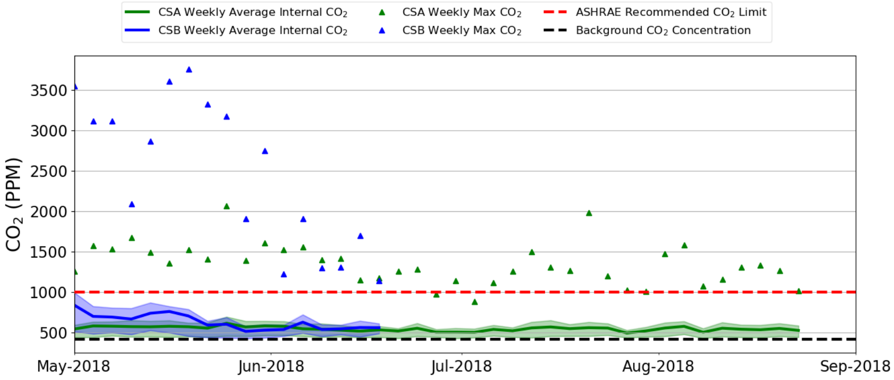


Figure 5.6: Average and maximum CO_2 levels across all rooms inside CSA and CSB over the summer. The faded band represents the inter-quartile range of values. The background CO_2 level (black dashed line) and ASHRAE recommended limit (red dashed line) are included for reference

Figure 5.6 shows how the average CO_2 internal concentration in summer in both PBSA was generally lower than in winter (see Figure 4.8 in Section 4.2.2.1 for comparison). This was likely due to increased window opening, particularly overnight (see Section 5.4.2 below). The effect was particularly pronounced in CSB. This can be shown by creating the same overnight CO_2 concentration distribution plot as in Section 4.2.2.1 for the monitored rooms in CSB. This is shown in Figure 5.7.

Figure 5.7 shows how the amount of time that the CO_2 concentration was

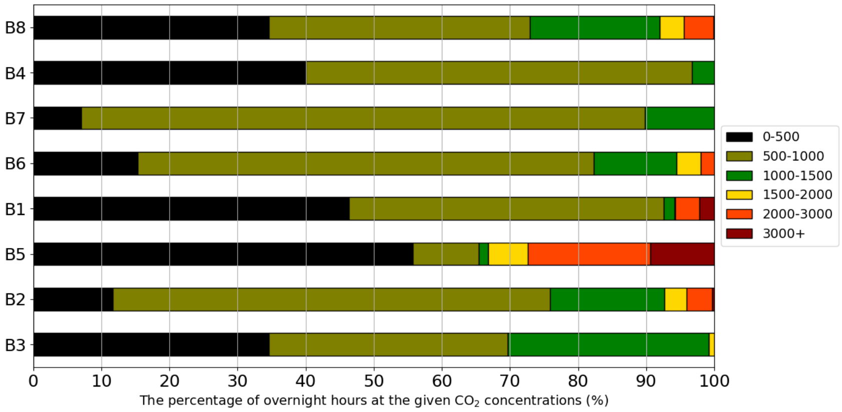


Figure 5.7: The percentage of overnight hours (23:00-07:00) at a given CO_2 level (PPM) in CSB rooms from May on wards

elevated overnight was significantly reduced compared to the heating season. Although room B5 did still spend 30% of the overnight hours above 1500PPM, which is clearly still an issue. The contrasting perceptions of "stuffiness" from the heating season to summer is also highlighted in the participants interviews in Section 5.2.4.3 below.

5.2.2.2 Indoor Relative Humidity

The weekly average internal and external RH is shown below in Figure 5.8.

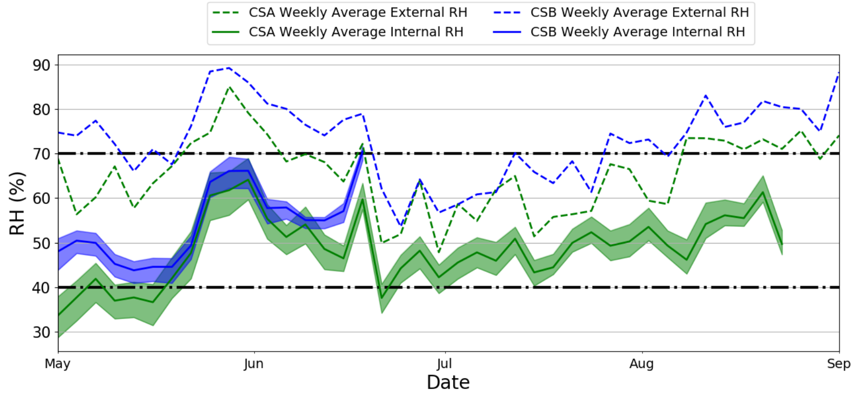


Figure 5.8: Weekly average internal and external RH over the summer. The faded band represents the inter-quartile range of indoor RH. The CIBSE recommended limits for dwellings of 40% to 70% RH are also highlighted by the black dashed line (CIBSE, 2003).

As Figure 5.8 shows the average weekly RH generally stayed within the 40% to 70% band from the middle of May onwards. However, there is a couple of periods in early and late June at which the average RH exceeded 60%. The main impact the high RH had during the summer was in contributing to overheating. This is shown below in Sections 5.2.3.4 and 5.2.3.5 where methods to quantify the “feels like” temperature are covered.

5.2.3 Overheating

The above section has shown that many rooms in both case studies were hot, and often for sustained periods, but that the conditions varied significantly between rooms. Overheating will now be assessed by applying the industry standard methods (as outlined in Section 3.5.5.2 of the literature review).

5.2.3.1 Static Metrics

Static metrics have been largely superseded by adaptive metrics to assess overheating in free-running buildings. However, they have still been widely used in previous studies (see Section 2.5.4.5). This thesis will use these metrics to allow for comparability with other studies. Plus there are arguments that, particularly during the night, static metrics may actually be more appropriate (see Section 2.2.2.3).

Each of the rooms has been assessed assuming that the room is occupied at all times, and during the nighttime only (e.g. 23:00 - 07:00). The interviews and previous literature have shown how PBSA rooms can be, and regularly are, occupied at all times of the day. As a reminder, a bedroom is deemed to have failed the CIBSE Guide A static criteria if it exceeds 24°C for more than 5% of occupied hours, or if it exceeds 26°C for more than 1% of occupied hours (see Section 3.5.5.2 for details). The static overheating results are displayed for CSA in Table 5.1.

Table 5.1 shows how all of the rooms in CSA failed the CIBSE Guide A static exceedance criteria. This was the case whether they were assessed as continuously occupied or occupied overnight only. Indeed, some rooms barely

	All Hours		Night	
	24 °C	26 °C	24 °C	26 °C
A1	99.1	66.7	99.5	66.8
A2	99.7	86.8	99.9	89.7
A3	59.9	28.8	58.9	25.7
A4	19.1	2.8	15.3	1.8
A5	78.0	49.5	75.9	49.1
A6	93.6	47.8	95.0	50.9
A7	97.2	74.7	99.4	89.7
A8	99.2	64.2	99.9	71.5
A9	91.5	60.7	92.0	63.6
A10	19.5	8.4	17.8	8.0
A11	98.4	83.8	98.5	84.2

Table 5.1: The percentage (%) of hours that exceeded the CIBSE Guide A static temperature limits in CSA.

	All Hours		Night	
	24 °C	26 °C	24 °C	26 °C
B1	22.8	7.7	12.8	2.9
B2	40.2	11.3	23.6	5.0
B3	35.7	12.0	33.6	12.9
B4	41.1	14.9	41.6	13.9
B5	33.9	13.6	19.1	8.6
B6	66.8	21.4	61.5	16.3
B7	34.1	7.3	18.2	1.4
B8	14.5	4.7	12.7	3.0
B9	11.4	0.1	7.6	0.0

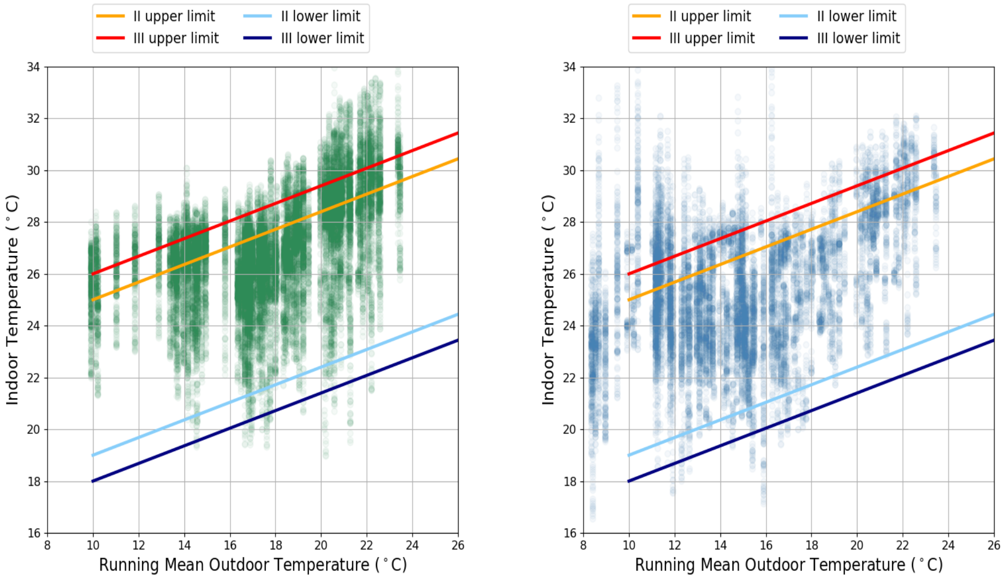
Table 5.2: The percentage (%) of hours that exceeded the CIBSE Guide A static temperature limits in CSB.

fell below the lower limit exceedance criteria throughout the entire year. Only one room (A4) even came close to passing either of the criteria.

Table 5.2 shows that just one room (B9) passed the upper limit criteria. Except for this every other room failed both criteria. However, the percentage exceedances were notably lower than for CSA. Nevertheless the majority of the rooms failed (particularly the lower criteria) by large margins.

5.2.3.2 Adaptive Metrics

As discussed in Section 2.2.2, static metrics are arguably too restrictive in free-running buildings. Thus adaptive metrics can also be used to assess overheating. Initially, scatter plots are shown below to help visualise the amount of time at which the internal temperature is within the adaptive comfort limits. These are shown below for CSA (Figure 5.9a) and CSA (Figure 5.9b).



(a) CSA adaptive scatter plot

(b) CSB adaptive scatter plot

Figure 5.9: Adaptive scatter plots for both case studies during the summer monitoring period. The plots shows the occasions during which the hourly average internal temperature in each of the rooms is within the BSEN 15251 comfort zones (CEN, 2007). Category II (± 2°C from $\boldsymbol{T_{comf}}$) is used when assessing new buildings, whereas category III (± 3°C from $\boldsymbol{T_{comf}}$) is viewed as acceptable in existing buildings (Nicol, 2013).

Figure 5.9 shows that from May on-wards there is significant time in which some of the monitored rooms in both CSA and CSB are exceeding the second and third upper category limits. Meanwhile there is relatively limited time in which temperatures fall below the lower limits. Also, particularly in the case of

CSB, exceedances are often occurring at relatively cool outdoor temperatures. Thus even when outdoor temperatures are not particularly warm, overheating conditions are still occurring. How the individual rooms fared is shown below in Figures 5.10 (CSA) and 5.11 (CSB).

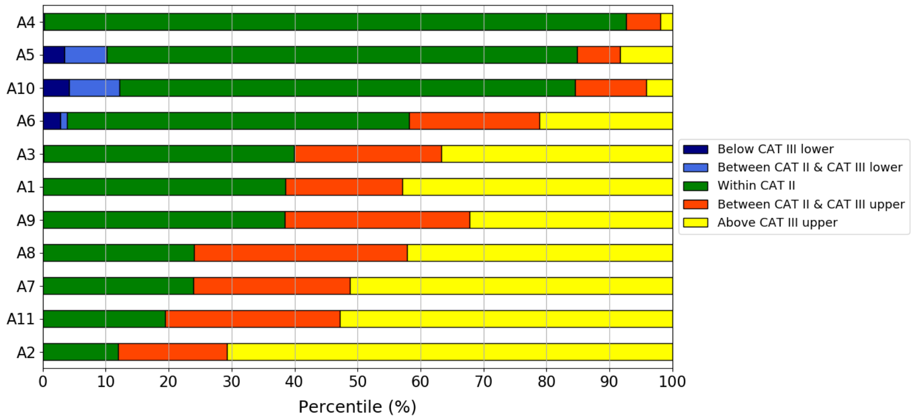


Figure 5.10: CSA adaptive overheating analysis for individual rooms. The chart shows the percentage of time during which the hourly average internal temperature was within the different categories in BSEN 15251 (CEN, 2007).

Figure 5.10 shows there to be significant variation regarding the extent of overheating in CSA. Indeed, while certain rooms overheated almost continuously, others barely overheated at all. Overall though, most rooms experienced significant periods of overheating. For instance, 7 of the monitored rooms spent over 50% of the summer period above category II. However, it is important to note that the participants left their rooms at different times over the monitoring period (details can be found in Section 3.4.2.1). For example, the monitoring in room A4 finished on the 2nd of July 2018.

Figure 5.11 shows that in general overheating was less severe in CSB whilst the participants were in residence. Please note that the CSB participants left their accommodation significantly earlier than those in CSA (see Section 3.4.2.1). Nevertheless, many rooms still experienced prolonged periods of overheating, and this happened before the warmest weather

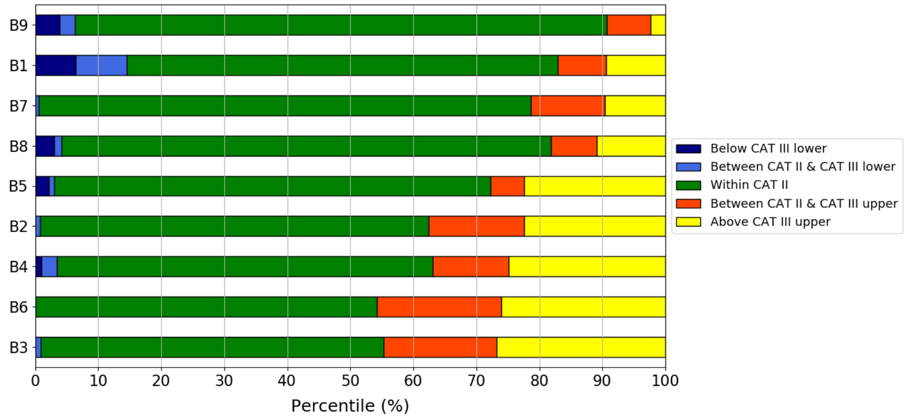


Figure 5.11: CSB adaptive overheating analysis for individual rooms. The chart shows the percentage of time during which the hourly average internal temperature was within the different categories in BSEN 15251 (CEN, 2007).

conditions had occurred.

5.2.3.3 TM52 Results

The charts displayed above provide an indication of the duration of the overheating within individual rooms. They also provides some indication of the severity (e.g. was the exceedance above category II or III). However, this analysis is relatively limited in terms of understanding the intricacies of the overheating conditions. This is where TM52 can be used Nicol (2013).

Details of the TM52 analysis method can be found in Section 3.5.5.2, but essentially it uses a three criterion system to assess overheating. This assesses the duration (criterion 1) and severity (criterion 2) of overheating, as well as whether an upper limit of acceptability was exceeded (criterion 3). This is supposed to represent “a limit beyond which normal adaptive actions will be insufficient to restore personal comfort” (Nicol, 2013).

Details of how to apply TM52 in occupied buildings is also covered in Section 3.5.5.2. In this case criterion 1 is applied from May till the end of monitoring period, while criterion’s 2 and 3 have been assessed over the entire monitoring period. If a room fails any two of the three criteria then it is classed as overheating. The results from the TM52 analysis are displayed

	Criterion 1	Criterion 2	Criterion 3	Result
A1	22.8 (Fail)	46 (Fail)	0 (Pass)	Fail
A2	45.2 (Fail)	73 (Fail)	54 (Fail)	Fail
A3	13.2 (Fail)	34 (Fail)	0 (Pass)	Fail
A4	0.1 (Pass)	0 (Pass)	0 (Pass)	Pass
A5	3.2 (Fail)	5 (Fail)	0 (Pass)	Fail
A6	3.1 (Fail)	7 (Fail)	5 (Fail)	Fail
A7	20.1 (Fail)	43 (Fail)	0 (Pass)	Fail
A8	11.8 (Fail)	26 (Fail)	0 (Pass)	Fail
A9	7.1 (Fail)	16 (Fail)	0 (Pass)	Fail
A10	0.8 (Pass)	3 (Fail)	0 (Pass)	Pass
A11	25.1 (Fail)	47 (Fail)	0 (Pass)	Fail

Table 5.3: The results of the TM52 adaptive overheating tests in CSA. The monitoring period was from October 2017 to September 2018.

below in Tables 5.3 and 5.4 for CSA and CSB respectively.

Table 5.3 shows that the majority of rooms in CSA (nine out of eleven) failed the TM52 adaptive tests. Nearly all rooms failed criterion's 1 and 2, whereas very few rooms failed criterion 3. Therefore, in general the bedrooms failed the assessment because they were consistently overheated for extended periods, but rarely because they became extremely hot. This has important implications for the occupant's health, well-being and comfort (see Section 6.1). It also important with regards to the causes of the overheating (see Section 5.4), and the most effective adaptive behaviour to restore comfort (see Section 5.3.2.3).

However, it is worth noting that certain rooms did pass the adaptive overheating tests (although A10 was the only room which passed and was occupied for the entirety of the monitoring period). The fact that these rooms passed despite the relatively extreme conditions that occurred over the summer of 2018 (see Section 5.1 for details), suggests that overheating is not an inevitability in these residences. The reasons certain rooms overheated extensively whilst other did not is explored below in Section 5.4. The results for CSB are displayed below in Table 5.3.

Table 5.4 shows that seven out of the nine monitored rooms in CSB

	Criterion 1	Criterion 2	Criterion 3	Result
B1	6.6 (Fail)	10 (Fail)	14 (Fail)	Fail
B2	13.4 (Fail)	18 (Fail)	47 (Fail)	Fail
B3	18.9 (Fail)	20 (Fail)	27 (Fail)	Fail
B4	22.2 (Fail)	27 (Fail)	78 (Fail)	Fail
B5	20.6 (Fail)	18 (Fail)	84 (Fail)	Fail
B6	22.1 (Fail)	17 (Fail)	4 (Fail)	Fail
B7	2.5 (Pass)	4 (Fail)	0 (Pass)	Pass
B8	6.6 (Fail)	10 (Fail)	4 (Fail)	Fail
B9	0.1 (Pass)	0 (Pass)	0 (Pass)	Pass

Table 5.4: The results of the TM52 adaptive overheating tests in CSB. The monitoring period was from November 2017 to July 2018.

failed the TM52 tests. Yet again, as with CSA, while many rooms overheated extensively, it is important to note that some did not.

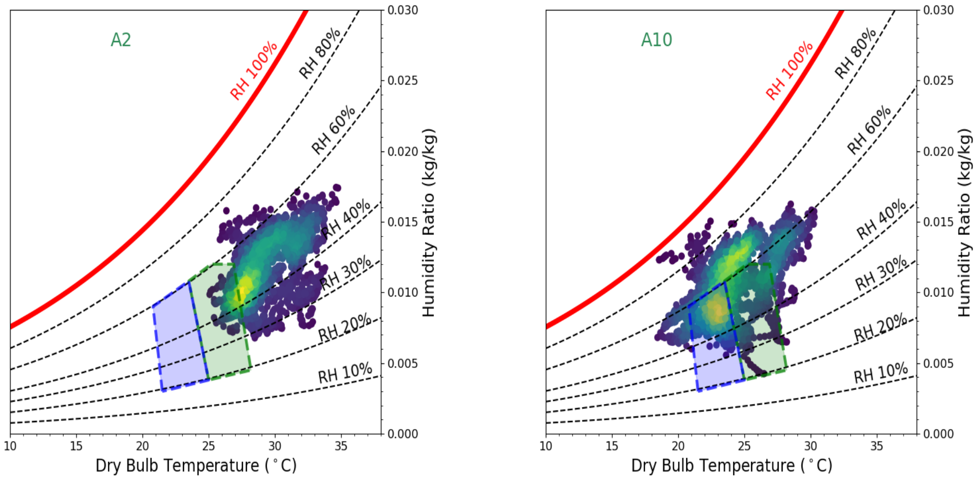
In contrast with CSA, the majority of the rooms failed all three of the criterion's. Thus bedrooms in CSB both overheated for sustained periods, and also exceeded the upper limit of acceptability. The reason that criterion 3 was exceeded more frequently was the number of occasions in which the external temperature were relatively cool, yet the internal temperatures were very warm.

In these periods (i.e. periods of low external temperatures and relatively high internal temperatures) the gap between the internal temperature and the adaptive comfort temperature ($\boldsymbol{T_{comf}}$) regularly exceeded the 4°C limit. This was particularly the case in early to mid May when the outdoor running mean temperature ($\boldsymbol{T_{rm}}$) was relatively low, and therefore so was $\boldsymbol{T_{comf}}$. Those times when $\boldsymbol{T_{comf}}$ was exceeded and yet the external temperature was relatively low can also been seen in Figure 5.9b above.

5.2.3.4 Psychometric Analysis

As discussed in Section 2.2, thermal comfort has a number of contributing factors. One of these factors is RH. Therefore psychometric charts can be used to get a better understanding of what the thermal conditions felt like for the participants. It can then also be assessed whether the conditions stayed within the comfort bands (see Section 2.2.1.1 for details).

Psychometric charts are displayed below in Figure 5.12 for two rooms in CSA. These two rooms had the warmest (A2) and coolest (A10) average temperatures in CSA over the summer monitoring period.

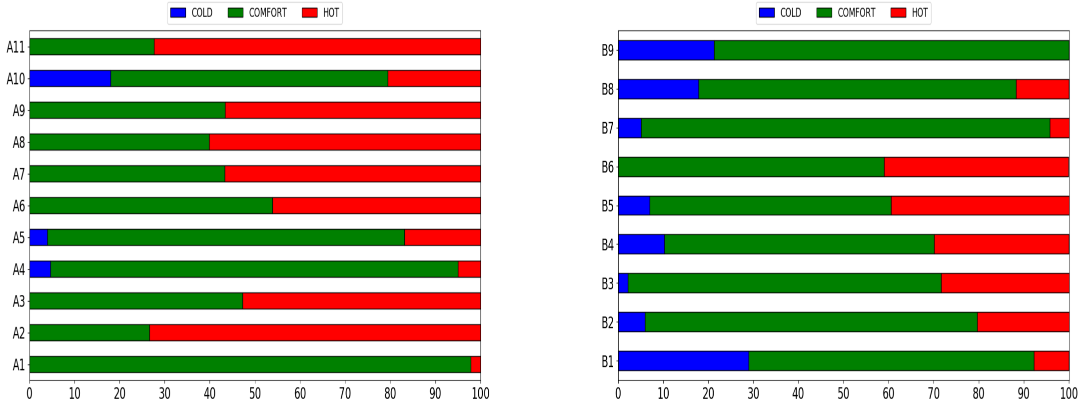


(a) A2 **(b)** A10

Figure 5.12: Psychometric charts showing the conditions in the CSA bedrooms with the warmest (A2) and coolest (A10) average temperatures over the summer monitoring period. The green area represents the 0.5 ***clo*** comfort band, while the blue box represents the 1 ***clo*** comfort band.

Figure 5.12 shows how the internal conditions in A2 were consistently warmer than the comfort area over the summer period. Whereas the conditions in A10 were generally within the comfort area, although high RH was an issue. The percentage of time that the conditions were within (or outside) the 0.5-1 ***clo*** comfort bands for both case studies has been plotted below in Figure 5.13.

Figure 5.13 shows how in CSA 6 of the rooms spent 50% or more of the summer monitoring period in the "hot" area. Yet in contrast, some rooms managed to stay largely within the comfort bands. In CSB the picture was more mixed. Several rooms spent a relatively large proportion of the summer monitoring period in the "hot" area, but several rooms also spent significant periods in the "cold" area. It is worth noting again that the CSB participants



(a) CSA **(b)** CSB

Figure 5.13: Charts showing the percentage of time over the summer in which the internal conditions inside the CSA and CSB study bedrooms were within the 0.5 to 1 ***clo*** comfort bands.

were only in their residences until the end of June. It is also interesting to note that there were no complaints of cold conditions over the summer period from participants at either case study.

5.2.3.5 Heat Stress

Section 5.2.3.2 above has shown how the majority of the monitored rooms in both case studies overheated throughout the summer months. Yet in some cases conditions became so warm that the "feels like" temperature exceeded the point at which meteorological agencies would be advising "caution" or even "extreme-caution" to health. The methodological details regarding how heat stress metrics work can be found in Section 3.5.5.2. It is worth reiterating that the heat index is only used when internal temperatures and RH exceed 27°C and 40% respectively.

A visual example of the heat index is shown below in Figure 5.14 for the room (A2), which had the average warmest temperature over the summer in CSA. Figure 5.14 shows how the conditions in room A2 frequently became so severe that they entered the "caution" area, and occasionally the "extreme caution" area. It also shows how such conditions were reached throughout the summer months.

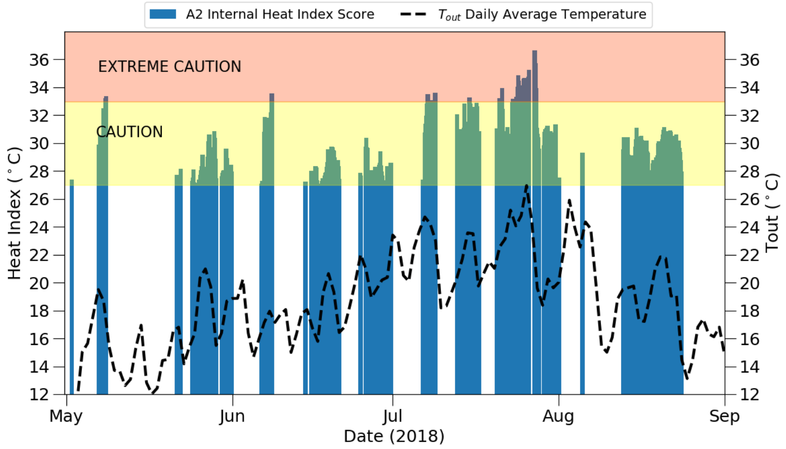


Figure 5.14: Chart showing the times in which the average hourly internal conditions in room A2 entered the "caution" or "extreme caution" area according to the heat index scale.

The same analysis has been applied to all the rooms in CSA and CSB. The results are displayed below in Tables 5.5 (CSA) and 5.6 (CSB). In Tables 5.5 and 5.6 the percentage of the summer monitoring period, and the total amount of time over the monitoring period, the bedrooms were within the particular heat index categories is shown.

	Monitoring Time (Hours)	Caution (%)	Extreme Caution (%)
A1	384	2.1	0.0
A2	2377	78.6	5.9
A3	2377	42.2	3.0
A4	1464	2.9	0.0
A5	2377	12.2	0.0
A6	1501	38.1	0.7
A7	2377	56.1	0.1
A8	2328	56.9	2.8
A9	2368	49.7	1.5
A10	2370	14.0	0.0
A11	2377	76.1	0.5

Table 5.5: Heat stress results for the monitored rooms in CSA. The monitoring period occurred from May 2018 to September 2018.

Table 5.5 shows the conditions in many of the bedrooms in CSA were regularly exceeding the "caution" status. In fact, all of the rooms exceeded this limit at some points, whilst five of the rooms exceeded this level for approximately 50% or more of the summer monitoring period. Furthermore, three of the rooms in CSA had conditions which exceeded the "extreme caution" level for a combined period of two days or more. These results raise serious issues regarding the health and well-being of the building's occupants during warm weather. The results for CSB are displayed below in Table 5.6.

	Monitoring Time (Hours)	Caution (%)	Extreme Caution (%)
B1	1195	7.0	0.0
B2	1193	13.7	0.4
B3	1110	18.2	0.5
B4	1094	21.8	4.3
B5	713	32.8	0.0
B6	852	30.6	0.0
B7	876	1.5	0.0
B8	867	7.5	0.0
B9	1194	0.0	0.0

Table 5.6: Heat stress results for the monitored rooms in CSB. The monitoring period occurred from May 2018 to July 2018.

Table 5.6 shows how many bedrooms also reached the "caution" category for sustained periods of time. This occurred despite the participants not being in the accommodation for the warmest parts of summer (see Section 3.4.2.2 for details).

5.2.3.6 Acute Overheating Examples

In addition to the overheating observations made above, there were several notable examples of acute overheating conditions. These highlight some of the particular design problems that increased the propensity of the buildings to overheat. They also show some of the areas in which overheating was likely to have particularly affected the building occupants.

Night Time Bedroom Temperatures

The initial parts of Section 5.2.3 have shown how many of the bedrooms overheated continuously for extended periods. Thus not only did they heat up during the day, but they retained the heat overnight (even when the external temperature decreased). In other words there was little nighttime cooling affect from the lower external temperatures. As an example, the nighttime (23:00-07:00) temperatures in the CSA monitored bedrooms are shown in Figure 5.15 during the 2018 heatwave (see Section 5.1 above for details about the heatwave).

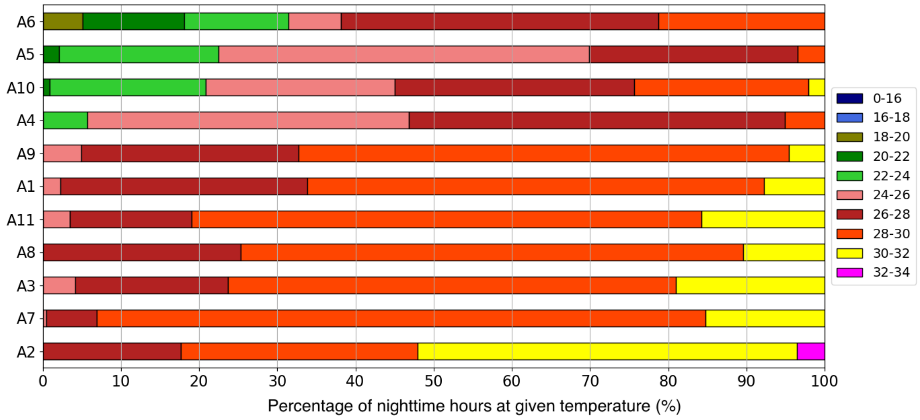


Figure 5.15: The hourly average overnight (23:00-07:00) temperatures in the monitored bedrooms during the UK summer 2018 heatwave. The heatwave occurred from the 22 June 2018 to the 7 August 2018 (MetOffice, 2018).

Figure 5.15 shows how 7 of the rooms exceeded 28°C for over 60% of all nighttime hours during the heatwave. Whilst A2 was above 30°C for over 50% of the period. Furthermore, very few of the rooms had any night time hours beneath 24°C (A6, A5 and A10 had just 32%, 22% and 18% respectively). These results show why many residents focused their complaints on how the excessively hot temperatures disrupted their sleep (as shall be discussed in Section 5.2.4.3 below). The causal factors that contributed to these buildings remaining so warm overnight (i.e. why they failed to cool down) is covered in Section 5.4 below.

Townhouse Bathrooms

The overheating conditions in the townhouse bathrooms in CSB were extreme. As an example a plot of temperature and relative humidity in the first floor bathroom in the CSB townhouses is shown below in Figure 5.16.

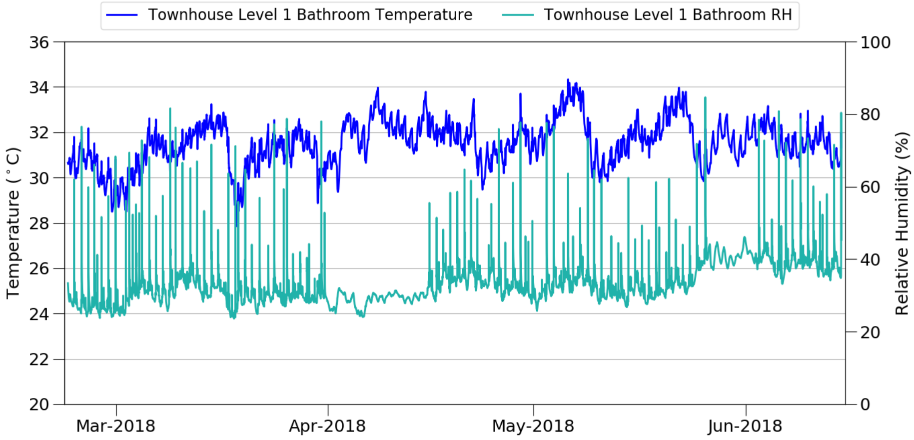


Figure 5.16: Chart showing the hourly average temperature and relative humidity in the bathroom on level 1 of a townhouse in CSB.

Figure 5.16 shows how the temperatures in the first floor bathroom rarely fell below 30°C over the period in which they were monitored (the bathroom temperature sensors were installed on the 20th February during the second interviews). The second and third floor bathrooms were marginally cooler, but were still very warm. Figure 5.16 also shows how during showers the RH rapidly increases to between 60-80%. An image of the bathroom and the diagram of the bathroom layout are also included below in Figure 5.17.

[redacted]

(a) CSB bathroom photo

[redacted]

(b) CSB corridor and bathroom layout

Figure 5.17: CSB Townhouse Bathrooms

The photo of the bathroom in Figure 5.17a shows how the space is relatively confined. Thus when the shower is used the RH level rises quickly, and according to one study participant “after a couple of minutes in the bathroom it becomes unbearable” [B2 - 22-11-17].

Figure 5.17 shows how the temperature is high all year round, and appears relatively unaffected by the external temperature. Thus it is likely that internal gains are the dominant heat source for the bathrooms. The layout of the bathroom and surrounding areas in Figure 5.17b shows why this is likely to be the case.

The ground floor of each townhouse contains a calorifier that stores the hot water for the building (see Section 3.3.2.3 for details on the DHW systems in CSB). The hot water pipework then runs up a central service area between the two bathrooms. Although access was not granted to the plant areas in order to check the insulation or the temperatures within them, the site’s FM did comment that “the townhouse on the 1st floor above the plant room is awful, it’s absolutely awful” [CSB FM - 01-09-19]. It seems likely that these plant areas are giving out significant amounts of heat all year round. Consequently, as the internal walls in the building are thin, these internal gains are resulting in overheated bathrooms.

CSA Glazed Staircases

Another particularly concerning design feature of CSA was the entirely glazed south and west facing stairway, with no obvious means of ventilation. The stairway is shown below in Figure 5.18a. Alongside this is a photo of the lobby area just outside of the lift (Figure 5.18b), which is next to the glazed stairway. The photo shows the electrical cupboard being cooled with a large fan. The significance of the photo is explained below.

The conditions inside the glazed stairway in Block B were monitored at the bottom (level -1) and the top (level 10). In both cases the monitoring device was carefully positioned to be out of direct sunlight. The monitored temperatures in the stairway over the 2018 summer heatwave are shown below in Figure 5.19. In addition the temperatures in the staircase in Block A were also shown. The Block A staircase is north facing and does not contain glazing

[redacted]

(a) The glazed south and west facing stairway in Block B of CSA **(b)** The electrical lift gear in CSA being cooled by a large fan

Figure 5.18: Photos showing large amounts of glazing in some of the CSA circulation areas

(see Section 3.3.1.1 to see the CSA floor plan). Also included in Figure 5.19 is the external temperature and the solar irradiance from the nearest met office station.

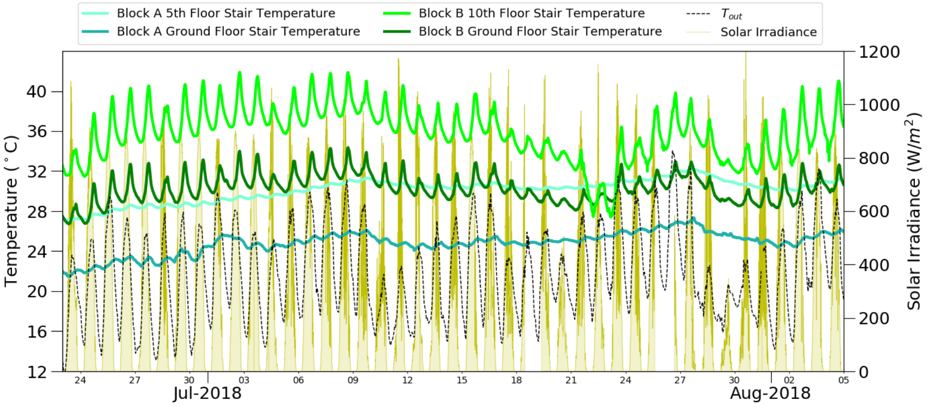


Figure 5.19: The temperature conditions in the CSA stairways during the UK summer 2018 heatwave. The solar irradiance is represented by the shaded area on the chart and shown on the right y-axis. The stairway temperatures and external temperatures are shown on the left y-axis.

Figure 5.19 shows how there are several days in early July in which the temperature in the stairway exceeded 40°C. The temperature profile is also heavily influenced by solar gains, and there is significant difference between the bottom and top of the staircase (this averaged approximately 10°C). Furthermore the temperatures in the Block A staircase (i.e. the staircase without glazing) were notably cooler. In essence, the glazed stairway in CSA is acting like a solar chimney. The problematic design issues with respect to overheating will be discussed further in Section 6.1.

The reason the red line has been added to Figure 5.18a is to highlight that the areas above the red line, “for at least a couple of years now those two floors have not been rented out at all. Yeah so 9 and 10 are not operating. They were just too hot to rent out” [CSA FM - 02-09-19]. Thus not only is overheating an issue for the residents, but it is incurring significant financial losses for the PBSA owners.

In addition to the problems identified above, the conditions in the lobby areas outside the lift (shown in Figure 5.18b) were so hot it was causing the lifts electrical circuits to malfunction. This in turn was causing the lift to cease operating. Therefore although it is not known to what extent the stairways were used by the occupants there there were occasions during the 2018 summer in which the CSA residents had no choice but to use the stairs, irrespective of the temperatures. In order to try and limit the lift maintenance problems the FM team had placed a large fan in-front of the electrical circuity. This was left permanently on with the cabinet remaining open for convective cooling (as shown in Figure 5.18b above).

CSA Corridors

Another particularly hot area in the CSA buildings was the corridors. These were shown to be almost always warmer than the (warm) bedrooms. The only notable exception to this was in the corridor outside room A10. In this case the corridor had windows allowing for ventilation (see Section 3.3.1.3 for details).

In the case of the other corridors they tended to have multiple internal heat gains sources, these came from hot water pipework above the ceilings, server rooms, and light fittings. Meanwhile these corridors had no mechanical ventilation installed, and all doors into and out of the corridors were fire doors that are supposed to remain shut at all times. Thus heat was being continually supplied to the corridors, but there was no systematic means of removing it. Evidence of the heat sources identified above is provided in Figure 5.20.

[redacted]

(a) Hot water pipework diagram showing the hot water pipework running above the length of the corridors in the ceiling

(b) Relatively Cooler Bedrooms

[redacted]

(c) Hot Server Cupboard Photo

(d) Hot Server Cupboard IR

Figure 5.20: Sources of heat gains in CSA corridors. Clockwise from top left the Figures show; a) the hot water pipework services running horizontally along the corridor ceilings; b) the relatively cooler bedrooms; c) the photo of the server cupboard; and d) the infra red image of the server cupboard highlighting the heat emanating from it

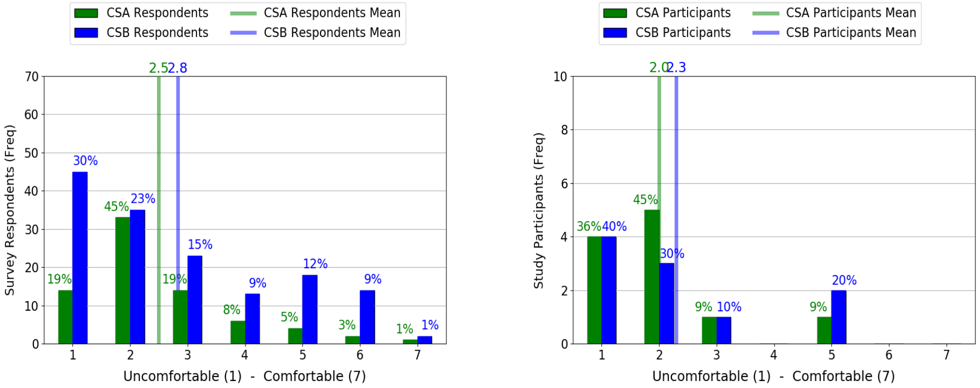
On a personal note this researcher can attest to the extreme conditions experienced in the corridors. During setting up of the monitoring equipment, and interviewing participants a fairly significant amount of time was spent travelling around the corridors. On many occasions, particularly during the summer interviews, just travelling from the common room to the participants bedroom was sufficient to break into sweat, and become thermally uncomfortable. Discussion surrounding the likely impact of the corridors on the thermal comfort of occupants is included in Section 6.1. It should also be noted that many residents raised the corridors as uncomfortable in the interviews (see Section 5.2.4.3 for details).

5.2.4 Occupant Feedback

The section below covers the occupants responses to summer conditions. Including both the whole building survey analysis, and the participant's interview responses. It does not include the participants behavioural or adaptive responses to the conditions. These will be covered in Section 5.3.

5.2.4.1 Thermal Comfort Survey Results

The results from the surveys on summer conditions are displayed below. These were carried out in August and June in CSA and CSB respectively (see section 3.4.6 for details on survey timing). The responses regarding the thermal conditions in summer are displayed below, these are followed by the responses on summer IAQ. The complete set of summary statistics for the survey data is also available in the Appendices for CSA (Appendix E.1) and CSB (Appendix E.2).

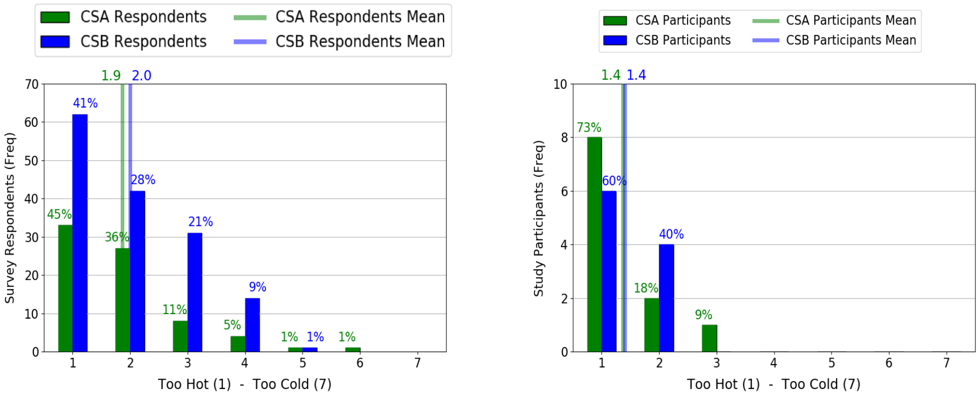


(a) Survey Respondents

(b) Study Participants

Figure 5.21: Survey results for "how would you describe the typical conditions in summer?"

Figure 5.21 shows that the survey respondents generally found the summer conditions to be uncomfortable. In the case of CSA over 60% of respondents answered two or below, and in CSB this score was 50%. It also shows that the study participants are in broad agreement with the building respondents. Figure 5.22 below shows the reasons for the respondent's thermal discomfort.



(a) Survey Respondents

(b) Study Participants

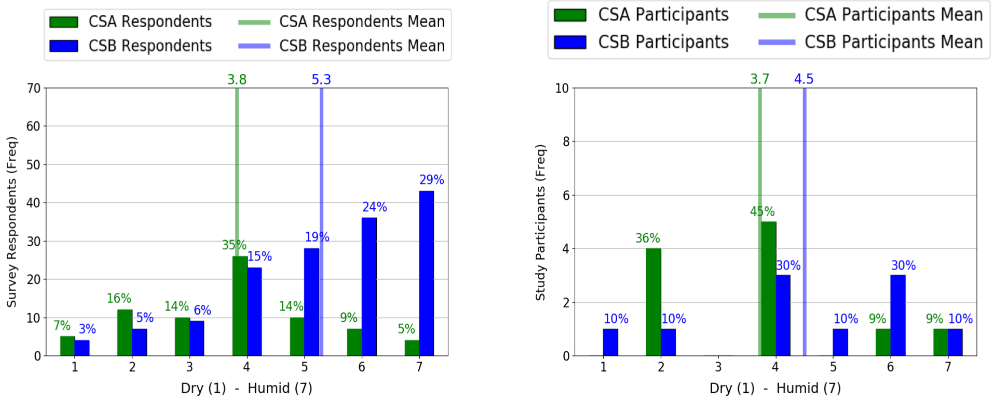
Figure 5.22: Survey results for "how would you describe the indoor temperature in summer?"

Figure 5.22 shows that, perhaps unsurprisingly, the survey respondents were overwhelmingly too hot during the summer. The survey results are striking in their clarity; in both case studies over 40% of respondents answered one to this question.

5.2.4.2 Indoor Air Quality Survey Results

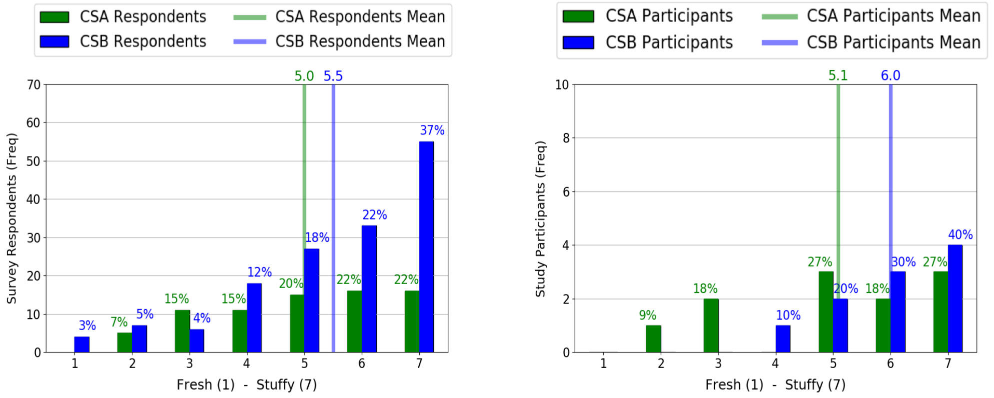
The survey results for the questions "how would you describe the typical indoor air in summer - dry (1) or humid (7)" and "how would you describe the typical indoor air in summer - fresh (1) or stuff (7)" are displayed below in Figure 5.23 and 5.24 respectively.

Figure 5.23 shows that the respondents in CSA were normally distributed regarding whether they thought the air was dry or humid in summer. However, the CSB respondents were significantly skewed towards humid. This does correlate with the RH results in Figure 5.8 in Section 5.2.2.2. This shows that, particularly when the external temperature rises, the average internal RH in CSB tends to be higher over the summer period than in CSA.



(a) Survey Respondents **(b)** Study Participants

Figure 5.23: Survey results for "how would you describe the typical indoor air in summer?"

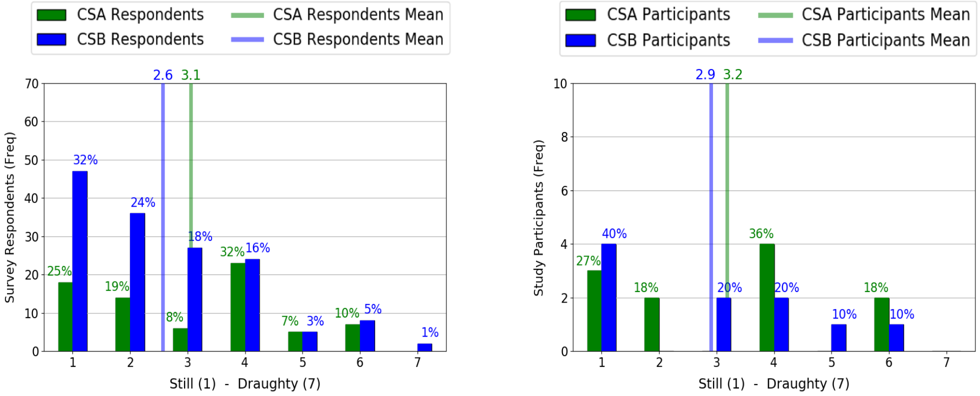


(a) Survey Respondents **(b)** Study Participants

Figure 5.24: Survey results for "how would you describe the typical indoor air in summer?"

Figure 5.24 shows that the respondents and participants in both case studies were skewed towards finding the air to be stuffy in summer. Indeed, 37% of all respondents in CSB answered 7 for this question. Thus not only did the occupants find the conditions too hot over the summer, they also found them too stuffy. The causes of the stuffy conditions is addressed below in the interview results in Section 5.2.4.3 and also in Section 5.4 on overheating causal factors.

One further set of survey results is shown below in Figure 5.25. This is the results for the question “how would you describe the typical indoor air in summer - still (1) or draughty (7)”. These results have been shown because they help illustrate why the PBSA inhabitants may have found the conditions stuffy.



(a) Survey Respondents **(b)** Study Participants

Figure 5.25: Survey results for “how would you describe the typical indoor air in summer?”

Figure 5.25 again shows the respondents in both case studies to be in agreement that the conditions were generally still throughout the summer. As explained in more detail below in Section 5.3.2.3, these still conditions were likely contributing to both the overheating and stuffy conditions.

5.2.4.3 Interview Results

The study participants were generally in agreement regarding the summer conditions; they were uncomfortably hot. The only notable exception was some of the basement residents from CSA. However, there were three main differences between the participants responses. This concerned the duration of overheating (did their bedroom consistently overheat, or just on specific occasions), the effect overheating had on them (how important was overheating in terms of comfort, and the usability of the space), and did they judge their adaptive behaviour to have an impact (to what degree did they feel they had control over the conditions).

Overheating Duration

The participant's responses on overheating duration divided into three main groups. Firstly, there were those that thought their rooms overheated constantly (including during winter), and that the conditions merely became even worse as outdoor temperatures rose. For example, "in fact it is always just been boiling to be honest" [B1 - 19-06-18], and "I mean, it's always too hot, but especially in summer at times it can get unbearable" [A9 - 22-08-18], and "yeh the rooms are too hot, they're definitely too hot, it doesn't really matter what the weather is like, although obviously it gets worse the hotter it gets" [A10 - 23-08-18].

Even in this grouping most of the participants did express a certain tolerance to raised indoor temperatures during warm weather. They accepted that without air conditioning indoor temperatures are likely to rise alongside external temperatures. Therefore, what frustrated, and angered many participants in this grouping was the prevalence and duration of the overheating i.e. why did overheating occur before the external temperatures had even become unduly warm. For example, "It's not really the heat during the hot weather that bothers me so much as just how hot it is all the time, even when it's not that hot outside. It's just always hot" [A3 - 24-08-18].

Secondly, there were those that felt it began fairly early in the shoulder seasons e.g. "yeah from about April onward it has just been really uncomfortable" [B9 - 19-06-18]. This grouping implied that their bedrooms would overheat even when external temperatures were still relatively cool. For example, "well I do have a weather app on my phone that I check regularly and I would say once it starts getting above 22°C outside that's when it can start being pretty bad in here" [B2 - 19-06-18]. This is probably the largest grouping across both case studies.

Finally, there were those that felt their rooms only became uncomfortably warm for relatively short duration's i.e. during the very warmest weather. For instance, "Well I thought that like fall [Autumn], winter, spring was fine, it was just summer was really hot. Like I think if it gets above 26 °C or something outside then it gets really bad in here" [A9 - 22-08-18] or "sometimes it has been too hot but not that much, and it never lasts that long because it always cools down overnight" [A5 - 24-08-18].

The grouping a particular participant fell into was a complex combination of how they used their room, the actual conditions in their room and their thermal comfort preferences. For instance, it was not the case that those participants whose rooms overheated most extensively were guaranteed to be in grouping that felt their room was constantly overheated.

The Importance of Overheating

The study participants varied considerably as to the importance of overheating to their overall PBSA experience. While many were apoplectic "the summer was just hell" [A7 - 24-08-18] and "Like it was terrible. It was so so terrible. I'd just wake up in the morning and be like oh great it is already really f***ing hot and it's not even 9am" [A3 - 24-08-18], and "you come in here [the bedroom] and think like I actually might vomit. Because I just walk in and it's so hot" [B1 - 19-06-18]. As shown by these quotes, anger, frustration and outrage were probably the most common sentiments expressed by the study participants when quizzed on the summer conditions.

However, a significant minority were more sanguine "I knew that the summer in London is short, so it will finish soon" [A2 - 24-08-18], and "it was definitely uncomfortably hot at times but I suppose it didn't bother me that much overall" [A9 - 22-08-18]. These participants acknowledged that their rooms overheated, but seemed relatively unfazed by it, and certainly it was less important than other aspects of their accommodation (e.g. location).

The vast majority of residents focused their complaints on nighttime temperatures. They felt the heat impacted on their sleeping, and therefore their ability to concentrate the next day. For example, "it makes you sleep badly, so a bit cranky. I think a lot of people in these halls were probably cranky this summer" [A10 - 23-08-18], and "you wake up and you feel all sweaty on your body and it is not very comfortable and it is not very clean for your body, so that is why it makes you feel not very good" [A1 - 26-07-18], and "yeah there are sometimes it has just been really bad and you're just like ahhhh you know, just so hot that you can't get comfortable" [B4 - 22-05-18].

The question that seemed to neatly divide the two groupings (i.e. those that were very uncomfortable and angry, and those that acknowledged it was an issue but it wasn't a major factor in their overall satisfaction with the PBSA) was as to whether they would stay in the accommodation again. For the first grouping, the summer conditions were a deal breaker and they would not consider staying in the accommodation again. For example, "like I would never, ever have stayed in this hall if I'd know what it was going to be like" [A3 - 24-08-18] and "I wouldn't stay here again just because I can't stand the heat, and also I want to be able to sleep you know" [B3 - 19-06-18].

Whereas, for the second grouping they acknowledged that they were uncomfortably hot on occasions, but this did not unduly influence their overall opinion of the accommodation. For instance, "I managed to find strategies to work around it, you know the heat. So yeah I guess I could still live another year in here" [A9 - 22-08-18].

The Effectiveness of Adaptive Actions

The adaptive actions occupants took (and their effect) to alleviate overheating is covered below in Section 5.3.2. Yet, inevitably, the fact that some occupants felt that they could not cool their rooms adequately impacted upon their feelings of control over the conditions, which in turn impacted upon their thermal comfort. Indeed, this seemed to be one of the defining differences between participants responses to indoor conditions in winter, and in summer. For instance, there were occasions in which the indoor temperatures were roughly similar in both seasons, yet in winter the participants could open a window and reduce the temperature, whilst in summer such actions had limited affect (see Section 5.4.4 below). This feeling of powerless over the indoor conditions inevitably fed into their overall feelings of thermal discomfort in summer.

Another key distinction between the responses to summer and winter conditions seemed to be the pleasure of thermal change. For example, in winter if you come in from cold outdoor conditions into an overly warm environment, this may feel pleasurable (at least initially). Whereas in summer if you are already hot, and then you come into an overheated environment, this is less enjoyable. For example, "Like in the winter when it was cold outside it was okay coming in and being very warm but since it's got warm outside it has just been too much" [B3 - 19-06-18]. These concepts are explored further in Section 6.1.4.

5.2.5 Summary

The section began by showing how the majority of bedrooms overheated during the 2018 summer, and in many cases the overheating was both severe and prolonged. This was the case whether they were assessed under static or adaptive metrics. It showed how the conditions were frequently so severe that they would be flagged as a "caution" to health if the participant's were expected to work under such conditions. It also highlighted specific examples of particularly acute overheating conditions that occurred (e.g. night-time temperatures, internal gains and glazed stairways).

It then went on to show how the buildings occupants were overwhelming uncomfortable during the summer, and this was because they were too warm. This was followed by the interview results. These showed that almost all participants were uncomfortable at times, whilst the majority were very aggrieved. They felt that the conditions were frequently too hot (even when the external conditions were not too warm), and that this particularly affected their ability to sleep, which in turn affected how they functioned the next day. The section concluded by using thermal comfort theory to suggest why participants may have felt so aggrieved with conditions in summer, that on some occasions were not so different to winter.

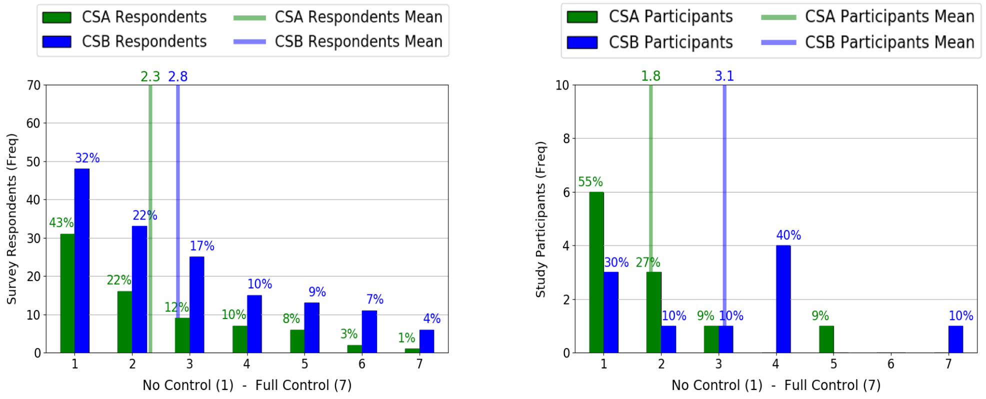
In summary, it seems important to emphasise that while some participants were relatively placid regarding the conditions, many were not. Indeed, anger, frustration and outrage were common, and the majority of participants were in agreement that summer conditions were unacceptable.

5.3 Occupant Behaviour

This thesis has shown how the majority of monitored bedrooms overheated, and that generally the participants (and survey respondents) were dissatisfied with the summer conditions. However, what has not yet been shown is the reasons why some rooms overheated extensively, while others did not, and the effectiveness (or not) of adaptive behaviours. This will be covered in the section below.

5.3.1 Survey Results

In the survey the following question was asked “how much control do you personally have over reducing the temperature in your room (cooling)?”. The results are displayed below in Figure 5.26.



(a) Survey Respondents **(b)** Study Participants

Figure 5.26: Survey results for “how would personal control do you have over reducing the temperature in your room (cooling)?”

Figure 5.26 shows that in both case studies the survey respondents generally felt that they had limited control over reducing the temperature in their rooms. Indeed 43% and 32% of the respondent’s in CSA and CSB respectively felt that they had no control at all. Similarly, the comments in the survey on this question were dominated by respondents expressing a frustration at the lack of control over cooling.

While the majority of survey respondents clearly felt that they had very little control over reducing the temperature, many did feel that they had at least limited control. Section 5.4 below will explore what is likely to have made the difference between the respondents.

5.3.2 Interview Results

The participants in both case studies adopted a range of behaviours to combat the warm temperatures. In general, as shown by the overheating results, these actions were relatively unsuccessful; at least in terms of reducing the monitored temperatures in their rooms. Yet it is this researcher's view that the occupants did make use of the available adaptive opportunities. Furthermore, this was often in considered, intelligent and sometimes innovative ways. Hence the buildings overheated irrespective of the actions taken by the occupants, and not because of them.

5.3.2.1 Vacate the Room

The most common response was simply to avoid their bedroom as much as possible. Therefore to use their bedrooms for sleeping only, and to return late in the evening do this. For example, "at 7am I get up and leave my room straight away, and only return to sleep at midnight or even 1am" [A10 - 23-08-18] and "yeh well even at like 1am I will still be in the yard just to cool myself down" [A2 - 24-08-18] and "I used to totally avoid my room until the night" [A7 - 24-08-18].

In this respect there was unanimity amongst the participants that "study" bedrooms could not be used for studying during the day in summer. This was despite the fact that many participants expressed clearly that, if possible, their preference would be to work in their bedrooms. For instance, "it's too hot to work in here. It was uncomfortable. It was also just because you know it was very hot in here so you just feel quite tired and demotivated.... you know lethargic" [B2 - 19-06-18] and "I've been trying to work in here but I've found that I've got a bad headache before and I just have to get out" [B3 - 19-06-18].

5.3.2.2 Restricted Behaviours

The interviews highlighted how participants often felt restricted in their actions. The primary annoyance for participants was the restricted window openings. The request for "at least a window that opens all the way... you know" [A6 - 06-07-18] was raised repeatedly. The majority of participants indicated that their primary issue with the restricted window openings was about insufficient airflow, and the thermal comfort benefits that more air flow would bring. For instance, "you just can't get any wind through the room" [A4 - 02-07-18], and "I think If there was just a bit of a draft it would make a big difference to how I feel" [B3 - 19-06-18].

There were also other actions in which participants felt impeded. For instance, blinds that were used to limit solar gains would also affect ventilation through the window, while bedroom doors had to remain shut at all times or the occupant risked a fine (all bedroom doors are fire doors). For example, "well yeah you can't have the blinds fully down or else you can't get the air coming in your room" [B2 - 19-06-18] and "yeah and you can't really do anything about it because you aren't allowed to prop the fire doors open because that is a fine able offence" [B6 - 29-05-18].

It also revealed how several participants felt that alleviating overheating impeded their ability to use their room for normal purposes e.g. ovens were not used in studio rooms as they added more unwanted heat. For example, "I even stopped using the oven because it would just make the room so hot to the point that I would need to leave to I just use the stove top" [A3 - 24-08-18].

5.3.2.3 Effective Actions

Certain actions were viewed as effective. For instance, nearly all the participants purchased a fan, and the majority felt that this did improve their comfort. For example, "well when I was in the room I just had the fan you know blasting directly on me so I just felt better" [A3 - 24-08-18]. Although this did mean that many questioned why they weren't provided automatically "I don't see why they couldn't include a fan or something... I think we pay enough" [A3 - 24-08-18].

There was one room in CSA, and two rooms in CSB in which some form of cross ventilation were feasible. All three participants suggested how they thought this improved ventilation, and enhanced convective cooling, or in the words of the participant "it feels so nice just to have draught... you know just take the edge of the heat" [A10 - 23-08-18]. The cross ventilation technique was also described by a resident in CSB, "well if there is a breeze and you have both windows open then it can get quite a powerful blast of air coming through which really helps when it is hot" [B2 - 19-06-18]. However, cross ventilation is only effective when it's windy, and therefore, as the same participant put it "if it is not windy, it doesn't matter what you do, this place is a sweat box" [B2 - 19-06-18].

In most cases, mechanical ventilation was provided at background rates only. However, several of the studio rooms in CSA did allow for higher mechanical ventilation rates (see Section 3.3.1.3 for details). The participants were generally appreciative of these systems, and most felt they were effective at bringing more air through the room. For instance, "I leave that switch on all the time [the ventilation boost mode] because like I find with the windows open it brings some wind in" [A3 - 24-08-18].

An additional unexpected, yet popular behaviour, was to move the bed to be directly beneath the window. At least four participants in CSA mentioned doing this during the heatwave period, for example "I moved my bed to the window because it was too hot... and that definitely helped because you just feel some more wind" [A8 - 24-08-18]. It is likely that the participants benefited from both the convective cooling affect of the cooler nighttime air passing over their bed, alongside the generally cooler temperatures at floor level due to thermal stratification.

Finally, many participants also spoke about how multiple strategies were used to cope with the heat. Although, some also expressed how such strategies meant forgoing normal everyday activities (e.g. cooking, or studying in their room). For instance, "Well basically when I get in I just have a cold shower, open up the window, get my fan on, and lie on my bed, or even sometimes the floor actually... but obviously that doesn't make me very productive. But then again, the only other alternative is just to get out altogether, and sometimes I do have to sleep" [A3 - 24-08-18].

5.3.3 Summary

The above section has that the survey respondents were unanimous in finding the conditions in summer uncomfortably hot. It also showed the range of actions the participants reported taking to alleviate overheating. It highlighted how participants often felt restricted in their actions, and how several participants felt that alleviating overheating impeded their ability to use their room for normal purposes.

It then went on to highlight the range of actions that occupants did view as effective, such as minimising the amount of time spent in the accommodation and sleeping on the floor. The interviews generally showed that the participants made use of the available adaptive opportunities, often in resourceful and innovative ways (e.g. moving the bed), but were fundamentally limited in their options due to the design of the building. This is discussed further in Section 6.

5.4 Overheating Causal Factors

As shown above in Section 5.2.1.1, whilst some rooms overheated extensively, others barely overheated at all (as assessed by the overheating standards). The section below examines the factors that may have resulted in these discrepancies using a combination of qualitative and quantitative analysis. It will also assess some of the adaptive actions undertaken by the participants, and show whether they were effective or not.

5.4.1 Summer Radiator Usage

Despite the overheating conditions, monitoring of the radiators revealed that heating was still on in some rooms as late as June 2018. In the case of CSA this only occurred for one room. All other rooms had turned their heating off by the beginning of May. However, in the case of CSA the heating was on in multiple rooms in mid-summer, which caused considerable frustration for the affected participants. The summer radiator usage is shown below in Figure 5.27 for the three rooms in which it occurred.

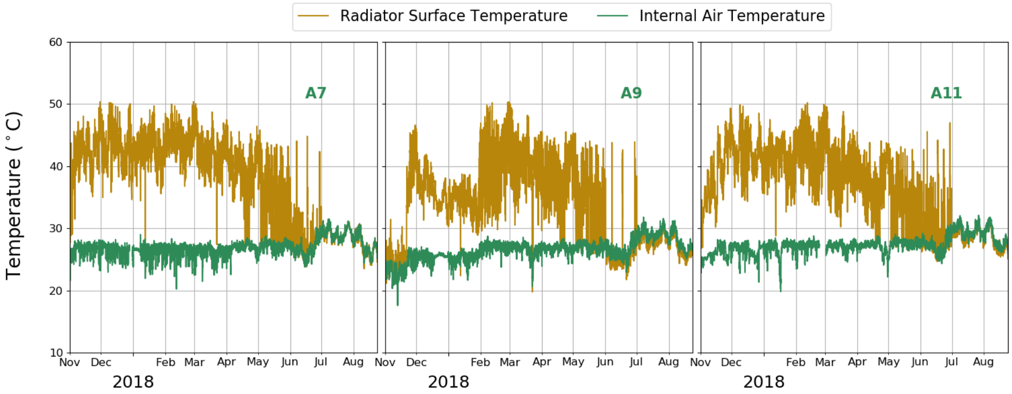


Figure 5.27: Examples of heating being provided during the summer in CSA.

It is not clear exactly why these rooms were affected, whilst others were not. Nor why some saw only spikes in heating (A9), or near continual heating (A11). The issues appear to be twofold. Firstly, why is the central system providing heating to the rooms. Secondly, when the temperature in the rooms is averaging around 25°C why is the TRV letting hot water flow into the radiator.

Unfortunately, the FM interviewed as part of the investigation was not working at the PBSA during the monitoring period and so had little more to offer than “that shouldn’t have happened, it should all be switched off centrally from, well it depends on the weather, but typically sometime in May” [CSA FM - 02-09-19].

5.4.2 Window Opening

The primary in-built mechanism the participants had to affect the conditions in their rooms during summer was to open their windows. The overall amount of time that the windows were open in the participant's bedrooms is shown below in Figures 5.28 and 4.19 for CSA and CSB respectively.

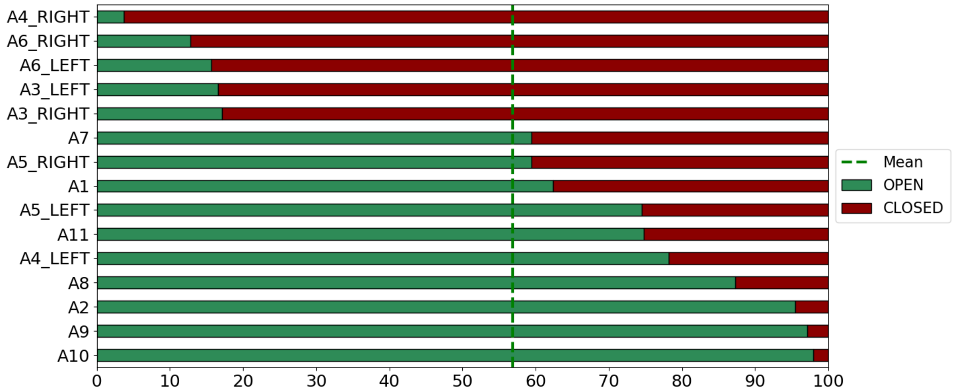


Figure 5.28: The percentage of the summer period in which the windows were open in the participant's rooms in CSA.

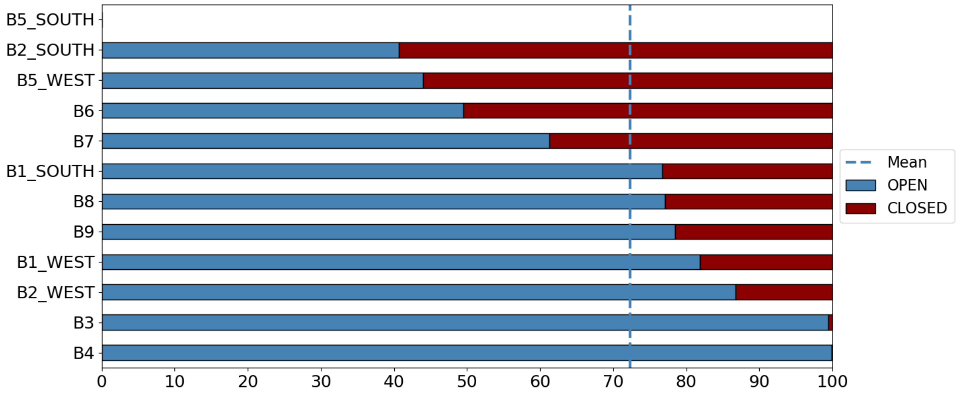


Figure 5.29: The percentage of the summer period in which the windows were open in the participant's rooms in CSB.

Figures 5.28 and 4.19 show that from May 2018 on wards the participant's windows were kept open for an average of 58% and 72% in CSA and CSB respectively. This concurs with the qualitative data in which the majority of participant's reported leaving their windows open most of the time in summer, although some did not like to open them overnight (due to insects, or noise), while others reported them blowing shut.

Interestingly, the rooms with lower percentages of window opening (e.g. A3) were often those that tended to remain cooler. The possible reasons these particular rooms remained cooler is covered in the Sections 5.4.3 and 5.4.4 below. It is also important to note that for the vast majority of the summer, in most of the rooms, the internal conditions were warmer than outside, and therefore having the windows open was generally the correct strategy.

Therefore despite the windows being generally open the rooms still overheated (see Section 5.2.3 above), and the occupants still reported the conditions to be stuffy (see Section 5.2.4.2 above). In many cases window opening was shown to be relatively ineffective at reducing temperatures. This often remained true even at night when external temperatures cooled considerably. However, the effect of window opening differed significantly between rooms; these differences are explored below in Section 5.4.4.

5.4.3 Internal Gains

Internal gains were likely a contributing factor to overheating in both case studies. This has been shown by the consistently hot corridors in both buildings, and the overheating bathrooms in CSA (see Section 5.2.3.6). However, while all the rooms in CSA are likely to have been affected by internal gains (although admittedly by differing amounts), this did not appear to be the key factor that differentiated between the severity of overheating.

This can be shown by examining two extreme cases in CSA i.e. the warmest and coolest bedrooms. Figure 5.30 shows the internal temperatures in each room, along with window opening, over a particularly warm period in mid-July 2018. Also shown on Figure 5.30 is the corridor temperatures immediately outside of each room.

Figure 5.30 shows how the corridor temperatures directly outside of these

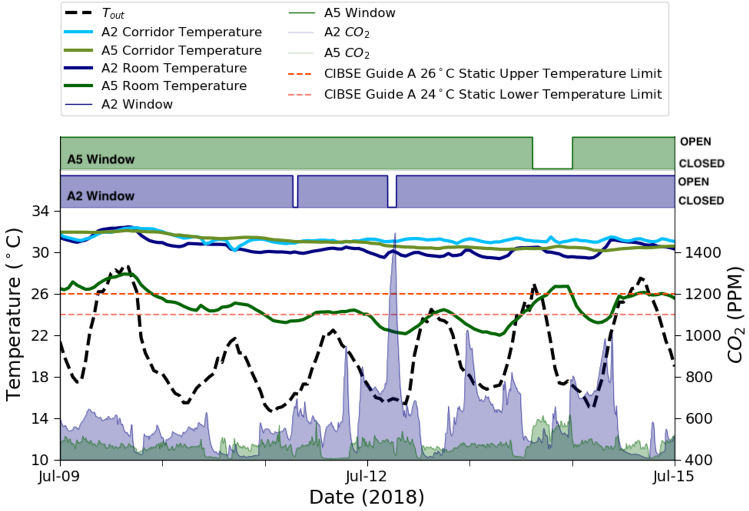


Figure 5.30: Chart showing the differences in room temperatures between A2 and A5 during a warm period in mid-July 2018, in which the corridor temperatures remain nearly identical.

KEY DESCRIPTION:
Window opening is shown at the top. The window is open if the area is shaded. CO_2 levels are the shaded area at the bottom of the chart, and are shown on the right y-axis. Corridor temperature, internal room temperature, and external temperature are shown on the left y-axis. The CIBSE guide A static temperature limits of 24°C and 26°C are also shown for reference (CIBSE, 2003).

rooms were nearly identical. Similarly, both rooms had their windows open for the majority of the period. Yet the temperature in A5 is generally 4 to 6°C cooler than A2. Indeed, while the temperature in A2 (30°C) indicates fairly extreme overheating and discomfort, the temperatures in A5 remains relatively moderate for the time of year (i.e. between 22 and 26°C)

Figure 5.30 also shows that when the external temperature drops (black dashed line) the internal temperature in A2 also falls, whereas it remains relatively stable in A5. This occurs despite the consistency of the temperatures in the two corridors.

Figure 5.30 suggests that there were two crucial differences that made the difference between warm (yet bearable), compared with hot and uncomfortable conditions. Firstly, A5 was more successful at removing unwanted heat, particularly once the external temperature drops i.e. the ventilation was better. This room had a larger window (and therefore a greater cross-sectional area of opening) and a mechanical ventilation system that could be “boosted” to deliver higher ventilation rates. The importance of ventilation will be covered again below.

Secondly, A5 (courtyard facing) was not affected significantly by solar gains whereas A2 (east facing) was. This meant that A2 kept receiving unwanted heat gains in the morning, as described by the occupant “in the morning it is super hot, because you know the sun. It shines in and my room just gets so hot that I have to leave” [A2 - 24-08-18]. Therefore the solar gains likely contributed to the internal temperature remaining warm. Furthermore, the occupant did not view the blinds as particularly effective at reducing solar gains, and also (as discussed in Section 5.3.2.2 above) they felt it impeded ventilation. For instance, “I haven’t really been closing them at all because if I pull them down then there is no air. So I don’t always pull it down. But like if it is super hot in the morning then I will pull it down for a little bit, but I don’t think they are that good at stopping it getting hot anyway” [A2 - 24-08-18].

Figure 5.30 suggests that in CSA where the ventilation was adequate, and solar gains were reduced, temperatures did remain broadly within comfort boundaries, even during very warm periods. This shall be further discussed in Section 6.1.

5.4.4 Ventilation & Solar Gains

The rooms that managed to remove unwanted heat once the external temperature dropped managed to limit the duration of overheating conditions far more effectively. Furthermore, these rooms also gave the occupant more agency over the indoor conditions i.e. they could make adaptive actions that were (at least somewhat) effective at cooling their rooms. There is both qualitative and quantitative evidence to support these assertions.

In CSB some townhouses bedrooms were dual aspect, while others were not. The charts below show the internal conditions in two bedrooms on the same corridor in one of the townhouses in early May 2018. Figure 5.31 is a single-aspect room (B3), whereas Figure 5.32 is a dual-aspect room (B2) with windows facing south and west (see Section 3.4.2.2 for details on the monitored rooms).

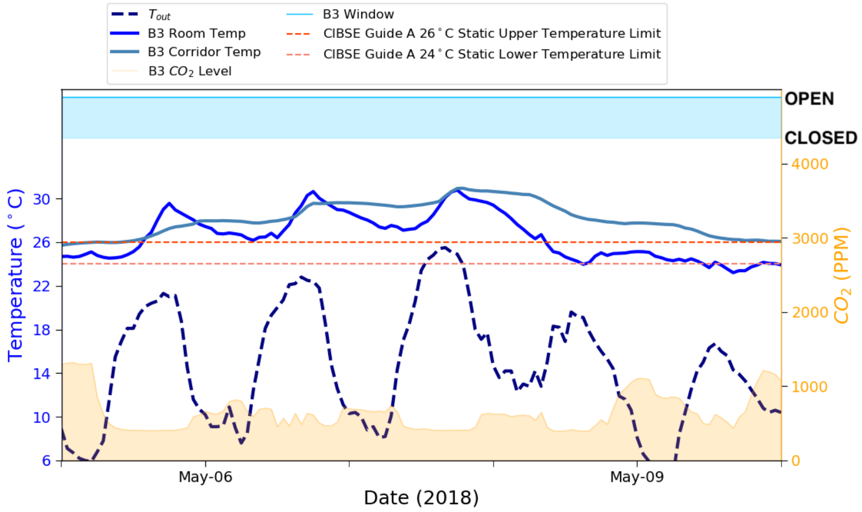


Figure 5.31: Single-aspect room in CSB during warm period in early May 2018 showing slower and more limited reduction in internal temperature.
KEY DESCRIPTION:
Window opening is shown at the top. The window is open if the area is shaded in blue. CO_2 levels are the shaded area at the bottom of the chart, and are shown on the right y-axis. Corridor temperature, internal room temperature, and external temperature are shown on the left y-axis. The CIBSE guide A static temperature limits of 24°C and 26°C are also shown for reference (CIBSE, 2003)

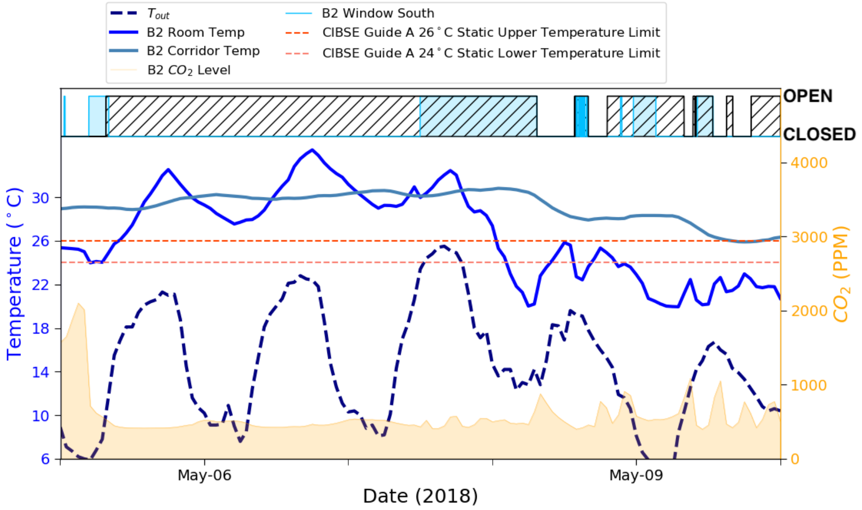


Figure 5.32: Dual-aspect room in CSB during warm period in early May 2018 showing rapid and substantial reduction in internal temperature
KEY DESCRIPTION:
Window opening is shown at the top. The window is open if the area is shaded. The south facing window in B2 is represented by the blue filled area, while the west facing window is represented by the black hatch pattern. CO_2 levels are the shaded area at the bottom of the chart, and are shown on the right y-axis. Corridor temperature, internal room temperature, and external temperature are shown on the left y-axis. The CIBSE guide A static temperature limits of 24°C and 26°C are also shown for reference (CIBSE, 2003)

Figures 5.31 (B3) and 5.32 (B2) show that both recorded high internal temperatures over this period; reaching maximum temperatures of 30.1°C and

32.9°C respectively. However, it is the reduction in temperature that highlights the significant effect that cross-ventilation can have on the internal conditions in the rooms.

Figure 5.32 shows how during the night on May 8th 2018 the temperature in the dual-aspect room reduces from approximately 32°C down to 18°C, and that this occurs when they have opened both windows. Indeed the occupant reduced the temperature to such an extent that they then closed their windows in response, triggering a sharp increase in temperature. Whilst there is a reduction in temperature in B3 it is significantly less marked (30°C to 24°C). Therefore arguably B3 remains uncomfortably warm as the temperature does not fall below the CIBSE Guide A static limit of 24 °C (as shown on Figure 5.31 by the dashed pink line).

The interviews from these two rooms support these findings. Although the participant's acknowledge that cross-ventilation is only effective if there is a breeze. For example, the occupant in B2 "well basically as long as you can see the trees moving slightly and I have both my windows open then it tends to be enough to get some breeze through, which helps a lot" [B2 - 19-06-18]. Whereas the occupant in B3 stated that "if I actually want to be cooled down by the breeze then I have to sit very close to the window. But even when it's windy I don't think opening the window has much effect, although I suppose it would be even worse if it was shut" [B3 - 19-06-18].

The limited effect that single-aspect windows with restricted openings have on the internal temperature can also be shown in CSA. In this case two bedrooms are shown that are on the same corridor (with identical orientation), but with two rooms between them.

Figure 5.33 shows that between July 25th and July 30th 2019 the participant in A8 leaves their window open (see the green shaded area at top of chart), whilst the participant in A7 leaves their window shut (shaded blue area at top of chart). The CO_2 concentration indicate that the occupant in A7 vacated their room over this period and left their window shut, which

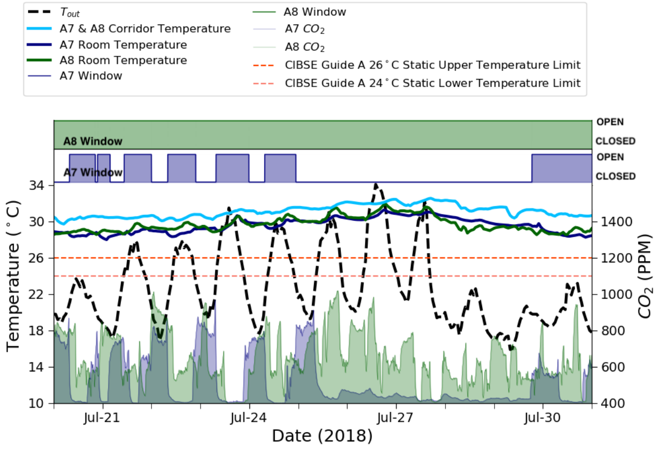


Figure 5.33: Chart showing the minimal impact window opening had on the difference in temperature between two rooms on the same corridor during a warm period at the end of July 2018.
KEY DESCRIPTION:
Window opening is shown at the top. The window is open if the area is shaded. CO_2 levels are the shaded area at the bottom of the chart, and are shown on the right y-axis. Corridor temperature, internal room temperature, and external temperature are shown on the left y-axis. The CIBSE guide A static temperature limits of 24°C and 26°C are also shown for reference (CIBSE, 2003).

may have had some effect on limiting internal gains. Nevertheless, Figure 5.33 shows that having the window open has little to no effect on reducing internal temperature in A7 compared to A8. This is despite the significant drop in outside temperature that occurred on July 28th 2018.

The final example from CSA is shown below in Figure 5.34. This is used to highlight the combined effect of solar gains and ventilation on internal conditions. A10 faces NNW, and the bedroom door opens onto a glazed corridor in which the windows can be opened. Whereas A9 faces NWW and is situated on an internal corridor with no external openings. Both rooms have their windows open for the entirety of the period shown in Figure 5.34.

Figure 5.34 shows that as the external temperature drops on July 10th the temperature in A10 reduces by 4°C (from 28°C to 24°C). However, in A9 the temperature reduction is far more limited, and the room conditions remain in an overheated state. This is due to two effects. In A10 the bedroom window and the corridor window could be opened at the same time, and according to the occupant "Well if those windows out there are open [windows in the corridor] then you can kind of here the woosh of the draught coming in round the side of the door and stuff, and it's just like ahhhh some relief" [A10 -

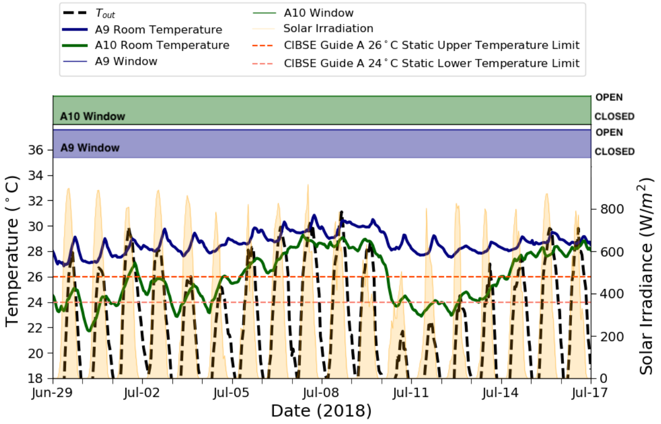


Figure 5.34: Chart showing the effect that differing ventilation mechanisms had on reducing temperatures in two rooms in CSA in mid July 2018.
KEY DESCRIPTION:
Window opening is shown at the top. The window is open if the area is shaded. External solar irradiance levels are the shaded area at the bottom of the chart, and are shown on the right y-axis. The internal room temperatures, and external temperature are shown on the left y-axis. The CIBSE guide A static temperature limits of 24°C and 26°C are also shown for reference (CIBSE, 2003).

23-08-18].

Figure 5.34 also show how A9 (facing NWW) tended to be affected by solar gains towards the end of the day, causing spikes in temperature. Yet in A10 (facing NNW) solar gains appeared to have a shortened effect on the internal temperature, allowing A10 to start reducing in temperature earlier in the day as the external temperature cools.

5.5 Summary

This chapter has showed that the overwhelming majority of survey respondents felt that the summer conditions were uncomfortably warm. This was confirmed in the interviews, in which almost all participants complained of overheating conditions at times. The majority of residents focused their complaints on nighttime temperatures, and the impact this had on sleep. Yet, while some viewed overheating as a major problem, others were more sanguine; for these participants overheating was infrequent, and relatively unimportant. Indeed, many participants still expressed how they would choose to live in the residences again.

The chapter went on to analyse the indoor conditions over the 2018 summer. It showed how the majority of monitored bedrooms overheated. In many cases the overheating was both severe and prolonged. However, some rooms barely overheated, and did not fail overheating tests. This section concluded by highlighting overheating issues specific to these case studies, but that are likely to affect the PBSA stock more widely (e.g. glazed stairways, internal heat gains in communal areas, and nighttime temperatures).

The chapter then examined occupant behaviour in response to overheating. The vast majority of survey respondents felt that they had "no control" over reducing the temperature in their bedroom. It showed how the study participants undertook a range of actions in attempts to alleviate overheating, and that they were particularly frustrated by the restricted window openings. They felt that the restricted openings severely limited the scope for ventilation; thereby reducing their ability to remove heat from their rooms, whilst simultaneously restricting opportunities for convective cooling of themselves.

The chapter concluded by showing a number of graphs that revealed how ventilation (or the lack thereof) was often the key difference in terms of an occupant's ability to alleviate overheating. These charts showed that while all rooms experienced uncomfortably high temperatures at times, in some rooms heat could be removed much more successfully once outdoor temperatures dropped. The room designs that appeared to be more successful at removing heat had either higher power mechanical ventilation systems, or allowed for cross ventilation. Consequently, those without such design characteristics could not removed unwanted heat, and therefore remained in an overheated state, often for extended periods.

Chapter 6

Discussion

This thesis began by identifying two interrelated issues with the UK's building stock. The first is the need to reduce operational energy usage in buildings. The second is to maintain, and where possible improve indoor environmental quality. PBSA were targeted for research due to the stock's high development rate, relatively homogeneous designs and the suggestion that the current design of PBSA may be leading to overheating issues, and wasteful energy practices.

During the literature review three clear gaps were identified in the current understanding of PBSA in operation. Firstly, several studies identified overheating as an issue in PBSA. However, the existing studies to date had two clear gaps. The first is whether students residents viewed overheating as a significant issue (none of the existing studies included surveys or interviews after or during occupant's were likely to have experienced warm weather conditions). The second is exploring what actions residents took to alleviate overheating conditions, and whether these had any effect.

Secondly, previous PBSA POE studies had identified that there was a gap between predicted and actual performance, and that this was considered to be "likely due to student's preferences and behaviour in operating the heating system and window opening" (Hernandez et al., 2014). However, neither this study nor any other found in the literature review offered any evidence supporting this assertion regarding window opening. Furthermore, it was not sufficiently explored as to why the occupant's behaviour may differ from that predicted, and therefore what could be done to help reduce the performance gap.

Thirdly, no previous UK PBSA POE study had included indoor monitoring of the CO_2 concentration. Therefore it had not been previously investigated whether these building types were providing adequate IAQ, and/or whether ventilation was sufficient. In order to address the gaps identified in the literature review two PBSA case studies were selected, and post-occupancy monitoring was conducted. The results are discussed below, divided into the three sections outlined above; overheating, heating controls and ventilation.

6.1 PBSA Overheating

In both case studies overheating was found to be widespread, severe and often prolonged. This finding is similar to the majority of other previous studies that have monitored PBSA indoor conditions e.g. (Altan et al., 2013; Quigley, 2016; Innovate UK, 2013). If anything the conditions were shown to be even more extreme, with the majority of rooms failing both static and adaptive overheating tests (see Section 5.2.3).

The increased severity of overheating is likely due to a combination factors. Firstly, the summer of 2018 was abnormally warm (see Section 5.1). Secondly, the monitored PBSAs (in particular CSA) exhibited a multitude of features that combined together to cause particularly acute conditions. Of particular concern was the fact that overheating was near continuous for some rooms, and that it frequently occurred even when the outside temperature was relatively cool. In some cases this led to conditions that, according to heat stress metrics, were hazardous to health (see Section 5.2.3.5).

The fact that the conditions observed in these buildings coincides so closely with the findings from other monitoring studies suggests that overheating is likely to be prevalent in many newly built PBSA developments. Nevertheless, it would be beneficial to undertake a study on a wider sample of PBSA to confirm this (see Section 7.4). Yet even without more evidence, it seems relatively uncontroversial to state that the newly built PBSA stock very likely has an overheating problem. Design and policy recommendations to address this issue are included in Section 7.3.

6.1.1 Occupant Views on Overheating

It has not been well established in previous PBSA monitoring studies whether overheating was a major issue for the residents (see Section 2.5.4.5). This is important, because the degree to which future design changes (and possible retrofits) may be required should be informed by the views of the occupants themselves. For instance, if overheating was just a minor inconvenience for the student occupants then it may not be worth researchers and practitioners addressing the issue further.

The surveys clearly showed that the majority of residents found the conditions to be uncomfortably warm (see Section 5.2.4). This contrasted sharply with the winter conditions, which were also often warm too, yet most residents reported being thermally comfortable (see Section 4.2.3.1). The contrasting survey results between summer and winter, despite overheating conditions occurring during both seasons (see Figure 4.6 for an example of winter overheating), also raised an interesting question with regard to adaptive overheating standards. This is covered in Section 6.1.4 below.

Another important aspect of the contrast between the thermal comfort survey results for each season is survey timing. These results show that it is important that surveys are conducted after residents have lived in their accommodation during warm weather conditions. Surveys that occur before this are likely to be unfairly favourable regarding the indoor conditions. Facilities management, universities and private providers should consider this when organising future accommodation surveys (see Section 7.3).

The interviews also corroborated the survey results. Nearly all of the residents were dissatisfied with the conditions, whilst several were very distressed, and notably angry as a result (see Section 5.2.4.3). Universities, accommodation providers, developers and investors should take note. As the student accommodation market matures, PBSA that become renowned for overheating may become more difficult to let.

The participants tended to focus their complaints on night-time temperatures (see Section 5.2.4.3). Indeed, the overnight (23:00-07:00) temperatures in CSA during the 2018 heatwave (see Figure 5.15) suggest the grievances were well founded. The complaints were due to the impact the conditions had on their sleep quality, and the corresponding affect on their well-being and ability to study.

Thus not only was overheating an issue of comfort and well-being, but, according to the participants, it also had an impact on their academic performance. This is clearly an issue for academic institutions as major coursework hand-ins and exams are often in the summer months. As such, the link between overheating, sleep quality and cognitive performance seems to be an area that could benefit from further research (see Section 7.4).

6.1.2 Adapting to Overheating

In previous studies (e.g. (RTA, 1995)) the authors have suggested that the actions of the inhabitants may have contributed to or even caused the overheating conditions. Although there was generally found to be a lack of data to support these suggestions with evidence (as discussed in Section 2.5.4).

The interviews and monitoring in these case studies suggest that residents generally undertook sensible adaptive actions to alleviate overheating e.g. windows were mainly open at night, and blinds were shut during the day (see Section 5.3.2). Therefore this research suggests that, in the case of these specific PBSAs, overheating mainly occurred as a result of design shortcomings, rather than occupant behaviour.

The most common adaptive behaviour adopted by the residents was simply to vacate their rooms as much as possible during warm weather (see

Section 5.3.2.1). Several of the participants simply stated that their room became unusable during the day. While many found the avoidance of their room an acceptable solution, it does raise the question of whether it is acceptable to provide accommodation in which your only personal space becomes unusable for periods of the year.

This may also partly explain why the participants focused their complaints on night-time temperatures. For, while the participants could avoid their rooms during the day, there are limited alternatives to sleeping in their bedrooms overnight. It has also been argued previously that taking additional adaptive measures is inevitably more limited whilst an occupant is sleeping, or attempting to sleep (Lomas and Giridharan, 2012).

One more key point of emphasis for the participants in terms of overheating was window design (see Section 5.3.2.2). Many participants accepted that their bedrooms would become warm during warm weather but that they just wanted a window that "opens properly" (i.e. opens wider). This is covered below in Section 6.3.2.

6.1.3 Overheating Design Risks

In CSA in particular there were a number of design features for which it was curious that they made it through the design and planning process, without being modified or altered. For instance, the ten-storey, fully-glazed, south and west facing staircase that lacked a means of ventilation (see Section 5.2.3.6). Unfortunately, thermal dynamic simulations are not required to asses if this space would overheat.

Therefore the fact that it was built in this way suggests a failure of both the design and planning process. Arguably, such designs may be more common in PBSA due to the slightly vague area that PBSA sit within the UK's planning and buildings regulations (PBSA are considered as non-domestic for building regulations purposes, and "outside of any use class" in UK planning legislation; see Sections 2.1.2.6 and 2.1.2.7). However, these linkages would be difficult to prove conclusively. Yet the fact that these features were allowed to be built suggests a wider, systemic problem with the UK's design and planning process with regard to overheating risk. Hopefully, this area should be improving through initiatives such as TM59, a design methodology for the assessment of overheating risk in homes (CIBSE, 2017b).

The design solutions that can reduce overheating risk (e.g. improved ventilation, improved solar shading, reducing internal gains) are well-known from previous studies, see for instance Porritt et al. (2012). Indeed, the results in this thesis also suggest that where these design features were included, the conditions in both cases studies tended to remain more tolerable (see Section 5.4.4). Plus, in the case of the ability to cross-ventilate, they also gave the occupant greater control over the conditions (provided there was a breeze).

However, further research is required in this area. For instance, it seems important to better understand whether PBSA, without major layout changes, can rely on passive cooling measures alone (i.e. no mechanical cooling) and remain comfortable during hot (or even warm) weather. Furthermore, how will passively cooled residences perform in twenty years when the UK's climate is likely to be significantly warmer, and heatwaves more common (Holmes et al., 2019). The potential further work in this area is covered in Section 7.4.

6.1.4 Adaptive Overheating Standards

As discussed in Section 6.1.1 above, the thermal comfort survey results differed significantly between summer and winter; with occupants reporting to be generally comfortable in winter, and uncomfortable in summer. Yet overheating conditions were observed in both seasons.

Adaptive overheating standards suggest that the comfort temperature ($\boldsymbol{T_{comf}}$) inside buildings is related to the outdoor air temperature (see Section 2.2.1.2 for details). Thus as the external temperature increases the internal temperature band within which the occupants are likely to be comfortable also increases. Hence an occupant's comfort expectations adapt over time to the changing external conditions (e.g. from season to season).

However, in this research there were some indications from the monitoring results and interviews that a warm internal environment of a certain temperature that was comfortable in winter, may have been regarded as uncomfortable in summer. In other words, as the external temperature increased, the participant's comfort temperature ($\boldsymbol{T_{comf}}$) may have stayed the same, or even decreased. It is important to note that there was limited conclusive evidence to support this suggestion; this is discussed in detail below. Nevertheless, the evidence from the interviews was compelling enough that it is worth discussing, and also exploring why this may have been the case, and how it could be researched in the future.

Firstly, as stated by Nicol "adaptive thermal comfort is a function of the possibilities for changes, as well as the actual temperatures achieved" (Nicol and Humphreys, 2002). In winter, when the internal environment was warm (or even overheating), the participant knew they had the capacity to cool their room down (i.e. by opening a window). For example, "because it is cold outside, I know that if it does get too hot I can just open the window and let the airflow in" [B2 - 21-02-18] (see Section 4.3.3.1 for more examples and evidence of this behaviour).

Whereas in summer, depending on the external conditions, such capacity rarely existed. The participant could open their window, and yet the internal environment would remain unchanged. For example, "I've had the windows open all day and at night, but it's still just so warm" [B4 - 22-05-18] (see Section 5.4.2 for more examples and evidence). Thus in winter possibilities for change existed that did not in summer. This could have affected an occupant's comfort levels, arguably even at similar internal temperatures.

Secondly, human beings have been proven to enjoy thermal change (Oseland, 1995). For instance, saunas, plunge pools or sunbathing are all examples of changes in thermal environment that many people may consider to be pleasurable activities. Perhaps the same logic could be applied to coming into a warm (even overheated) environment on a cold winters day. Whereas conversely, if you're already warm from being outside, then returning to an overheated environment may feel oppressive. It may be possible that this could be the case even if the internal temperature was similar to that experienced in winter, at least initially.

There was some qualitative evidence to support both these suggestions. For instance, the quote from this participant on the conditions in winter “well in these past few weeks it has been quite cold outside, so it has been more bearable inside. It actually feels nice when it is cold outside coming into the warmth you know” [A10 - 05-02-18]. As opposed to this quote on the summer conditions, “You know when it’s already hot outside and then you come in and it’s so hot in here too and I just think ’ahh I just want to lie down and not move’” [A10 - 23-08-18] .

However, there are a number of other possible explanations for these findings. For instance, it could just be that the internal environment was that bit warmer (e.g. 2°C) in summer, which made the difference between comfort and discomfort. It could also be that the preference for thermal change only occurs upon initial entry to the building, and once occupants have adapted to the conditions, then adaptive thermal comfort theory still applies.

This study did not collect the data to be able to study this area in more detail. More thermal comfort research would be required to gather evidence to support this theory. One such method could be to undertake regular sampling of the participant’s comfort levels at different internal temperatures throughout the year. This is discussed further in Section 7.2.1.

To conclude this section on overheating there are a number of key points. Firstly, this study corroborates previous PBSA monitoring studies in that both PBSA overheated. This adds further evidence to suggest that the design of PBSA makes them inherently susceptible to overheating. Secondly, overheating was a major issue for many participants, affecting comfort, well-being, and possibly even academic performance. Thirdly, the interviews and monitoring suggested that the participants generally made use of the available adaptive measures. Therefore overheating was principally a result of design shortcomings, rather than occupant behaviour.

6.2 PBSA Heating Controls

Previous studies have emphasised the importance of adequate heating controls for thermal performance, and also to prevent the risk of overheating in PBSA e.g. (Quigley, 2016; Vadodaria, 2012). The findings in this study corroborates those previous studies, and strengthens the case for adopting different heating systems and controls in future PBSA designs (see Section 7.3.3.2).

This study suggests that centrally controlled wet-heating systems with TRVs in individual rooms did not provide adequate control for either occupant satisfaction, or efficient use of space heating. This was evidenced by the fact that occupant satisfaction with the controls was low; as shown in both the surveys and interviews (see Section 4.3.2). In addition, the majority of the rooms were over heated during the heating season, and as such were unnecessarily warm (see Section 4.2.1.1).

There were also examples of rooms being heated for extended periods (i.e. multiple consecutive days) while they were unoccupied (see Section 4.3.3.5). However, exactly how prevalent the heating of unoccupied rooms was in these case studies could not be determined. Therefore neither could the savings be estimated if improved heating controls could have reduced the amount of time unoccupied rooms were heated. How this evidence could be gathered is covered in Section 7.2.2.

6.2.1 Comparison with UK Domestic Heating Studies

In Section 2.4.2.2 studies were reviewed that had analysed the use of heating in UK dwellings. In these studies, the mean monthly temperature for the living rooms and bedrooms in a range of UK dwellings was found to be 19.3°C and 18.9°C respectively (Shipworth et al., 2010). This compares with a mean monthly average temperature of 25.2°C and 23.1°C for the participant's study bedrooms in CSA and CSB respectively.

The significant differences in internal temperatures between the PBSA monitored in this study, and a typical set of UK homes can also be observed graphically. Figure 2.8 shows the scatter plot of mean daily internal versus external temperature from the CARBHES data set (see Section 2.4.2.2 for details). Meanwhile Figure 4.4 shows the same plot for the conditions inside all of the monitored bedrooms across both case studies.

Viewed together, these charts clearly show how for the same external conditions, the internal temperature inside both PBSA are considerably warmer than the average internal temperatures recorded in UK dwellings from the CARBHES data set. Indeed, the coolest internal temperatures in CSA tended to be above the mean temperatures recorded in the Kelly et al. (2013) study. This indicates that it is likely that these PBSA (particularly CSA) were heated to a significantly warmer temperature than what may be considered "typical" in UK dwellings.

Obviously, there are important differences between PBSA and domestic dwellings (as is discussed in Section 2.4.2.2). These may make it desirable to have warmer conditions in PBSA. Indeed, the internal temperatures in the UK dwellings may not be desirable, and are likely to be skewed by the periods in which the occupants are out, and the dwelling is unheated. Nevertheless, it seems unlikely that the temperatures in PBSA need to be 4-5°C warmer than typical UK dwellings, and it is likely that the set-point temperatures in PBSA could be reduced somewhat without unduly impacting on comfort.

Similarly, the average heating usage on weekdays was predicted to be between 8.2-8.8 hours for UK dwellings (Shipworth et al., 2010; BRE, 2013b). This would equate to having the heating on for approximately 30-40% of the time (depending on how it was used over the weekend). Again, this contrasts sharply with CSA in which the heating was on for upwards of 80% of the time over the heating season (see Section 4.3.1.1).

However, it does correlate more closely with CSB, in which occupants had greater control of the heating system, but heating was also centrally regulated (see Sections 3.3.1.3 and 3.3.2.3 for details of the respective heating systems).

In CSB the heating was on for an average of 35% of the time in the participant's bedrooms. However, it is not possible to assess to what degree the participant's heating behaviour is reflective of typical households when they are provided with control, and to what degree the reduction in usage was attributable to the centrally controlled restricting of space heating hours.

6.2.2 Heating Controls and Window Opening

In previous studies there have been assertions made about how occupants may have used their windows regularly during the heating season e.g. (Hernandez et al., 2014; Hopkison and James, 2006), yet this has never been validated. This study confirms that in these two particular case studies windows were used regularly, and for long periods throughout the heating season (see Section 4.3.1.2).

The findings suggest this was primarily done for two main reasons; to prevent overheating, or to provide sufficient ventilation to achieve adequate IAQ (IAQ is covered in Section 6.3 below). There were other aspects that also were also important with regard to regular window opening, such as responsiveness, confusion and lack of financial implications (see Section 4.3.3 for more details).

This study generated both quantitative and qualitative evidence to suggest that ineffective heating controls can lead to increased window opening during cold weather (see Section 4.3.3.1). It has also been estimated in this study that the extended opening of windows during cold weather may be responsible for a sizeable share of the overall heat losses in PBSA studybedrooms (see Section 6.2.3 below).

One important finding from the window opening during the heating season is that while the majority of window opening events were short, it is the longer duration events that made up a large proportion of the total time the window was open (see Figures 4.21 and 4.22). This finding has a number of important implications.

Firstly, it shows that for many of the participants maintaining comfortable conditions in their rooms was dependant upon having their window open consistently, and not just for short purge events. This is the result of many rooms being persistently overheated, under-ventilated or both. Indeed, many participant's expressed how closing their window while they were in the room would rapidly lead to poor IEQ (see Section 4.3.1.2).

Secondly, assuming that the ventilation and heating control can be improved (see Section 7.3 for recommendations), these results suggest that the targeting of long duration window opening events could be an effective method for limiting thermal losses through open windows. For instance, window opening events of longer than 12-hours were responsible for approximately 65% (7,538 hours) and 70% (7,398 hours) of the total time the windows were open in CSA and CSB respectively. Design recommendations to specifically target these events are also included in Section 7.3.

6.2.3 Window Opening Heat Losses

In Section 4.3.4.2 it was estimated that window opening during the heating season may be responsible for a sizeable share of the overall heat losses in certain participant's rooms. The rooms that were estimated to have the highest heat losses from window opening were those in which the windows were open for extended periods, during times at which the temperature differential between inside and outside was substantial (e.g. a warm room on a cold winters day).

However, it was also shown in Sections 4.2.2.1 and 4.3.4.1 that many rooms were under ventilated. This is also covered below in Section 6.3. Therefore the results suggest that providing adequate IAQ in many rooms requires an increase in the planned ventilation rate to these rooms.

An increase in the ventilation rate would inevitably increase the infiltration and non-window losses in these rooms (i.e. the red section in the bar charts in Figures 4.37 and 4.38). It would also likely have an effect on the electrical load of the building due to increased energy consumption from ventilation fans. As such, the energy savings from reducing window opening in the heating season would be partly offset by the requirement to increase the planned ventilation rate. Although the losses could be somewhat reduced if a heat recovery system was used (e.g. MVHR).

The finding that window opening can lead to sizeable heat losses is supported by the study on window opening heat losses that is included in Section 2.4.3.3 of the literature review (Jack et al., 2016). In this study they found that "window opening has the potential to cause a significant additional heat loss relative to the baseline performance of a dwelling in cases of high thermal performance or extreme window opening behaviours" (Jack et al., 2016).

The study does not confirm what constitutes "extreme" behaviour. Yet it would seem that, at least some of the rooms monitored as part of this research, may fit both of these criteria. For instance, both PBSA could be said to have high thermal performance i.e. low U-values and relatively airtight (See Sections 3.3.1.2 and 3.3.2.2 for energy efficiency characteristics of the case studies). Alongside which four rooms in CSA and two rooms in CSB had their windows open for more than half of the heating season. Although there is limited comparative evidence on long-term window opening behaviour in dwellings, this behaviour seems likely to be considered "extreme".

However, there are important differences between the dwelling design in the (Jack et al., 2016) study, and the PBSA monitored as part of this research. The most important being the ventilation rate achieved when the windows are open. This is significantly greater in the (Jack et al., 2016) study. For example, in (Jack et al., 2016) it is between 1.3-3.1 ACH whereas in this study it was more commonly around 0.5 ACH (see Section 4.3.4.1). This difference in ventilation rates will result in significantly lower heat losses for the PBSA during the periods in which the windows are open.

Due to the necessity to improve the overall thermal performance of dwelling's in the coming years (see Section 1.1.3), winter window opening seems like an area that would benefit from further research. Otherwise there is a risk that increased window opening in new or retrofitted dwellings built to high thermal performance standards may act as a rebound effect; reducing the overall energy saving benefits of improved envelopes. How this area may be further researched will be covered in Section 7.4.

6.2.4 Occupant Preferences for Heating Controls

Alongside potentially leading to energy wastage, inadequate heating controls also appeared to effect occupant satisfaction (see Section 4.3.2.5). The dissatisfaction was primarily due to a lack of control. As such, the participants were near unanimous in their desire for greater control. In CSA this was simply to be able to control the temperature at all. In CSB it related primarily to the centrally controlled timer system, and the desire to have heat on demand at all times of the day.

It is this authors view that ignorance of the respective heating systems led some participants to simply give up on interacting with their heating system altogether. Instead, they chose to use the window, which they knew gave them a guaranteed, instant response. In other words they chose the simplest strategy; leaving the heating on one setting, then adjusting the temperature via the window. Indeed, in the case of CSA, there was no obvious alternative to this strategy.

Although many participants expressed how using their window provided them with a means of thermal control, this was far from ideal. In many cases this meant the participants had to choose between being too hot, or having a cool draught of winter air. This controls strategy was also particularly inadequate at night (see Section 4.3.2.2). The controls that may be best suited to PBSA are discussed in Section 7.3.

Overall, the results suggest that heating controls in PBSA need to provide a number of key characteristics, and that the heating systems in these particular case studies (i.e. wet-heating systems with TRVs) often failed to deliver these. Firstly, the results suggest that the individual heating systems in new PBSA, built to modern energy efficiency standards with small study bedrooms, do not need to deliver lots of heat (providing windows are not used regularly). For example, rooms in which heating was rarely used did not see significant falls in temperature (see Figure 4.28).

The findings from the interviews suggested that the heating system should also be responsive (occupants reported wanting instantaneous change), easily understandable (the majority of participants did not fully understand their heating system), and capable of switching off to prevent overheating (see Section 4.3.3.1 for overheated rooms during the heating season). In addition, preferably the controls should help conserve energy by preventing the heating of spaces which are unoccupied or have their windows open (see Section 4.3.3.5 for examples of this occurring). The design recommendations for heating controls that may better deliver these characteristics are provided in Section 7.3.

6.3 PBSA Ventilation

Insufficient ventilation and air movement have been raised as a concern in a PBSA study previously (Li et al., 2017) (see Section 2.5.4.6 for further details). However, no previous UK PBSA study was found that included monitoring of CO_2 concentration.

6.3.1 Inadequate Ventilation in CSB Townhouses

This study has showed that the rooms lacking some form of mechanical ventilation did not provide adequate ventilation. This is evidenced by the high CO_2 concentrations in all of the CSB townhouse rooms. These were the only rooms without some form of mechanical ventilation (see Section 3.3.1.3 and 3.3.2.3 for details on the ventilation systems). The lack of ventilation was shown to be particularly concerning overnight (23:00-07:00), with many rooms in CSB regularly exceeding 2000PPM for extended periods (see Figure 4.10).

The precise levels at which CO_2 concentrations cause health impacts is uncertain (see Section 2.3.3). Nevertheless, it seems plausible that occupants regularly exposed to conditions exceeding 2000PPM are likely to be effected by some SBS symptoms (e.g. headaches, fatigue and difficulty concentrating). In the case of CSB 4 of the rooms had CO_2 concentrations above 2000PPM for 30% of all nighttime hours during the heating season.

The participants in these rooms certainly felt as if they were affected by SBS symptoms, with all complaining vociferously about the conditions (see Section 4.2.3.3). They complained of feeling "tired", "waking up with headaches" and even feeling "ill" and "nauseous". As such, these participants felt that they had to open their windows regularly, or else they would suffer from poor IAQ. Although, some felt the opening of windows was not always possible at night due to the thermal comfort implications (see Section 4.3.2.2 for details).

One interesting finding from the interviews is that the participants in the townhouses suggested that they could not use their trickle ventilators in their windows due to the noise they would make when open. The participants felt that the noise was loud enough to prevent them from sleeping. As such, they would seemingly rather sleep in a stuffy environment, or with their windows sightly open, than with the trickle ventilators open.

Therefore due to unforeseen eventualities (e.g. acoustic implications) the participants did not use their windows as the designers expected. For instance, guidance suggest that trickle ventilators should remain largely open (HM Government, 2010a). As such, POE has helped to highlight a surprising issue that was restricting how occupants were operating the building, and thus causing a gap between expected and experienced IAQ. The implications and recommendations emanating from this finding are discussed in Section 7.3.3.4.

However, because the participants in these bedrooms had their trickle ventilators closed, it is difficult to state conclusively whether they would have had IAQ issues had they been open. For instance, if there had not been acoustic issues and the trickle ventilators had been open, would they have experienced IAQ issues, and would they of been of the same severity? This is an area that will be covered in Section 7.4.

As with health, understanding of the link between elevated CO_2 concentrations and cognitive performance is both limited, and mixed (see Section 2.3.3). Although, in one study overnight concentrations averaging 2395PPM were shown to affect the subjects' performance in a logical thinking test the next day (Strøm-Tejsen et al., 2015). Several of the rooms in CSB averaged these concentrations overnight on multiple occasions. Certainly it seems logical that if you're waking feeling tired, nauseous or with a headache, then your academic performance is likely to be affected. Thus, as with overheating bedrooms, it is likely that insufficient ventilation may impact upon an occupant's academic attainment, as well as their comfort.

One final point on CO_2 concentrations and health is that the HSE recommends a workplace exposure limit (the average value over an 8-hour period) of below 5000PPM. As detailed in Section 4.2.2.1, at least two of CSB townhouse rooms definitely exceeded this exposure limit. It is also important to point out that other CSB townhouse rooms may have also have exceeded the exposure limit. This would depend upon how far above 5000PPM the CO_2 concentration reached over the period (even if an entire 8-hour period was not above consistently above 5000PPM, the concentration still could have averaged over 5000PPM).

The fact that the HSE exposure limit was exceeded in these rooms suggests that the stuffy conditions may not have just been uncomfortable, but actually unsafe. This should be a significant cause for concern for developers, FMs and universities. Recommendations for reducing the likelihood of such conditions occurring in future PBSA schemes is included in Section 7.3.

6.3.2 Ventilation & Overheating

The other important ventilation finding is with respect to overheating. It has been estimated that 4-5 ACH are required for effective thermal comfort ventilation (NHBC, 2012). In this study the estimated ventilation with the window open was significantly below this rate (see Section 4.3.4.1). This had two important impacts for summer thermal comfort.

Firstly, in many cases the ventilation rate was insufficient to remove unwanted heat, even when the external temperature dropped. This was shown in Section 5.4.4 by comparing two rooms in CSA on the same corridor during a warm period (see Figure 5.33). In this case one room has its window open, whilst the other has its window closed. This contrasting window opening behaviour seemingly makes no discernible difference to the internal temperature in the two rooms. That is despite the external temperature dropping significantly over the period.

Therefore Figure 5.33 alongside other evidence in Section 5.4.4 suggests that top-hung restricted opening windows in single-aspect PBSA rooms are not capable of delivering sufficient ventilation to help maintain thermal comfort during warm weather periods. They are not effective at removing unwanted heat, nor according to the study participants, do they generate sufficient air movement within the rooms for effective convective cooling (see Section 5.3.2.2). Although no large study of PBSA window types was found (see Section 2.1.2.9) this author suspects that these window types are likely to be the most common in new PBSA developments. This view comes from conversations with PBSA designers, as well as desktop research in which PBSA rooms can be viewed online.

However, as covered in Section 2.4.3.1, any alternative window design will still need to restrict openings to between 100-150mm. These requirements could be met, whilst significantly increasing the opening area, by adding external louvres to PBSA windows (an example photo is shown in Figure 6.1). Furthermore, as discussed above in Section 6.1.4, ventilation can also be enhanced by using larger mechanical ventilation systems or by making cross-ventilation possible. Those rooms in this study that provided one of these features were shown on occasions to be more effective at removing unwanted heat (see Section 5.4.4).

In summary, there are two main points concerning ventilation in PBSA

Figure 6.1: Example photo of PBSA window with louvres that would increase the opening area, while meeting health and safety requirements (LABM, 2020).

that this study has highlighted. Firstly, those rooms lacking mechanical ventilation were not adequately ventilated. Therefore the only means these participants had of maintaining adequate IAQ was to have their windows consistently open while in their rooms. Secondly, in the majority of rooms, the ventilation rate was not sufficient to help alleviate overheating, either by removing unwanted heat or providing sufficient air movement for convective cooling.

6.4 Reporting the Results

One of the primary aims for this research was to feedback operational insights from the performance of PBSA buildings to those responsible for designing and constructing future PBSA (see Section 7.3.3 for the design recommendations). The motivation behind this was for the research to deliver real world impact i.e. to improve the future performance of PBSA.

One of the strategies used to accomplish this was to embed the researcher within a construction company. This provided the researcher with unique access to design documentation, buildings and crucially the practitioners responsible for designing and building PBSA. Being embedded in the organisation had a number of advantages, principally the ability to report back the results via a range of different mechanisms (i.e. not just through formal documentation) in order to maximise impact (these processes are covered in Section 7.3.1 on feedback and organisational learning).

However, being embedded within an organisation can also present a number of challenges in terms of dissemination and publication. For instance, in this case the researcher was required to sign a Non-Disclosure Agreement (NDA). This agreement requires that any information related to the sponsor's building will not be disclosed without their approval. In reality, this means that specific details about the building (e.g. location, layouts, images) that are valuable context for the reader will be redacted prior to publication of the thesis.

Thus for a researcher the potential advantages for impact gained principally via access must be weighed up against the restrictions placed on publication or dissemination of the findings. Indeed, this is just one aspect of a wider dilemma affecting the entire AEC industry. This is the fact that publishing POE findings is undoubtedly beneficial for the AEC industry as a whole, yet for the particular organisation concerned it may bring negative commercial, reputational and even legal risks. Hence why many POE studies remain, perhaps unsurprisingly, unpublished (Leaman et al., 2010).

6.5 Summary

This chapter has presented a discussion of the results. It has focused on three main areas; overheating, heating controls and ventilation. Throughout the chapter design issues have been highlighted (e.g. limited personal heating controls, restricted window openings, and fully glazed stairways).

It has then been suggested how these factors affected the participant's comfort, well-being, and possibly even academic performance. It also discussed how these design issues affected how the participants used the building (e.g. staying away from their rooms in summer, or increased window opening during the heating season).

The chapter concluded by discussing the implications for reporting of the results of researchers being embedded in partner organisations. The next chapter will provide a summary of the key findings in relation to the research questions, after which the implications and recommendations resulting from the research will be presented.

Chapter 7

Conclusions, Implications & Recommendations

This chapter outlines the conclusions from the research, alongside the implications and recommendations for a range of different stakeholders.

7.1 Key Findings in relation to research questions

7.1.1 RQ 1

Can occupants control indoor environmental conditions in the heating season, what are the influencing factors, and how does their behaviour affect energy demand?

Occupants generally could control the thermal conditions in the heating season. However, the controls were far from optimum. In CSA thermal control could only be achieved by opening windows, otherwise the rooms tended to overheat. In CSB, the majority of participants reported finding the controls to be confusing and unresponsive. As such, the majority of participants also reported leaving their heating set on high, and resorted to using their window for thermal control.

The influencing factors behind the participant's behaviour differed between the two case studies. In CSA, the occupants had no real means of thermal control except for their windows. As such, unless the participants were thermally comfortable with warm indoor conditions (e.g. 24°C and above), the window had to be used regularly.

In CSB, the occupants were confused about the timing of the centrally controlled heating systems, how TRVs work and therefore when they could, and could not have heat. Therefore many simply resorted to “getting the heat when you can”, and then opening the window if it became too hot. Furthermore, in the CSB townhouses the windows were used regularly to keep the room sufficiently ventilated. In the participant’s view, this necessitated keeping the heating on high. This was done to prevent their rooms becoming uncomfortably cold during the periods in which they had their windows open to ensure adequate IAQ.

Aside from the energy efficiency implications this control strategy had a number of drawbacks. Firstly, participants felt that they had to choose between hot and stuffy conditions, or uncomfortably draughty conditions. Secondly, using the window as the means of thermal control meant that frequent adjustments were required in order to maintain an acceptable indoor temperature. This was particularly problematic whilst attempting to sleep as adjustments could not be easily made. As such, occupants reported being either “boiling” or “freezing” in the morning, depending on their window choice from the preceding night.

This research has provided evidence to support what multiple previous authors have suggested; that windows are used frequently, and for long periods throughout the heating season in PBSA. A model was used to make an estimate of the heat losses due to window opening. It suggested that heat losses due to window opening could be up to 44% of the room’s total heat losses. Thus window opening is likely to have a significant impact upon the thermal performance of PBSA, and this may negate some of the efficiency gains from fabric improvements. For instance, there is limited benefit in a “fabric first” approach if the fabric is routinely opened.

7.1.2 RQ 2

To what extent do occupants make use of the available adaptive opportunities to meet their thermal requirements during warm weather conditions, and what affect do these actions have on the building's internal environment?

The results showed that overheating was prevalent in both case studies. In CSA it was particularly severe, and long-lasting in many of the rooms. Although CSA residents were in their accommodation throughout the summer, whereas CSB residents were not. The surveys and interviews both showed that the vast majority of the occupants were uncomfortably warm. Furthermore, some of the participants were particularly upset and angry about their living conditions. Many of the participants complained about the impact the conditions had on their sleep, and therefore their ability to study the following day.

The occupants generally made good use of all the available adaptive opportunities. By far the most popular solution was simply to avoid their bedrooms as much as possible during warm weather conditions. The second solution that was perceived to deliver real benefits was the use of a fan. However, other adaptive opportunities (e.g. window opening) were reported by the participants to be of limited effect, whilst some actions were not allowed (e.g. propping open the bedroom door). Analysis of the IEQ data was also used to show the limited effect that window opening had on the internal temperature in certain rooms.

Those rooms in which window opening was both reported (qualitatively) and shown (quantitatively) to have a greater effect were those in which some form of cross-ventilation was possible. This was either via enhanced mechanical ventilation (drawing outside air in through the open window) or where the room was multi-aspect (although this was only advantageous if there was a breeze). Complaints about the window restrictors were unanimous across all the participants. Furthermore, many of the residents felt that the internal blinds were ineffective at reducing solar gains, and when pulled down would restrict ventilation further.

However, it is worth noting that some of the rooms barely overheated. This is despite the abnormally warm conditions during the summer of 2018. There were two crucial differences between those rooms that overheated extensively, and those that did not. Firstly, those rooms that allowed for some form of cross-ventilation were more effective at removing the unwanted heat once the external temperature dropped (i.e. overnight). Secondly, those rooms that were not affected by solar gains, either through orientation or shading of the PBSA itself, experienced more limited temperature rises during the day. Thus despite the extreme conditions observed in many rooms the results suggested that where ventilation is sufficient, and solar gains can be minimised, the conditions in these buildings can remain acceptable during warm weather conditions.

There is one final important point to stress from these results. There may be some that argue that as students are young, tend to live in PBSA for just one year, and may not spend their summer in the residences, that overheating is not that important. While this may have been the case for a few of the participants, for the majority it was not. For them overheating was a serious issue that affected their comfort, well-being and ability to study effectively whilst at university.

7.2 Limitations of Study

There are a number of limitations that have been identified throughout this research. These have been grouped into two main subsections and are outlined below.

7.2.1 Research Design

One of the limitations of the research design is that it was not possible to correlate specific internal or external temperatures, CO_2 concentrations or time-periods, with the participant's feelings on comfort or why they took a particular adaptive measures. This was because data collection from the participants (i.e. interviews) only occurred on three occasions throughout the year.

This limitation meant that it was not possible to investigate the specific external or internal temperatures at which the participant's became uncomfortable, or to compare the temperatures at which occupants reported being comfortable in winter against summer. It would also have been beneficial to explore the CO_2 concentrations at which the participant's reported feelings of stuffiness, or to quiz occupants at the specific time they undertook a particular adaptive action (e.g. opening a window) why they did that. Such real-time feedback from the participants could have helped better merge the social and technical elements of the study into a truly integrated set of results. This would have been likely to produce many interesting insights on occupant comfort in PBSA.

Continuous collection of occupant feedback throughout the monitoring period could have been achieved through the use of an app on the participant's phone. This would have allowed the user to input data throughout the monitoring period, which could then be time stamped and compared against the data at the particular time the occupant reported it. However, the benefits of such methods would depend upon the degree to which the occupant chose to interact with the app. Furthermore, there would likely be issues of data collection and security, alongside development of the app, that would need to be overcome. Overall, it was not considered feasible to administer such a system during this study.

There were also a couple of limitations regarding the samples in both case studies. In CSA, there was a lack of east facing rooms that looked over the Caledonian road (i.e not including east-facing rooms that looked over the courtyard). For instance, there was only one room (A1), and in this room the participant left in mid-July. This room was shown to be particularly warm, and the temperature profiles indicated it was significantly affected by solar gains in the morning. However, it could not be investigated whether this was also the case in a wider sample of rooms that were east facing.

In CSB, all of the townhouse rooms were in the same townhouse. Thus it was not possible to assess whether this particular townhouse was more affected by ventilation and overheating problems than the other townhouses. Although the similarity of the design suggests that similar issues would have been likely to affect the other townhouses. If the budget and time had allowed it would have been beneficial to collect data from a wider sample of townhouse rooms.

7.2.2 Data Collection

This study collected a range of data to analyse the internal conditions, and how the participant used the building. This included internal temperature, RH, CO_2 concentration, window opening, radiator surface temperature, and three sets of interviews. Despite this there were a still number of aspects in which the data available limited the scope of the analysis, and thus collection of additional variables could have provided extra insight for addressing the research questions.

This was particularly true of occupancy. There were multiple instances in which could occupancy have been accurately determined, it would have allowed for more conclusive findings regarding particular aspects of PBSA performance. For instance, the actual amount of time the participant spent in an overheated or overly dry environment was unknown, and instead assumptions regarding occupancy were used (e.g. the occupant is in their rooms between 23:00-07:00). Occupancy data could also have provided an answer as to the amount of time the heating was on, and the rooms were unoccupied. This would have allowed for an estimation of the potential savings from limiting the heating of unoccupied rooms, and thus whether this is a major energy conservation area to target, or a minor issue not worthy of further attention.

Initially, it was assumed that CO_2 concentration could be used to infer occupancy. However, there were a number of issues with just using CO_2. The primary one being that the participants opened their windows regularly, which meant the CO_2 concentration would often fall to near background concentrations. At which point it was not possible to know whether the room was occupied or not. Furthermore, a number of the better ventilated rooms in CSA saw relatively minimal increases in CO_2 concentration throughout the monitoring period.

As discussed in Section 2.3.4, determining occupancy is not straightforward. The most accurate methods tend to rely on combining multiple variables, such as movement sensors, CO_2 concentration and light levels, and then analysing the data using an algorithm. Adding in these extra sensors would have added more cost and technical complexity to the monitoring, as well as likely encountering additional ethical implications. Therefore it was not considered feasible within the time frame and budget of this research project to include an effective occupancy monitoring system.

Another area that proved to be a limitation was in collecting radiator surface temperature only. This provided an indication of whether the heating was on or off, but it could not be used to determine the radiator setting or the amount of energy consumed for heating in that particular room. This limited the ability to show conclusively the relationship between particular behaviours, and the impact on heating energy consumption.

For instance, if heating energy consumption had been monitored, this would have allowed for a far more accurate determination of the final part of the first research question "...and how does their behaviour affect energy demand". In this case, the heating consumption could have then been compared against other metrics, such as the percentage of time the window was open or the internal temperature. It could also have been used to show the amount of heat required to maintain the internal temperature in a room for a given external temperature, and how this changes when the window is either open or closed.

This could have been rectified by using heat meters to monitor the actual amount of heat used by each participant. The heat in each room was not metered because it was not considered feasible to install heat meters in each of the participants rooms. Metering of the heat would have required some relatively invasive and expensive works. It was judged that the PBSA managers would not have permitted this to occur.

Another limitation of the results was in understanding the behaviours of the wider building population. The interviews provided rich data on how the participant's used their windows and heating systems, alongside their occupancy patterns and other adaptive measures. However, the surveys were overly focused on conditions, rather than control of the conditions or how the occupant used the building. Collecting this data in the surveys would have allowed for greater insight into how the wider building population used the buildings, and also to better understand how representative the participant's actions were of the wider PBSA population.

The fact that such data was not collected limited analysis of the survey results to primarily questions of comfort, as well as extremely limited questions around control (e.g. how much control do you personally have over the following...). For instance, this meant that it was not known how frequently the survey respondent's used their windows, and for how long, and therefore whether the participant's behaviour was representative of the respondents. In hind-sight, more questions should have been added on user behaviour.

One final limitation was the fact that CO_2 sensors had an upper limit of 5000PPM. As such, the actual maximum value of CO_2 concentration reached in several rooms was unknown. If the sensors had been capable of exceeding this limit it may have provided even more weight to the presentation of the ventilation results, particularly when these were being shared with the author's industrial sponsor.

7.3 Implications & Recommendations

This research has a identified a range of implications and recommendations for different stakeholders. These are detailed below in separate subsections.

However, before outlining the implications from this study for the PBSA sector more widely, it is necessary to address the implications for the particular PBSA that were monitored. In this author's view there are two particular areas of concern that should be prioritised.

Firstly, the results suggest that in CSA (at least on the upper floors) the overheating risk should be addressed. The conditions experienced during the 2018 summer were extreme, and possibly even unsafe at times. The evidence for this comes from the occupant feedback, internal temperature analysis, overheating assessments and the use of heat stress metrics. The university and accommodation provider have a duty of care to their residents (who are paying significant rental costs) to provide improved conditions during warm weather.

These measures could include retrofitting the buildings, either by improving solar shading (e.g. installing external blinds or brise-soleils) and/or enhancing ventilation (e.g. installing guards so that the windows could be opened fully, or upgrading the mechanical ventilation system). The other option to consider could be mechanical cooling, these could be portable units or permanent fixtures. At the very least, the study suggests that providing every occupant with an effective fan should be considered.

The second area of high concern is the ventilation in the CSB townhouses. Once again, arguably the conditions were not just uncomfortable, but may even have negative health and academic performance implications. In this case, the acoustic performance of the trickle vents should be investigated. If they cannot be opened without creating disturbing levels of noise it should be considered whether the trickle vents, or even the windows need to be replaced.

If neither of these interventions is possible, occupants should at least be reminded of the importance of ventilating their rooms regularly, and particularly to allow for some form of ventilation overnight (e.g. leaving their windows on the partially open catch). Inevitably this behaviour will have thermal comfort and energy usage implications. Nevertheless, the severity of the CO_2 concentrations recorded in certain townhouse rooms suggests that addressing this area should be prioritised.

7.3.1 Feedback & Organisational Learning

One of the primary aims of this research was to provide feedback to the construction company (part sponsors of the PhD research) on the performance of their existing PBSA, which could help to drive design improvements in future PBSA developments. Therefore one of the key outcomes and areas of impact from this research is that the construction company have recently completed a PBSA building with resistance electrical heaters, external shading overhangs, and windows with security grills, such that they can be fully opened.

Some of the trends may have occurred without this research project. However, according to the construction team the evaluation of the existing residences was critical in providing the evidence base with which to drive through design changes, and not just opt for the status quo (i.e. to do what was done last time). It is this author's hope that such design changes will significantly improve occupant comfort and reduce carbon emissions at the new PBSA.

To achieve impact on the design process within an organisation it is important to briefly cover the concept of organisational learning. This is the process of creating, retaining, and transferring knowledge within an organisation (Ahmed and Wang, 2003). It occurs when there is a change in knowledge within an organisation (Argote and Miron-Spektor, 2011).

If you want the research to impact on the design of buildings then you need to ensure that the knowledge created (i.e. through conducting POE) is effectively retained and transferred within an organisation. The knowledge must also be available to the appropriate person, at the right time, and in the right form to successfully impact design decisions. If the design is altered or informed by POE findings, then there has effectively been a change of knowledge within the organisation regarding that particular design aspect or decision. In which case organisational learning has occurred.

The key point here is that organisational learning (i.e. POE influenced design) will not necessarily occur simply by conducting POE and writing up the findings. Therefore if the researcher wants to affect design change, it is paramount that they consider at the outset of the project what levers are available to them to affect organisational learning. In undertaking this process, they may find this affects their selection of the most appropriate evaluation techniques, the timing of the POE itself, and also whether it is worthwhile attempting to instigate some kind of formal or contractual relationship with the organisation.

This is an important point, as the available levers through which the researcher can create and transfer knowledge are inevitably impacted by the researcher's relationship to the practitioner organisation. For example, it is this author's belief that in the case of this project, had the author not been embedded within the practitioner organisation, it would have been significantly more difficult for the research to have achieved the same impact. However, this must be balanced against the possible impacts upon dissemination that such a relationship could entail (see Section 6.4).

It is worth briefly considering some of the ways in which knowledge was effectively created and transferred in this project. One method was through lunchtime presentations. This provided the opportunity for the author to provide feedback, and discuss the findings with a range of different stakeholders at one time. It was often the case that the attending stakeholders also entered discussion with one another during these events regarding particular design aspects. It is worth noting that one of the key reasons for the success of the presentations was that the meeting invite was distributed by someone relatively senior within the organisation, and particularly relevant stakeholders were specifically targeted with follow up correspondence to ensure they attended.

However, it is this author's conviction, that the most effective method for knowledge transfer was simply by regularly being in the same location as the practitioners, and therefore available to those making design decisions at the time in which they are making them. For example, there were multiple occasions during which an email was sent, or discussions were held over a coffee, whereby a member of the organisation questioned this author about specific findings from the POE's and how these might affect the design decisions they were currently making. If this author had not been known and available to members of the organisation, it seems less likely these important conversations would have occurred. Hence the point above regarding the importance of considering the relationship between the researcher and the organisation.

In summary, it is vital that future researchers undertaking POE who wish to impact the design process consider the role of organisational learning at the outset of the project. Furthermore, it is this author's experience that it was through being embedded within the organisation that presented many of the best opportunities for creating and transferring knowledge that can ultimately impact the design process.

7.3.2 Regulations & Compliance

Both of the case studies investigated during this research passed overheating assessments using DSMs at the design stage, yet in many of the monitored rooms in both buildings overheating was found to be frequent and long-lasting. One of the approaches to addressing this issue is to improve the accuracy of DSMs. This is already occurring through initiatives such as TM59, which this research suggests should be routinely adopted when modelling overheating in PBSA.

Another approach would be for the regulations to require buildings to prove that they are comfortable in operation. That is, once built and occupied, developers could be required to provide evidence showing that, for instance, the building does not overheat or was adequately ventilated. Such approaches are already becoming more common for demonstrating energy performance. Therefore rather than relying on design stage predictions, new regulations require operators to disclose their operational energy performance (e.g. through initiative such as Display Energy Certificate (DEC)s or in the future a NABERS-UK rating). It could be argued that a similar approach could be conducted for IEQ.

Undoubtedly there would be many difficulties in designing a regulatory regime to monitor and prove adequate IEQ in operation. Nevertheless, if it were to occur, the shift towards demonstrating IEQ compliance in-use would inevitably focus minds amongst practitioners to design for ensuring adequate IEQ in operation, and not to design for compliance. It may also have the effect of practitioners further interrogating and questioning the outcomes of DSMs.

7.3.3 PBSA Design

There are a range of implications for the designers of PBSA on specific areas of PBSA performance. These have been split into three subsections; heating controls, overheating and ventilation. However, before these specific areas are covered it is worth covering how to make future PBSA POE ready.

7.3.3.1 Making Buildings POE Ready

Undertaking POE in these case study buildings has generated a number of important insights into the operational performance of PBSA. However, gathering the data to provide these insights was a relatively difficult and time consuming process. It has been argued previously that conducting regular POE (and incorporating it into design process) is an important step in creating better performing buildings (see for instance Section 2.5.1). Therefore one crucial step in this process is to reduce the time and costs involved in conducting POE.

One way to reduce the workload required is to construct buildings that are already POE ready. A lot of the steps required to make this happen are already occurring due to various “smart building” initiatives. Although there is some ambiguity about this expression, a smart building is generally considered to be one that is capable of using technology to share information about what occurs in the building and between the various systems so as to optimise the building's performance.

Therefore if such data is already being routinely generated in buildings then theoretically the time required to collect the data should be dramatically reduced. Hence designers could rapidly evaluate the performance of their buildings which could be used to improve both the performance of the existing building, and that of future buildings. In this regard POE could become an on-going process in which buildings are routinely monitored and assessed for optimisation opportunities.

However, it has been shown previously that the integration of new technologies into buildings is often inadequate, and that control systems are unnecessarily complex (Innovate UK, 2016b). Therefore in the shift towards relying on technology and ever greater amounts of data, care should be taken to ensure that the systems installed in buildings are manageable by typical FM personnel. Otherwise there is a risk that buildings which seemingly offer great performance at the design stage "may quickly assume vicious circles of deterioration and dysfunctionality" in operation (Leaman et al., 2010).

7.3.3.2 Heating System & Controls

The findings suggested that PBSA heating controls need to provide a number of key characteristics. These have been discussed in Section 6.2.4. In this author's opinion, the characteristics required of the space heating systems in PBSA would be best served by relatively small resistance heaters (e.g.1-2kW). These would be linked with individual thermostats in each room to control the heating at a certain internal temperature set-point (e.g. 22°C). More localised controls should help reduce the amount of winter overheating, as was shown to affect the monitored PBSA in Section 4.2.1.1.

These heaters should also be installed with timers. These would turn-off the heater after a certain time period, unless the occupant chooses to re-activate it. This should help to prevent the heating of unoccupied spaces for long-periods, as was shown to occur in Figure 4.31. In addition, as long as the ventilation is adequate (see Section 7.3.3.4 below), the heating controls could also be linked with automatic relays in the windows. These would prevent the window from being open and the heating being on at the same time, as occurred regularly in these two case studies (see Table 4.3.1.3).

Finally, electric resistance heaters would also reduce the amount of hot water pipework in the buildings. This should help to conserve energy, while simultaneously helping to address both winter and summer overheating (see Section 7.3.3.3 below). The elevated bathroom and corridor temperatures throughout the monitoring period suggested that high internal gains were an issue (see Section 5.2.3.6).

Another limitation of this study is that an electrically heated PBSA was not also monitored for comparison. However, the findings in this study, along with the existing literature, suggest that such an approach is likely to be preferable to wet-heating systems. Although careful consideration would be required regarding the electrical capacity implications of entirely electrically heated PBSA.

Furthermore, as renewables continue to constitute a greater proportion of electricity generation over the coming years (CCC, 2015), the carbon emissions of electrically heated buildings should continue declining relative to gas (providing that they are well-maintained and managed). Indeed, updated carbon factors in SAP10 should make achieving compliance with UK building regulations using electric resistance heaters significantly less challenging (BRE, 2019).

DHW could be generated using heat-pumps. These could make use of cheaper (lower-carbon) electricity overnight to charge thermal stores in each apartment block ready for the morning shower peak. It is likely that to reach the required DHW temperatures immersion heater top-ups would also be needed.

The thermal stores should be located in plant areas that are well-ventilated, and also well-insulated from the accommodation areas (see

Section 5.16 for the potential issues caused by heat gains from plant located within accommodation areas). Heat pumps should outperform purely electric showers from an electrical consumption perspective (again, providing the system was well-designed and managed). This would also prevent potentially costly and challenging peak electrical loads occurring in the morning due to the high demand for showering.

7.3.3.3 Overheating

As discussed in Section 2.5.4.5, the design factors that are likely to be causing overheating in PBSA have been covered previously. This section will build on the evidence from the previous PBSA monitoring studies e.g. (Altan et al., 2013; Quigley, 2016; Innovate UK, 2013) to provide some PBSA focused overheating design guidance.

However, before providing the guidance, it is important to comment on the role of dynamic thermal simulation to assess overheating risk. It has has been shown in previous studies that buildings that pass overheating risk assessments can still overheat e.g. (Symonds et al., 2017). Indeed, the overheating study for CSB was reviewed as part of this research, which suggested no risk of overheating. The reasons that modelling overheating is particularly challenging are covered in Section 2.2.2.5.

There are on-going measures to improve the accuracy and reliability of overheating modelling e.g. TM59 (CIBSE, 2017a). These measures should help reduce the gap between modelled and real performance. However, as well as improving modelling processes, it is recommended that designers should also be guided by feedback from their existing buildings. For instance, if the design is very similar to an existing building that has been shown to overheat, then alterations should be considered. Arguably, these should occur regardless of whether or not it has passed an overheating modelling assessment.

Ventilation

One of the key complaints from occupants was that there was not enough air movement in their rooms to remove unwanted heat, or provide a cooling draught (see Section 5.3.2.2). It was also shown that the participants in certain rooms, which allowed either for cross-ventilation or enhanced mechanical ventilation, could remove heat more effectively, particularly once the external temperature dropped (see Section 5.4.4). Furthermore, the limited effect window opening had in single-aspect rooms was shown in Figure 5.33.

These findings suggest a number of recommendations for PBSA are required to enhance ventilation, and therefore help alleviate overheating. Firstly, alternatives to the top-hung restricted windows should be considered. These windows must increase the opening area, while still adhering to the health and safety requirements. An example of a window type that could meet both these requirements is provided in Figure 6.1. These windows types may also help promote the opening of windows at night, where insects, noise and security were raised as concerns (see Section 4.3.2.2).

Secondly, the layout of PBSA should allow for cross-ventilation wherever possible. Design alterations could be made to increase the number of corner bedrooms (e.g. B2), or to allow ventilation through the corridors (e.g. A10). The sizing of ventilation units should be increased to allow for higher ventilation rates (e.g. 2ACH). This would be particularly useful for night-time purging (see an example of this occurring in Figure 5.30). It should also be considered whether it is feasible, whilst meeting fire regulations, to allow bedroom doors to be propped open i.e. the internal doors within apartments are not also fire doors.

In addition, the results suggest that some form of ventilation should be considered in all circulation areas in the building e.g. corridors and stairways (see Section 5.2.3.6 for examples of these areas overheating). Alongside improved management of internal gains, allowing for ventilation in these areas could help prevent the build up of heat in circulation spaces, which in turn is likely to affect habitable areas.

Solar Gains

The solar gains recommendations for PBSA study bedrooms are relatively generic. Nevertheless, it seems worth repeating them as this author has seen very few UK PBSA with external shading, and external shading has been shown in modelling to be effective at reducing overheating risk (Porritt et al., 2012). Therefore it is recommended that external shading (e.g. brise-soleils) should be sufficiently considered at the design stage, including whether internal blinds alone are an adequate shading method, or whether they should be used to supplement external shading.

More specifically to PBSA, designers should consider alternatives to large fully-glazed circulation areas (e.g. stairways). In the case of CSA these were shown to cause extreme overheating (see Section 5.2.3.6). If glazed areas area required, then an effective means of ventilating these spaces should be included.

Internal Gains

The overheating bathrooms in the CSB townhouses, and the overheating corridors in both case studies (see Section 5.2.3.6) suggest that unwanted internal gains were an issue. Again, most of the measures suggested below are relatively common place, but they seem worth reiterating due to the issues found in these case studies.

Firstly, heating services, particularly thermal stores, should be carefully located so that gains are not distributed into occupied spaces within buildings. These areas should also be provided with ventilation to remove heat e.g. external louvres. Secondly, all pipework and heating services should be thoroughly insulated. Finally, the electrification of heating in these buildings (see Section 7.3.3.2 above) would also be likely to reduce the impact of unwanted heat gains.

7.3.3.4 Ventilation

The results suggested that where no form of mechanical ventilation was provided the CO_2 concentrations in bedrooms consistently reached unacceptably high levels (see Section 4.2.2.1). Therefore it is recommended that mechanical ventilation should be installed as standard in PBSA study bedrooms.

It is also recommended that designers and researchers should consider noise performance when selecting trickle ventilators for windows. The findings from the interviews suggested this was an important issue for the participants that prevented them from using them as anticipated (see Section 4.2.3.3). This is also likely to be an area that requires further investigation (see Section 7.4 below).

7.3.4 Facilities Management

The FM team have an important role in PBSA performance in terms of both how to operate and control the central services, and also in providing information, guidance and support to the residents. The findings have suggested a number of recommendations for PBSA FM teams.

Firstly, make sure all occupants are aware of the heater timing schedules (see Section 4.3.3.3 for why this is needed). Then remind them of this at multiple occasions throughout the year. Similarly, provide guidance on how their TRV works, and estimates on the temperatures that particular settings would provide (e.g. setting 3 is approximately 21°C).

Secondly, remind students at the beginning of winter about not leaving their windows open, and the impact this will have on energy usage, carbon emissions, and ultimately global warming. See Section 4.3.1.3 for estimates of the amount of time the windows were open and the heating was on in the participant's bedrooms. Also, occupants should be reminded to switch off all heaters before they leave for long breaks (e.g. Christmas holidays). There was evidence of occupants leaving their windows open and heating during extended absences from the accommodation (see Figure 4.31).

Guidance should also be provided to occupants about the importance of opening trickle vents for IAQ. Finally, during hot weather periods, information should be circulated about the best mechanisms for keeping rooms cool, and similarly what behaviours to avoid.

7.3.5 Universities

Where universities are involved in providing accommodation they should specify that internal conditions remain within certain comfort ranges (e.g. temperature, RH and CO_2 concentrations). On-going monitoring should be used to assess whether accommodations are complying with the specifications.

Universities should also make sure that accommodation surveys only happen after residents have experienced warm weather conditions in their accommodation (see Section 6.1.1 for why this is necessary). This will help to give the universities a more accurate picture of how their accommodation is performing all year round, and any design changes that may be required.

7.3.6 Research Communities

One of the key implications from this research is the value of conducting research alongside a partner organisation from industry. This gave the researcher the opportunity to feed back the findings directly and promptly to those responsible for making future design decisions. This gave the research real-world impact that may not have been achieved without this collaboration i.e. if the findings have been disseminated entirely through typical academic channels.

This relationship also allowed the researcher to better understand the rationale for particular design decisions, and the processes through which decisions are made. This provided greater appreciation for the commercial and regulatory environment within which companies are operating. Hence the presentation of the results could be focused on areas that were likely to resonate with practitioners, and to offer practical solutions that were expected to be feasible. For instance, stressing the risks to developers of discomfort in PBSA in terms of the potential impact on future rental income, and suggesting relatively low-cost measures that could make a real difference to occupants (i.e. the provision of fans in warm weather).

Another area that this research could have implications for other researchers is the collection and analysing of data from a combination of sources to uncover insights on building performance. This multi-parameter analysis, alongside graphical presentation of the results, allows the researcher to investigate (and present to the reader) a number of complex, inter-connected relationships.

For instance, it allows insight into what occurred (e.g. the window was opened every morning, and left open for extended periods (window monitoring)), why it occurred (e.g. the conditions were extremely stuffy in the morning (CO_2 monitoring)), the impact this had on internal conditions (e.g. the internal temperature dropping), and the effect on energy consumption (e.g. the radiator providing more heat in an attempt to maintain the internal temperature (radiator surface temperature monitoring)). Without monitoring all of these parameters critical aspects of how IEQ affects occupant behaviour, which in turn affects IEQ and energy consumption may be missed.

Finally, qualitative data gathered via interviews with the occupants can be compared against the findings from the multi-parameter analysis. This can help to confirm or deny what the data shows. It also provides a more vivid insight into how those conditions made that particular occupant feel. Thus the qualitative feedback helps bring the analysis to life; this proved to be particularly impactful when presenting the feedback to the partner organisation.

7.4 Future Work

This section outlines potential future work that could be undertaken in this research area. It has been split into two parts. The first part addresses specific topics researched in this thesis that would benefit from further investigation. The second part considers how interventions could be used in future POE studies.

7.4.1 Further Investigation of Specific Issues

There have been a number of issues raised about the performance of PBSA in these two case studies. Future work could be used to investigate these issues further, and also to assess how prevalent these are in the wider PBSA stock.

Both these case studies, as well as numerous other monitoring studies have found overheating to be a serious issue. It would be valuable to understand just how prevalent overheating is in the wider PBSA stock, and therefore how many students are likely affected by overheating during warm weather. This could be done by a significantly wider survey of a sample of PBSA buildings or FM teams. If the sample was large enough, it could even investigate whether the PBSA that reported overheating problems shared particular design characteristics.

Another method that could have been used to gain further insights on overheating in PBSA would be to construct a simple model of heat gains and losses in the study bedrooms during warm weather periods. This would be similar to the model constructed for winter window opening (see Section 3.5.8). It could make use of the empirical data collected during the monitoring to explore the adaptations that may have reduced the prevalence of overheating.

For example, it could be used to consider how a reduction in solar gains of a certain amount may have affected overheating, or if the ventilation rate could have been doubled overnight what affect would this have on the internal conditions. This research could then be used to inform what possible passive measures could be undertaken in the PBSA stock to reduce the incidences of overheating (see Section 7.4.2 below).

Another finding from this study was that overheating occurred in winter too. This was particularly the case in CSA (see Section 4.2.1). It was also found that in CSA the radiators continued to provide heat even when the room air temperature was significantly above the TRV control temperature; the TRVs were supposed to be preset and locked at approximately 20-23°C (see Section 3.3.1.3 for further information). Hence the TRV controls failed in this building. This caused both occupant discomfort and wasted energy.

However, during this research the causes of the TRV failures (or possible wider heating control issues) were never clearly identified. The issue was raised with the FM at CSA during an interview but no explanation was provided. One further investigative method could have been to contact the TRV manufacturer and ask about the possible causes, or alternatively ask a plumber for assistance in exploring the issue. One final step could have been to replace the TRV in one of the radiators and then monitor the radiator performance and the impact upon internal conditions (see Section 7.4.2 below).

This research also found serious IAQ issues in those rooms that were not mechanically ventilated. However, as noted previously (see Section 2.5.4), no other study including CO_2 monitoring was found for this building type in the UK. As such, it seems important to investigate how prevalent IAQ issues are in the wider stock. If some PBSA are less affected, it would be beneficial to understand the design differences that may have helped reduce the issue.

One of the surprising findings from this research was the whistling trickle vents reported by the occupants in the CSB townhouses. This was a serious issue for the occupants, which often prevented them from using their trickle vents as the designer's anticipated. No published research was found describing the issue, or identifying the potential causes. As trickle vents are often an integral part of the ventilation strategy in new build dwellings this is an important issue that warrants further investigation.

The first step in this investigative process could be to collect evidence of this issue by asking the occupants to record the noise when it occurs, or by setting up recording devices in unoccupied rooms. This evidence could then be shown to a range of stakeholders including the window manufacturer, the main contractor (or the sub-contractor who installed them), and the FM team. The aim being to discover whether it is a design fault or an installation issue, and therefore to be able to provide recommendations to rectify the problem in future buildings. It would also be good to better understand how widespread the problem is, and thus how many people may not be using their trickle vents as intended.

This research has suggested that window opening during the heating season may be responsible for significant heat losses. However, this was not directly measured in this thesis, and instead was estimated using a simplified model. One method for investigating this further would be to meter heating consumption in rooms directly, alongside monitoring window opening. This would allow heating consumption to be correlated against window opening, and also to visualise the actual effect on heating consumption as the window opens. Another method could be to use more sophisticated models (e.g. DSMs) to replicate the monitored conditions observed in this thesis, and compare it against standard modelling assumptions for PBSA.

7.4.2 Intervention based POE

This research has identified a number of design issues in each case study building. The next step would be to undertake interventions and then monitor the effect that these have had. This could be done via both environmental monitoring and occupant feedback. This could be used to provide an empirical evidence base regarding potential passive design measures and their impact on IEQ and occupant comfort. This would provide a further useful resource for practitioners, alongside relying on DSMs, which as covered in Section 2.2.2.5 are not necessarily accurate for modelling overheating.

Some potential adaptive measures could be to trial a number of the design recommendations made in this thesis (see Section 7.3.3 above). Realistically, the lower the cost and the less works required, the greater the chance of the intervention being approved. Therefore one particularly attractive design area could be to investigate improved solar shading, for example via either brise soleils or external shutters. In this case two very similar rooms (one with and one without the intervention) could be monitored alongside one another to investigate the effectiveness of the intervention.

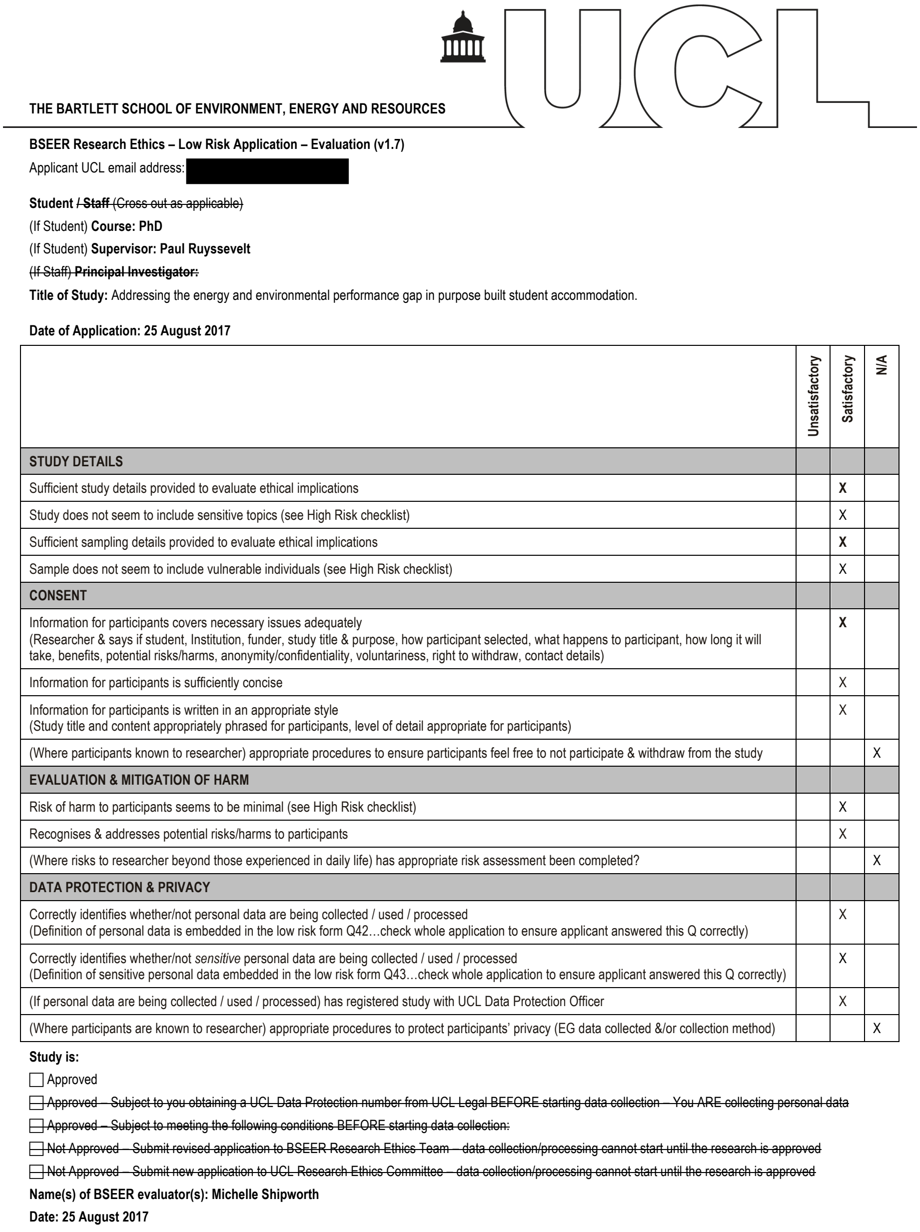
Appendix A

Ethics & Data Protection

A.1 Data Protection

“I am pleased to confirm that this project is covered by the UCL Data Protection Registration, reference No Z6364106/2017/09/02 social research.”

A.2 Ethics Approval



THE BARTLETT SCHOOL OF ENVIRONMENT, ENERGY AND RESOURCES

BSEER Research Ethics – Low Risk Application – Evaluation (v1.7)

Applicant UCL email address: [redacted]

Student ~~/ Staff~~ ~~(Cross out as applicable)~~
(If Student) **Course: PhD**
(If Student) **Supervisor: Paul Ruyssevelt**
~~(If Staff) **Principal Investigator:**~~
Title of Study: Addressing the energy and environmental performance gap in purpose built student accommodation.

Date of Application: 25 August 2017

	Unsatisfactory	Satisfactory	N/A
STUDY DETAILS			
Sufficient study details provided to evaluate ethical implications		X	
Study does not seem to include sensitive topics (see High Risk checklist)		X	
Sufficient sampling details provided to evaluate ethical implications		X	
Sample does not seem to include vulnerable individuals (see High Risk checklist)		X	
CONSENT			
Information for participants covers necessary issues adequately (Researcher & says if student, Institution, funder, study title & purpose, how participant selected, what happens to participant, how long it will take, benefits, potential risks/harms, anonymity/confidentiality, voluntariness, right to withdraw, contact details)		X	
Information for participants is sufficiently concise		X	
Information for participants is written in an appropriate style (Study title and content appropriately phrased for participants, level of detail appropriate for participants)		X	
(Where participants known to researcher) appropriate procedures to ensure participants feel free to not participate & withdraw from the study			X
EVALUATION & MITIGATION OF HARM			
Risk of harm to participants seems to be minimal (see High Risk checklist)		X	
Recognises & addresses potential risks/harms to participants		X	
(Where risks to researcher beyond those experienced in daily life) has appropriate risk assessment been completed?			X
DATA PROTECTION & PRIVACY			
Correctly identifies whether/not personal data are being collected / used / processed (Definition of personal data is embedded in the low risk form Q42…check whole application to ensure applicant answered this Q correctly)		X	
Correctly identifies whether/not *sensitive* personal data are being collected / used / processed (Definition of sensitive personal data embedded in the low risk form Q43…check whole application to ensure applicant answered this Q correctly)		X	
(If personal data are being collected / used / processed) has registered study with UCL Data Protection Officer		X	
(Where participants are known to researcher) appropriate procedures to protect participants' privacy (EG data collected &/or collection method)			X

Study is:
☐ Approved
☐ ~~Approved – Subject to you obtaining a UCL Data Protection number from UCL Legal BEFORE starting data collection – You ARE collecting personal data~~
☐ ~~Approved – Subject to meeting the following conditions BEFORE starting data collection:~~
☐ ~~Not Approved – Submit revised application to BSEER Research Ethics Team – data collection/processing cannot start until the research is approved~~
☐ ~~Not Approved – Submit new application to UCL Research Ethics Committee – data collection/processing cannot start until the research is approved~~
Name(s) of BSEER evaluator(s): Michelle Shipworth
Date: 25 August 2017

Appendix B

Participant Recruitment

B.1 Example Recruitment Email

Subject: Earn £20 for taking part in research study about your halls

Dear XX resident,

We're looking to recruit 10 participants for a study to investigate two things:

- How students heat and cool their study bedrooms
- And whether the rooms are comfortable

What does the study entail?

- Having small environmental sensors placed in your room – this will take a maximum of 30 minutes
- Two 15-minute phone interviews (one in winter, and one in summer) to share your opinions on your room and how you use it

That's it.

In return you will be given **£20 in amazon vouchers**.

You will also help us better understand how to build comfortable low-energy student accommodation in the future.

For more details on the study please see the attachments below.

If you wish to participate or for any further information please reply to
[redacted]

Thank you for your interest,
Anthony Marsh

B.2 Participant Information Sheet

[redacted] Monitoring Participant Information Form

You are being invited to take part in a research study. Before you decide whether or not to take part, it is important for you to understand why the research is being done and what it will involve. Please take time to read the following information carefully.

What is the purpose of the study?

The study will examine the amount of energy used in new student accommodation, and whether the buildings are comfortable.

Why have I been invited to participate?

Because you are a resident at the [redacted]

Do I have to take part?

No, it's up to you to decide whether or not to take part. If you 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 without giving a reason.

What will happen to me if I take part?

Monitoring of environmental conditions in your bedroom

Three small sensors will be put in your bedroom to monitor the environmental conditions (see sensor information sheet for more details). This will take no longer than 30 minutes. After the sensors are installed you will be able to use your room exactly the same as before.

Interviews

You will also be asked to complete two 15-minute interviews (one in winter, and one in summer). The interviews will ask your opinions on the comfort of the residences, and about how you control the internal conditions (e.g. temperature, fresh air levels) in your room.

What are the benefits of taking part?

By taking part in this study you will contribute towards understanding how we can reduce energy usage in student accommodation without compromising health and comfort. As compensation for your participation all participants will receive **£20 worth of online shopping vouchers**.

What are the possible disadvantages and risks of taking part?

The only disadvantage to you will be the time taken to install the sensors and for completing the interviews. There are no risks associated with participation.

Will what I say be kept confidential?

Yes, no one will be identified in any way (for further details see confidentiality statement)

What will happen to the results of the research study?

The results will be written up as part of Anthony Marsh's PhD thesis. They will also be reported back to the key stakeholders involved in the building of the residences. Particular aspects may also be published in academic journals. You are welcome to a copy of any reports, publications or presentations from the study – please contact Anthony Marsh (details above).

Who is organizing and funding the research?

Anthony Marsh is organizing the research as a PhD student at UCL. The research is funded by the Engineering and Physical Sciences Research Council (https://www.epsrc.ac.uk/).

B.3 Sensor Information Sheet

[redacted] Monitoring
Sensor Information Sheet

The iBEM B3 is an indoor environmental quality sensor. It needs to be plugged in and connected to the WiFi network. It will be used to monitor the following…

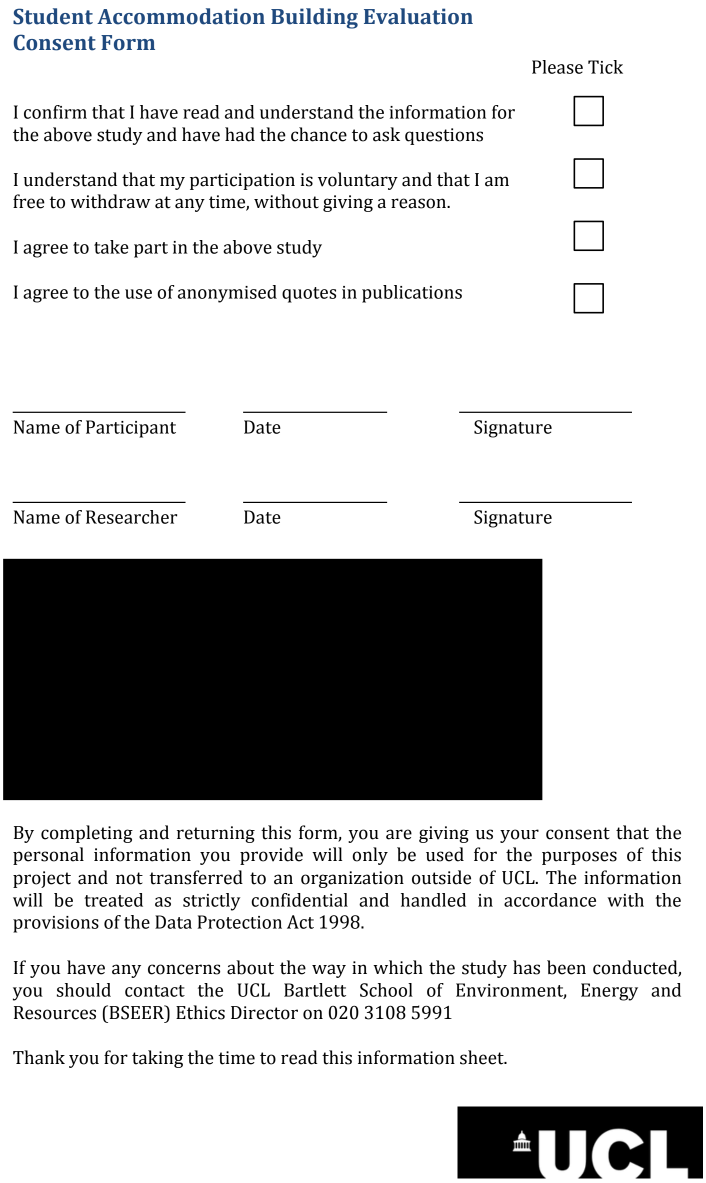
- Temperature
- Relative Humidity
- Carbon Dioxide
- Light levels
- $PM_{2.5}$

The EL-USB-5 data logger will monitor when you open and close your window. It stores the data internally and does not need to be connected to power or the WiFi network.

The HOBO temperature sensor will be used to monitor when your radiator is on or off. It stores the data internally and does not need to be connected to power or the WiFi network

If you require any further information about any of the sensors please contact [redacted]

B.4 Consent Form



Student Accommodation Building Evaluation
Consent Form

	Please Tick
I confirm that I have read and understand the information for the above study and have had the chance to ask questions	☐
I understand that my participation is voluntary and that I am free to withdraw at any time, without giving a reason.	☐
I agree to take part in the above study	☐
I agree to the use of anonymised quotes in publications	☐

Name of Participant ________ Date ________ Signature ________

Name of Researcher ________ Date ________ Signature ________

[redacted]

By completing and returning this form, you are giving us your consent that the personal information you provide will only be used for the purposes of this project and not transferred to an organization outside of UCL. The information will be treated as strictly confidential and handled in accordance with the provisions of the Data Protection Act 1998.

If you have any concerns about the way in which the study has been conducted, you should contact the UCL Bartlett School of Environment, Energy and Resources (BSEER) Ethics Director on 020 3108 5991

Thank you for taking the time to read this information sheet.

Appendix C

Monitoring Information

C.1 CSA Monitoring Periods

ROOMS	Start	End	Duration (Days)
A1	30/10/2017	26/07/2018	269
A2	30/10/2017	24/08/2018	298
A3	30/10/2017	06/07/2018	249
A4	30/10/2017	24/08/2018	298
A5	31/10/2017	02/07/2018	244
A6	31/10/2017	24/08/2018	298
A7	01/11/2017	24/08/2018	298
A8	30/10/2017	24/08/2018	298
A9	30/10/2017	22/08/2018	296
A10	02/11/2017	23/08/2018	297
A11	30/10/2017	23/08/2018	297

Table C.1: The duration of monitoring in each room in CSA

C.2 CSB Monitoring Periods

ROOMS	Start	End	Duration (Days)
B1	21/11/2017	19/06/2018	211
B2	21/11/2017	19/06/2018	211
B3	21/11/2017	19/06/2018	211
B4	21/11/2017	19/06/2018	211
B5	21/11/2017	22/05/2018	183
B6	22/11/2017	29/05/2018	190
B7	22/11/2017	29/05/2018	190
B8	22/11/2017	29/05/2018	190
B9	22/11/2017	19/06/2018	211

Table C.2: The duration of monitoring in each room in CSB

C.3 CSA Sensors

PBSA	FLOOR	ORIENTATION	ROOM CODE 2	AREA	TYPE
CSA	5	E	CSA1	CENTRE	HOBO
CSA	5	E	CSA1	CORIDOR	HOBO
CSA	5	E	CSA1	DESK	HOBO
CSA	5	E	CSA1	BED	iBEM
CSA	5	E	CSA1	RAD	HOBO
CSA	5	E	CSA1	WINDOW	ELTEKTEK
CSA	5	E	CSA2	CENTRE	HOBO
CSA	5	E	CSA2	CORIDOR	HOBO
CSA	5	E	CSA2	DESK	HOBO
CSA	5	E	CSA2	BED	HOBO
CSA	5	E	CSA2	CENTRE	iBEM
CSA	5	E	CSA2	RAD	HOBO
CSA	5	E	CSA2	WINDOW	ELTEK
CSA	1	NWW	CSA3	CENTRE	HOBO
CSA	1	NWW	CSA3	CORIDOR	HOBO
CSA	1	NWW	CSA3	DESK	HOBO
CSA	1	NWW	CSA3	BED	HOBO
CSA	1	NWW	CSA3	CENTRE	iBEM
CSA	1	NWW	CSA3	RAD	HOBO
CSA	1	NWW	CSA3	WINDOW_L	ELTEK
CSA	1	NWW	CSA3	WINDOW_R	ELTEK
CSA	1	NWW	CSA4	CENTRE	HOBO
CSA	1	NWW	CSA4	CORIDOR	HOBO
CSA	1	NWW	CSA4	DESK	HOBO
CSA	1	NWW	CSA4	BED	HOBO
CSA	1	NWW	CSA4	CENTRE	iBEM
CSA	1	NWW	CSA4	RAD	HOBO
CSA	1	NWW	CSA4	WINDOW_L	ELTEK
CSA	1	NWW	CSA4	WINDOW_R	ELTEK
CSA	2	SEE	CSA5	CENTRE	HOBO
CSA	2	SEE	CSA5	CORIDOR	HOBO
CSA	2	SEE	CSA5	DESK	HOBO
CSA	2	SEE	CSA5	BED	HOBO
CSA	2	SEE	CSA5	CENTRE	iBEM
CSA	2	SEE	CSA5	RAD	HOBO
CSA	2	SEE	CSA5	WINDOW_L	ELTEK
CSA	2	SEE	CSA5	WINDOW_R	ELTEK
CSA	G	NWW	CSA6	CENTRE	HOBO
CSA	G	NWW	CSA6	CORIDOR	HOBO
CSA	G	NWW	CSA6	DESK	HOBO
CSA	G	NWW	CSA6	BED	HOBO
CSA	G	NWW	CSA6	CENTRE	iBEM
CSA	G	NWW	CSA6	RAD	HOBO
CSA	G	NWW	CSA6	WINDOW_L	ELTEK
CSA	G	NWW	CSA6	WINDOW_R	ELTEK
CSA	3	NWW	CSA7	CENTRE	HOBO
CSA	3	NWW	CSA7	DESK	HOBO
CSA	3	NWW	CSA7	BED	HOBO
CSA	3	NWW	CSA7	CENTRE	iBEM
CSA	3	NWW	CSA7	RAD	HOBO
CSA	3	NWW	CSA7	WINDOW	ELTEK
CSA	3	NWW	CSA8	CENTRE	HOBO
CSA	3	NWW	CSA8	CORIDOR	HOBO
CSA	3	NWW	CSA8	DESK	HOBO
CSA	3	NWW	CSA8	BED	HOBO
CSA	3	NWW	CSA8	CENTRE	iBEM
CSA	3	NWW	CSA8	RAD	HOBO
CSA	3	NWW	CSA8	WINDOW	ELTEK
CSA	6	NWW	CSA9	CENTRE	HOBO
CSA	6	NWW	CSA9	CORIDOR	HOBO
CSA	6	NWW	CSA9	DESK	HOBO
CSA	6	NWW	CSA9	BED	HOBO
CSA	6	NWW	CSA9	CENTRE	iBEM
CSA	6	NWW	CSA9	RAD	HOBO
CSA	6	NWW	CSA9	WINDOW	ELTEK
CSA	7	NNW	CSA10	CENTRE	HOBO
CSA	7	NNW	CSA10	CORIDOR	HOBO
CSA	7	NNW	CSA10	DESK	HOBO
CSA	7	NNW	CSA10	BED	HOBO
CSA	7	NNW	CSA10	CENTRE	iBEM
CSA	7	NNW	CSA10	RAD	HOBO
CSA	7	NNW	CSA10	WINDOW	ELTEK
CSA	G	W	CSA SA G	STAIR_A	HOBO
CSA	5	W	CSA SA 5	STAIR_A	HOBO
CSA	G	NWW & SW	CSA SB G	STAIR_B	HOBO
CSA	10	NWW & SW	CSA SB 10	STAIR_B	HOBO

Table C.3: Complete list of sensors in CSA

C.4 CSB Sensors

PBSA	FLOOR	ORIENTATION	ROOM CODE 2	AREA	TYPE
CSB	1	S & W	CSB1	BED	HOBO
CSB	1	S & W	CSB1	DESK	HOBO
CSB	1	S & W	CSB1	CENTRE	iBEM
CSB	1	S & W	CSB1	RAD	HOBO
CSB	1	S & W	CSB1	CORIDOR	HOBO
CSB	1	S & W	CSB1	WINDOW	ELTEK
CSB	1	S & W	CSB1	WINDOW	ELTEK
CSB	2	S & W	CSB2	BED	HOBO
CSB	2	S & W	CSB2	DESK	HOBO
CSB	2	S & W	CSB2	CENTRE	iBEM
CSB	2	S & W	CSB2	RAD	HOBO
CSB	2	S & W	CSB2	CORIDOR	HOBO
CSB	2	S & W	CSB2	WINDOW	ELTEK
CSB	2	S & W	CSB2	WINDOW	ELTEK
CSB	2	W	CSB3	BED	HOBO
CSB	2	W	CSB3	DESK	HOBO
CSB	2	W	CSB3	CENTRE	iBEM
CSB	2	W	CSB3	RAD	HOBO
CSB	2	W	CSB3	CORIDOR	HOBO
CSB	2	W	CSB3	WINDOW	ELTEK
CSB	3	E	CSB4	BED	HOBO
CSB	3	E	CSB4	DESK	HOBO
CSB	3	E	CSB4	CENTRE	iBEM
CSB	3	E	CSB4	RAD	HOBO
CSB	3	E	CSB4	CORIDOR	HOBO
CSB	3	E	CSB4	WINDOW	ELTEK
CSB	3	S & W	CSB5	BED	HOBO
CSB	3	S & W	CSB5	DESK	HOBO
CSB	3	S & W	CSB5	CENTRE	iBEM
CSB	3	S & W	CSB5	RAD	HOBO
CSB	3	S & W	CSB5	CORIDOR	HOBO
CSB	3	S & W	CSB5	WINDOW	ELTEK
CSB	3	S & W	CSB5	WINDOW	ELTEK
CSB	1	N/A	CSB1	BATHROOM	HOBO
CSB	2	N/A	CSB2	BATHROOM	HOBO
CSB	3	N/A	CSB3	BATHROOM	HOBO
CSB	1	S	CSB6	BED	HOBO
CSB	1	S	CSB6	DESK	HOBO
CSB	1	S	CSB6	CENTRE	iBEM
CSB	1	S	CSB6	RAD	HOBO
CSB	1	S	CSB6	CORIDOR	HOBO
CSB	1	S	CSB6	WINDOW	ELTEK
CSB	1	E	CSB7	BED	HOBO
CSB	1	E	CSB7	DESK	HOBO
CSB	1	E	CSB7	CENTRE	iBEM
CSB	1	E	CSB7	RAD	HOBO
CSB	1	E	CSB7	CORIDOR	HOBO
CSB	1	E	CSB7	WINDOW	ELTEK
CSB	2	W	CSB8	BED	HOBO
CSB	2	W	CSB8	DESK	HOBO
CSB	2	W	CSB8	CENTRE	iBEM
CSB	2	W	CSB8	RAD	HOBO
CSB	2	W	CSB8	CORIDOR	HOBO
CSB	2	W	CSB8	WINDOW	ELTEK
CSB	2	E	CSB9	BED	HOBO
CSB	2	E	CSB9	DESK	HOBO
CSB	2	E	CSB9	CENTRE	iBEM
CSB	2	E	CSB9	RAD	HOBO
CSB	2	E	CSB9	CORIDOR	HOBO
CSB	2	E	CSB9	WINDOW	ELTEK

Table C.4: Complete list of sensors in CSB

Appendix D

Interviews

D.1 CSA Interview Details

Room	Interview	Date	Time	Duration
A1	1	30/10/2017	15:20	07:01:00
A2		30/10/2017	18:13	04:07:00
A3		30/10/2017	11:22	04:32:00
A4		30/10/2017	14:17	05:25:00
A5		31/10/2017	10:19	05:27:00
A6		31/10/2017	12:16	04:35:00
A7		30/10/2017	17:51	07:31:00
A8		30/10/2017	10:24	08:47:00
A9		30/10/2017	18:36	07:36:00
A10		02/11/2017	19:40	13:29
A11		30/10/2017	15:20	07:01:00
A1	2	05/02/2018	19:05	15:02:00
A2		05/02/2017	21:27	12:49:00
A3		07/02/2018	18:32	13:36:00
A4		07/02/2018	21:28	16:24:00
A5		05/02/2018	20:37	08:11:00
A6		07/02/2018	20:55	12:16:00
A7		05/02/2018	18:26	17:54:00
A8		05/02/2018	20:18	15:40:00
A9		06/02/2018	19:43	17:29:00
A10		05/02/2018	22:07	18:36:00
A11		05/02/2018	19:05	15:02:00
A1	3	26/07/2018	11:22	15:13:00
A2		24/08/2018	15:16	09:38:00
A3		06/07/2018	13:15	15:53:00
A4		24/08/2018	13:50	28.1
A5		02/07/2018	11:21	13:43:00
A6		N/A	N/A	N/A
A7		24/08/2018	17:34	16:57:00
A8		24/08/2018	09:37	10:10:00
A9		22/08/2018	16:45	21:42:00
A10		23/08/2018	20:23	13:26:00
A11		26/07/2018	11:22	15:13:00

Table D.1: CSA Interview Details

D.2 CSB Interview Details

ROOMS	Interview	Date	Time	Duration
B1	1	21/11/2017	18:34	15:26
B2		21/11/2017	19:30	11:03
B3		21/11/2017	19:44	04:31
B4		21/11/2017	20:16	06:44
B5		21/11/2017	19:57	06:34
B6		22/11/2017	10:19	07:12
B7		22/11/2017	11:42	05:51
B8		22/11/2017	14:51	09:05
B9		22/11/2017	19:01	06:28
B1	2	21/02/2018	19:38	15:30
B2		21/02/2018	17:47	28.11
B3		21/02/2018	18:16	13:56
B4		21/02/2018	19:08	12:56
B5		21/02/2018	19:38	15:30
B6		13/02/2018	10:26	08:45
B7		13/02/2018	15:03	15:14
B8		13/02/2018	14:28	16:09
B9		21/02/2018	20:01	07:32
B1	3	18/06/2018	19:47	14:29
B2		19/06/2018	17:52	41.46
B3		19/06/2018	19:22	15:30
B4		22/05/2018	17:24	18:41
B5		N/A	N/A	N/A
B6		29/05/2018	16:30	14:43
B7		29/05/2018	12:03	16:03
B8		29/05/2018	13:20	12:23
B9		19/06/2018	18:52	19:23

Table D.2: CSB Interview Details

D.3 CSA Example Occupancy Diary

[redacted]

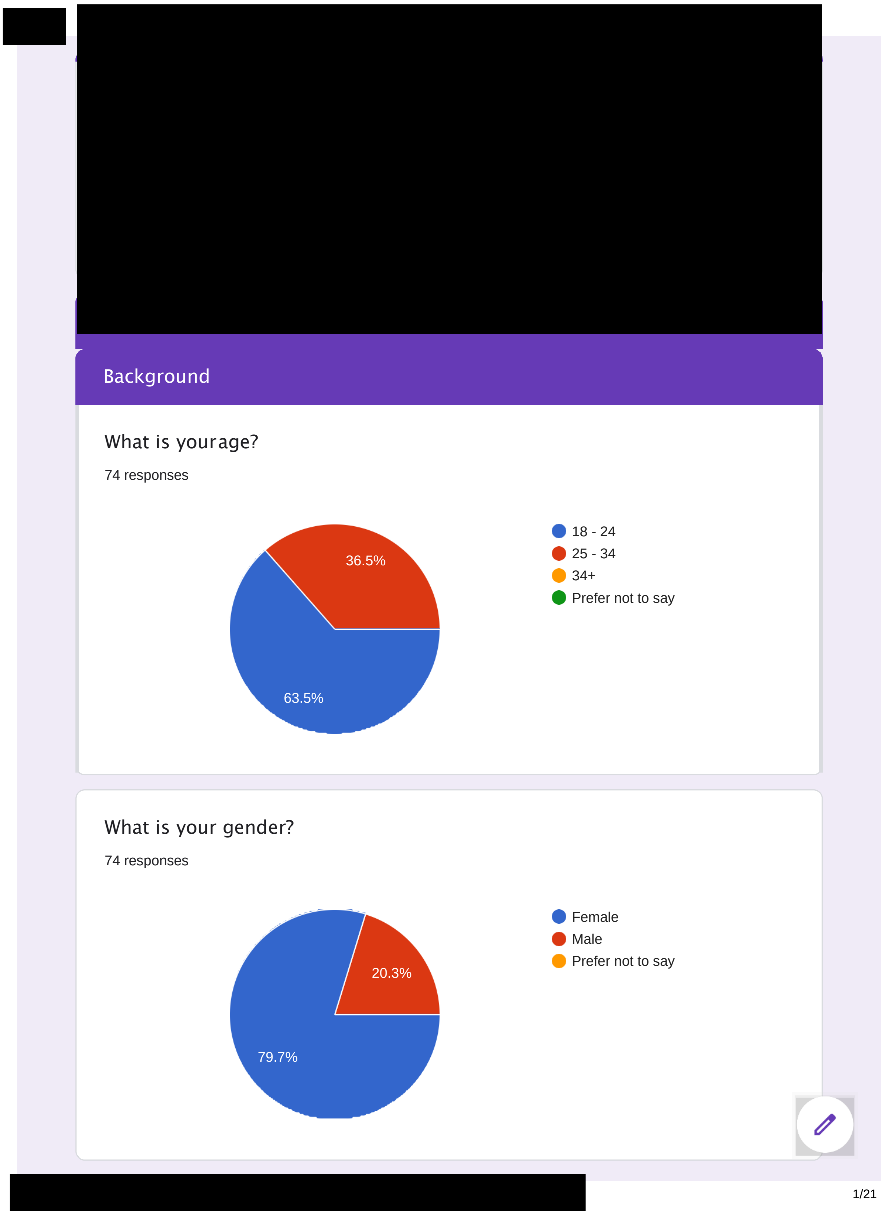
D.4 CSB Example Occupancy Diary

[redacted]

Appendix E

Survey Summary Statistics

E.1 CSA Survey Summary Statistics



[redacted]

[redacted]

Background

What is yourage?

74 responses

● 18 - 24
● 25 - 34
● 34+
● Prefer not to say

What is your gender?

74 responses

● Female
● Male
● Prefer not to say

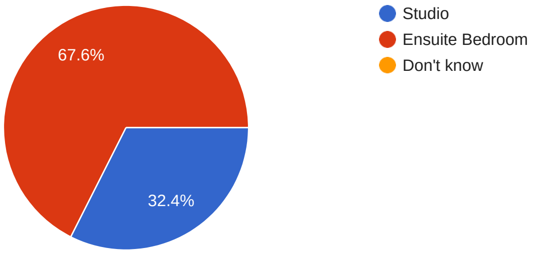
[redacted]

1/21

[redacted] [redacted]

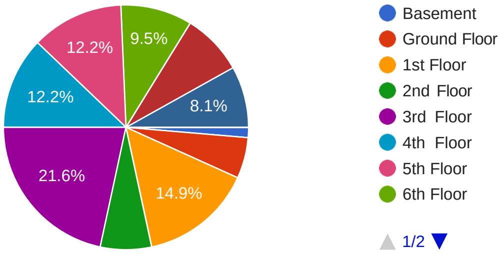
Which kind of room do you live in?

74 responses



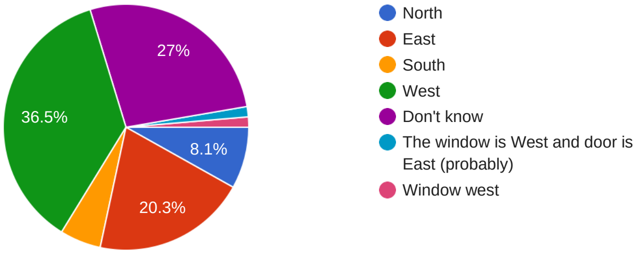
Which floor do you live on?

74 responses



What direction does your bedroom face?

74 responses

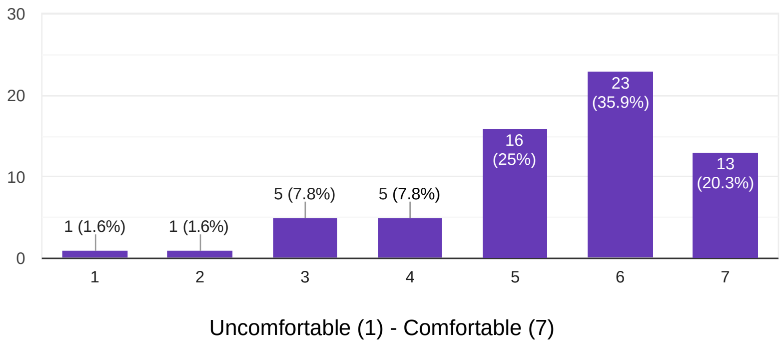


[redacted]

Winter Comfort

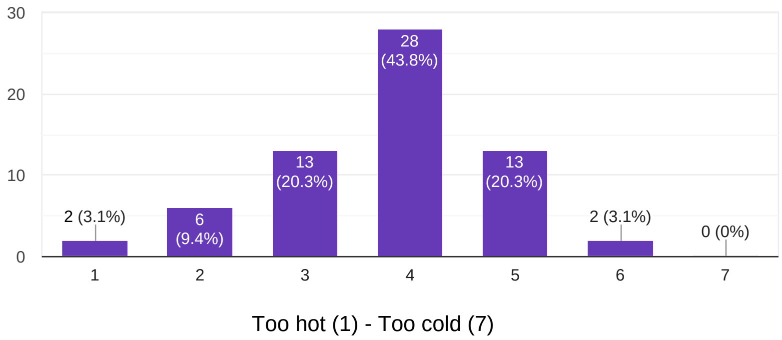
Indoor temperature in winter?

64 responses



Indoor temperature in winter?

64 responses

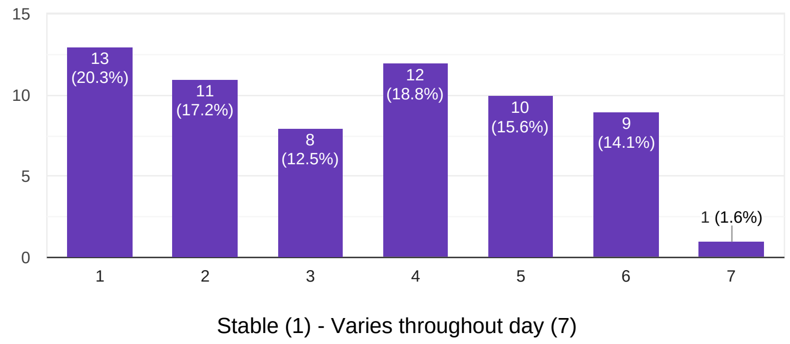


[redacted]

[redacted]

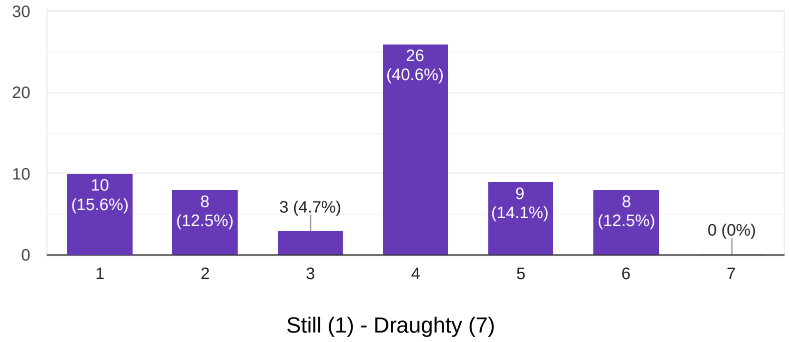
Indoor temperature in winter?

64 responses



Indoor air in winter?

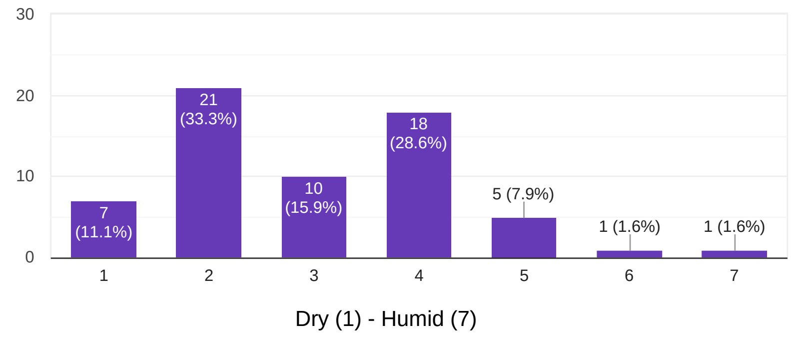
64 responses



[redacted]

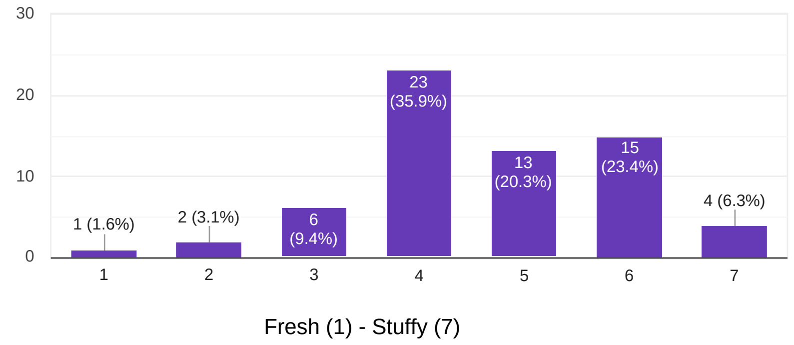
Indoor air in winter?

63 responses



Indoor air in winter?

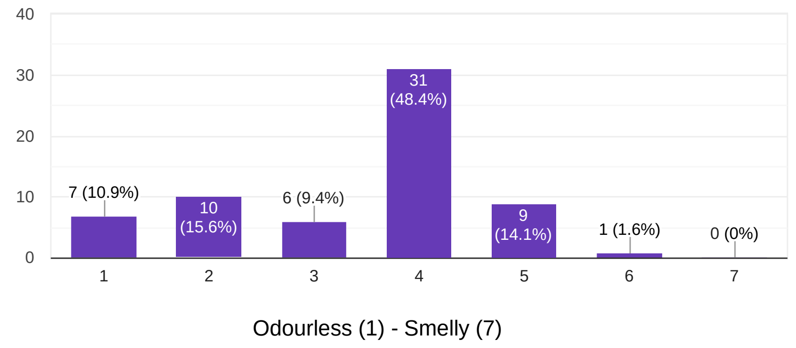
64 responses



[redacted] [redacted]

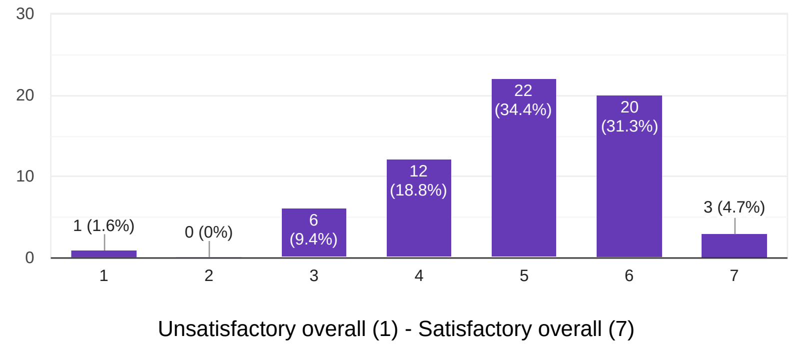
Indoor air in winter?

64 responses



Overall conditions in Winter

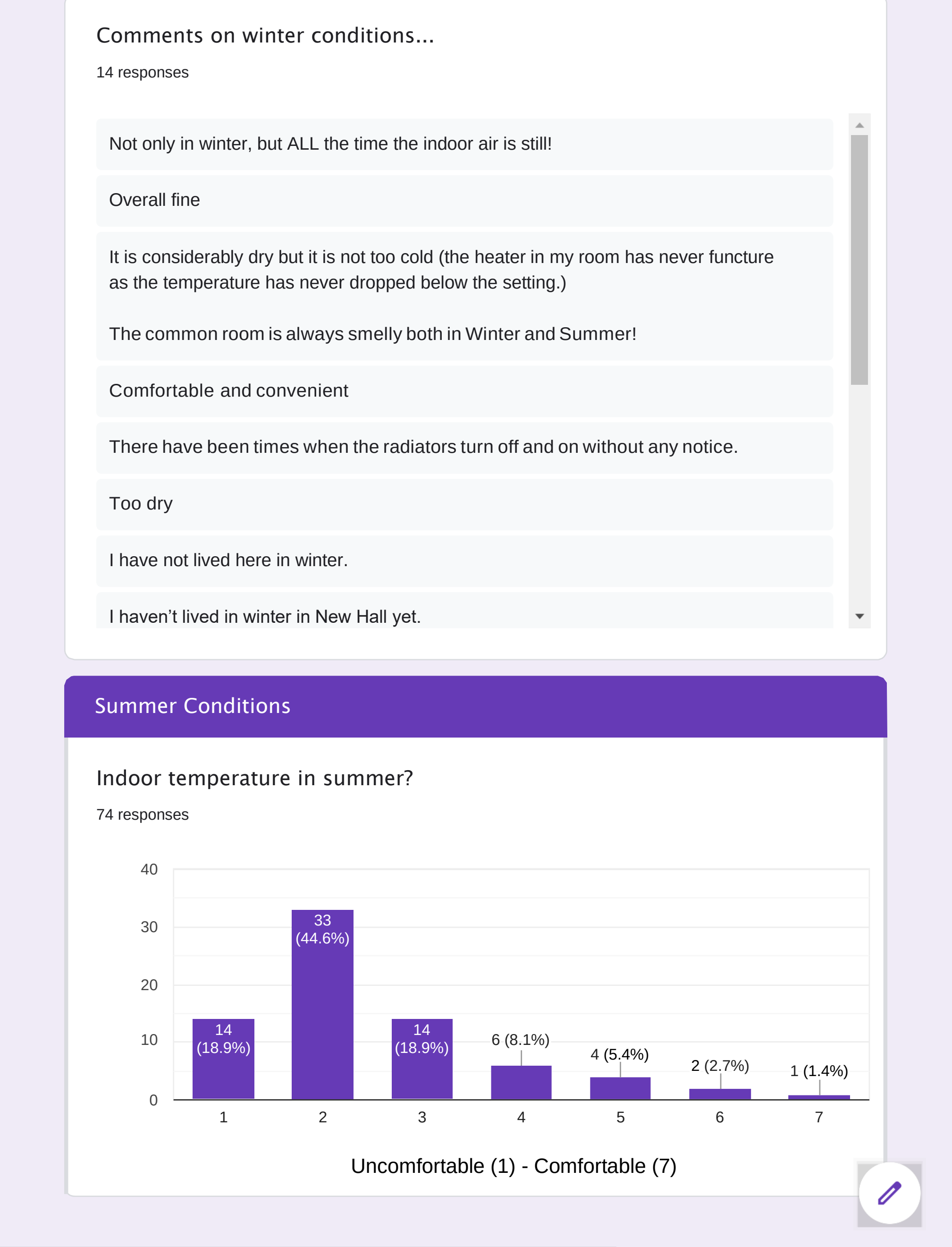
64 responses



[redacted]

[redacted]

[redacted]



Comments on winter conditions...

14 responses

Not only in winter, but ALL the time the indoor air is still!

Overall fine

It is considerably dry but it is not too cold (the heater in my room has never functure as the temperature has never dropped below the setting.)

The common room is always smelly both in Winter and Summer!

Comfortable and convenient

There have been times when the radiators turn off and on without any notice.

Too dry

I have not lived here in winter.

I haven’t lived in winter in New Hall yet.

Summer Conditions

Indoor temperature in summer?

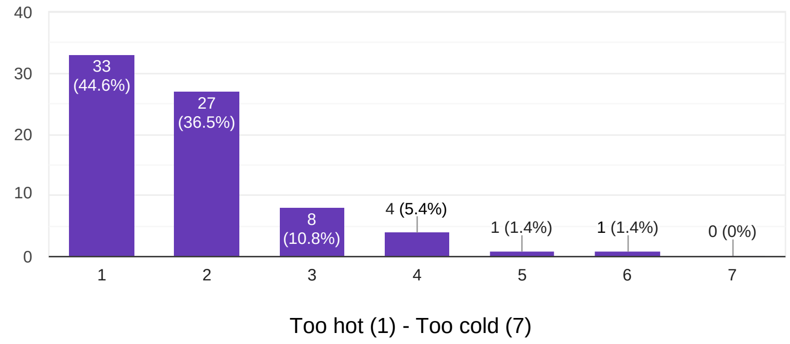
74 responses

[redacted]

[redacted] [redacted]

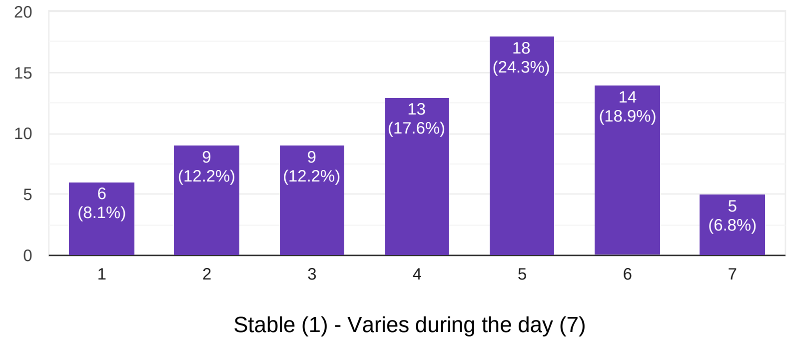
Indoor temperature in summer?

74 responses



Indoor temperature in summer?

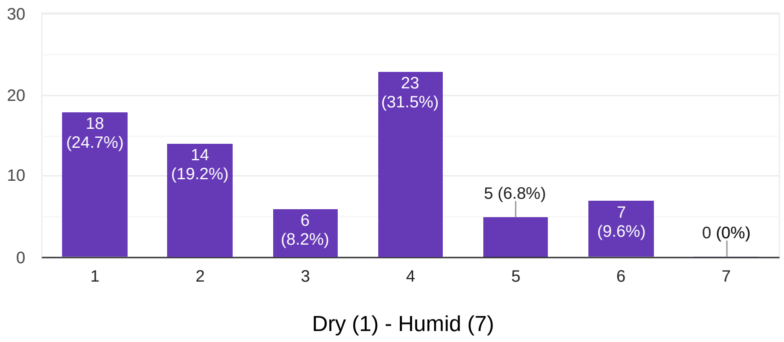
74 responses



[redacted]

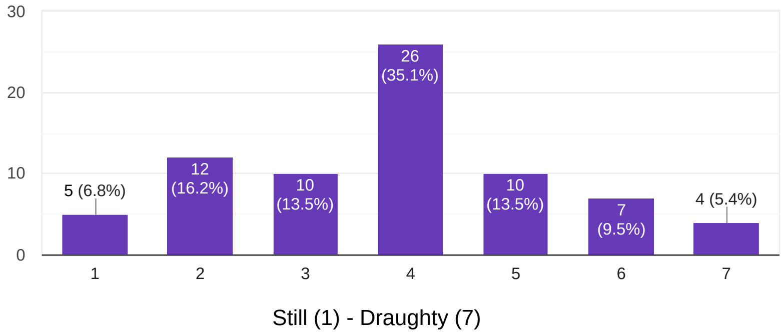
Indoor air in summer?

73 responses



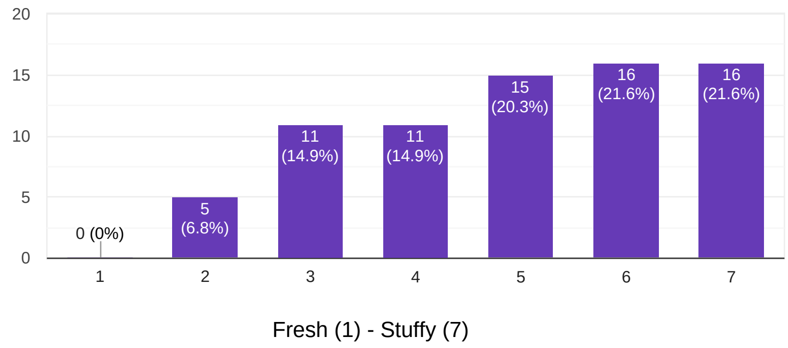
Indoor air in summer?

74 responses



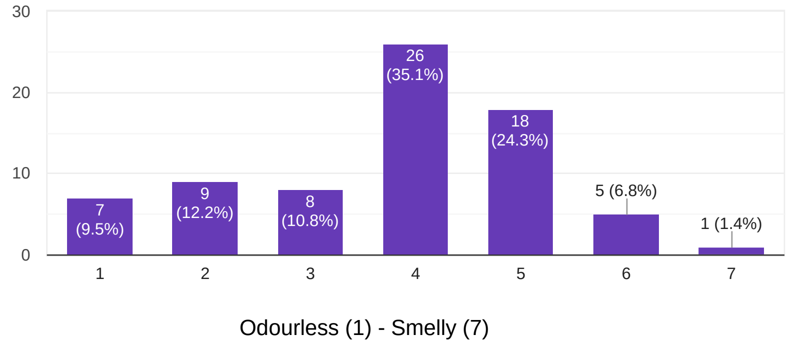
Indoor air in summer?

74 responses



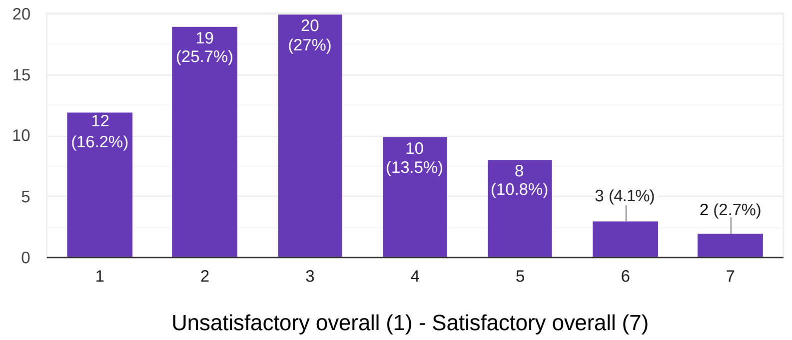
Indoor air in summer?

74 responses



Overall conditions in Summer

74 responses



Comments on summer conditions...

22 responses

can smell the food from indoor.

The upper floors become much too hot in the summer, and are at times uninhabitable.

It's too hot and stuffy to stay in the room in the afternoon.

unsatisfactorily hot in summer especially in July

The ventilazation in the corridors could be better

It is considerebly hot! Since the window can open only slightly, air in the room is pretty still (I have to buy my own fan in Summer). Only in rainy or windy days that I can be in my room!

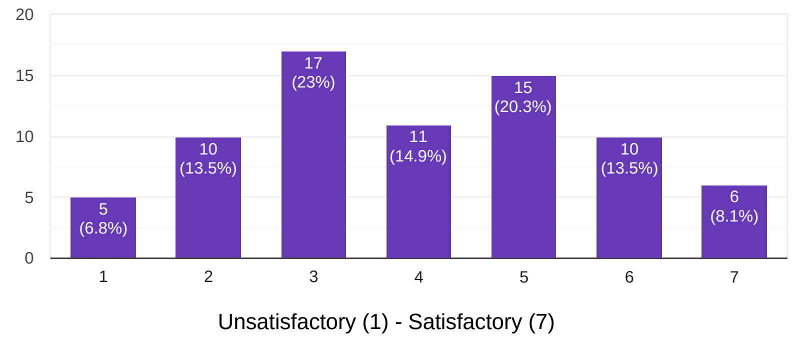
Air conditioning did not do anything to combat the heat, room temperature was regularly over 30°

During the hot days, the room was too hot and I had to go outside of my room

Noise

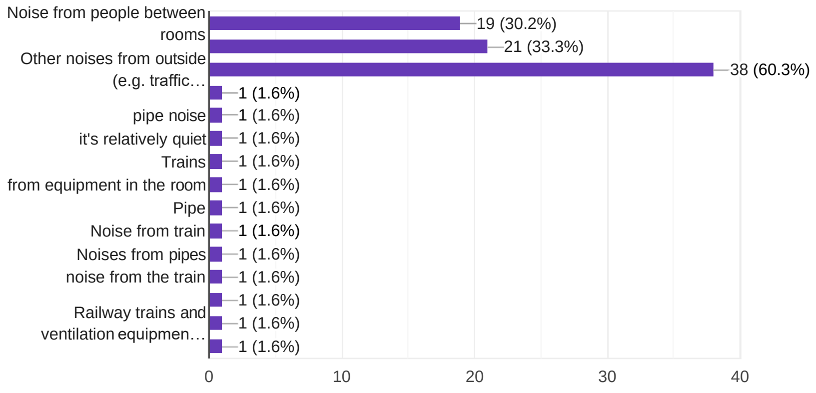
Noise levels overall

74 responses



If unsatisfactory, which sources of noise did you find particularly disruptive? (tick all that apply)

63 responses



Comments on noise and its sources...

21 responses

The rooms are not particularly sound proof, and as such one can hear their neighbour

Some railway workers always work with huge noise around 2 AM.

Loud noise from the street (motorcycles and emergency cars)

overground at night and the beep sound from the door of the common room

actually if you close the window, the noise cannot be heard, but the problem is if the window is closed, the air and temperature can be terrible.

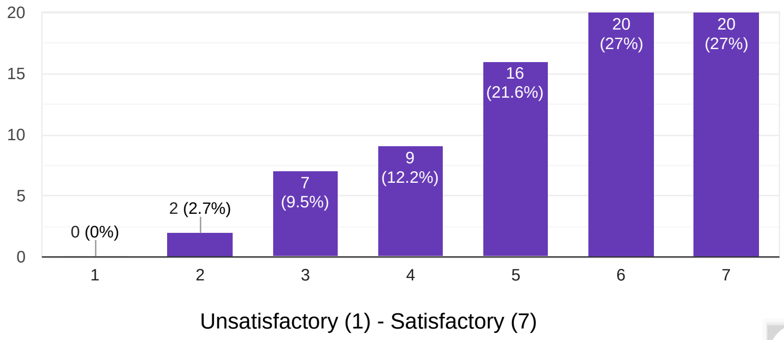
the train outside the window, but the most important is the pipe noise

Mostly, it is about noise from outside. My room is at the back near the railway so there are always noise from trains (almost throughout day and night and very frequent during day time). Apart from that is the noise from the construction and people outside. I am not sure where it come from but even lauging sound can be heard in the room (I always open the window unless it will be too hot inside). Noise from people

Lighting

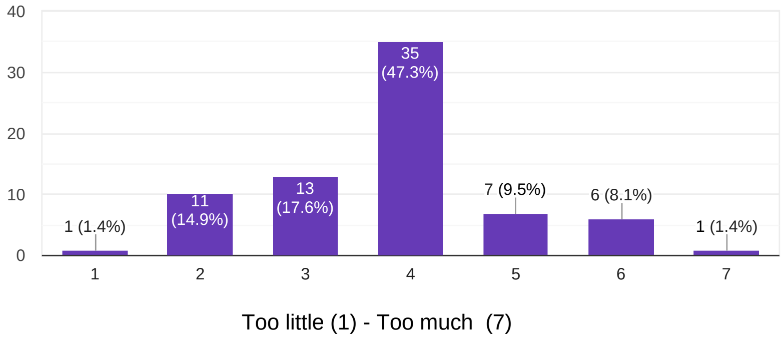
Lighting overall

74 responses



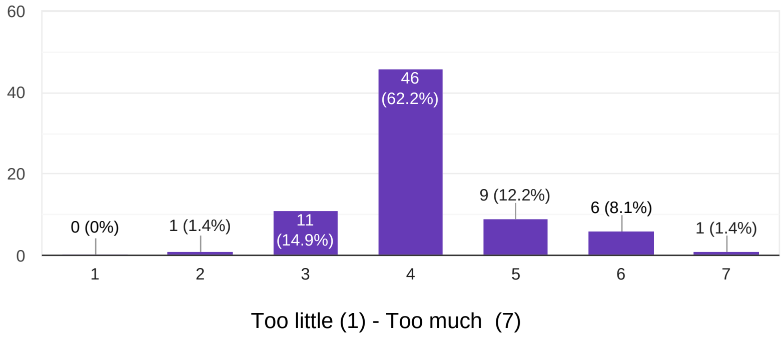
Natural Light

74 responses

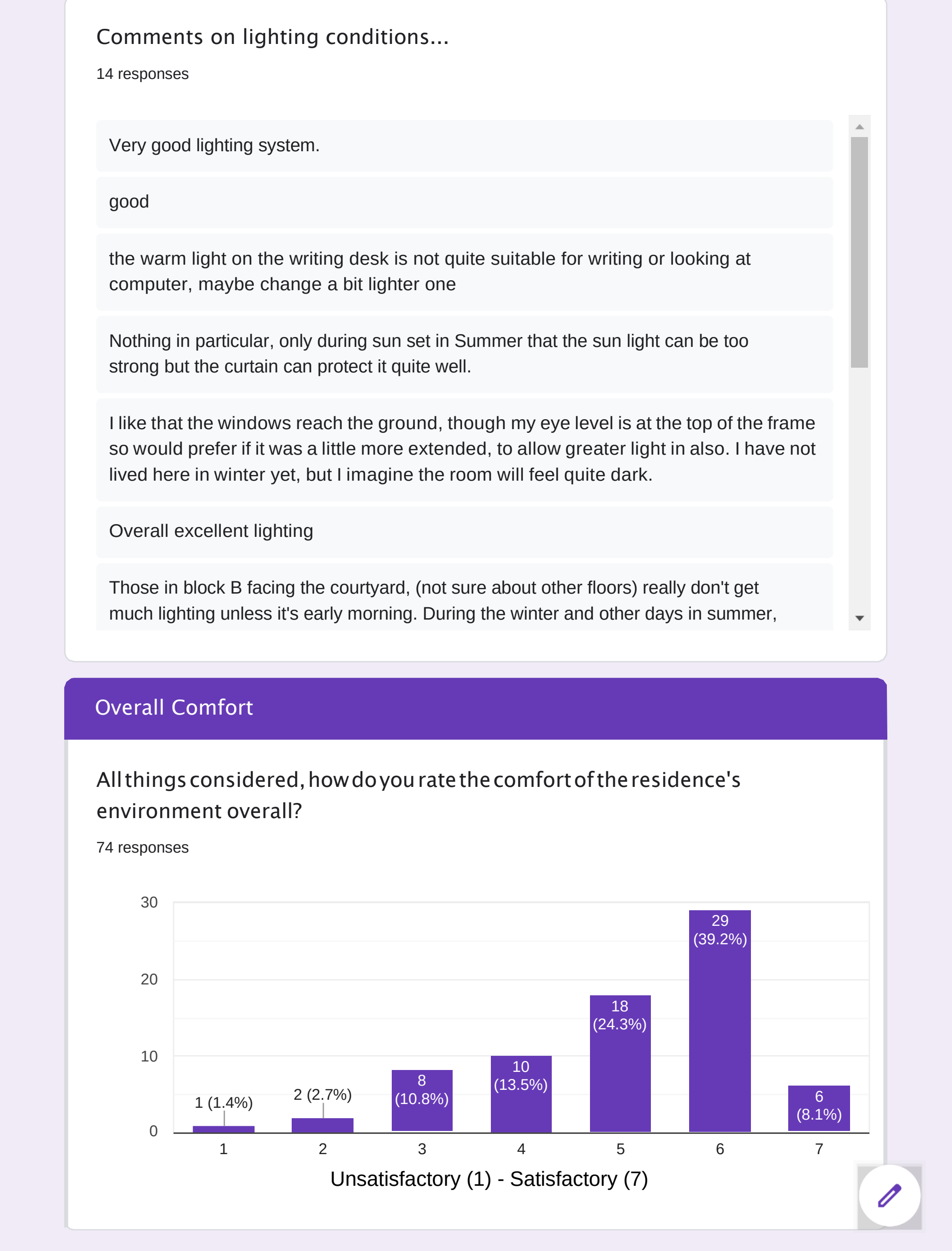


Artifical Light

74 responses



[redacted] [redacted]



Comments on lighting conditions...

14 responses

Very good lighting system.

good

the warm light on the writing desk is not quite suitable for writing or looking at computer, maybe change a bit lighter one

Nothing in particular, only during sun set in Summer that the sun light can be too strong but the curtain can protect it quite well.

I like that the windows reach the ground, though my eye level is at the top of the frame so would prefer if it was a little more extended, to allow greater light in also. I have not lived here in winter yet, but I imagine the room will feel quite dark.

Overall excellent lighting

Those in block B facing the courtyard, (not sure about other floors) really don't get much lighting unless it's early morning. During the winter and other days in summer,

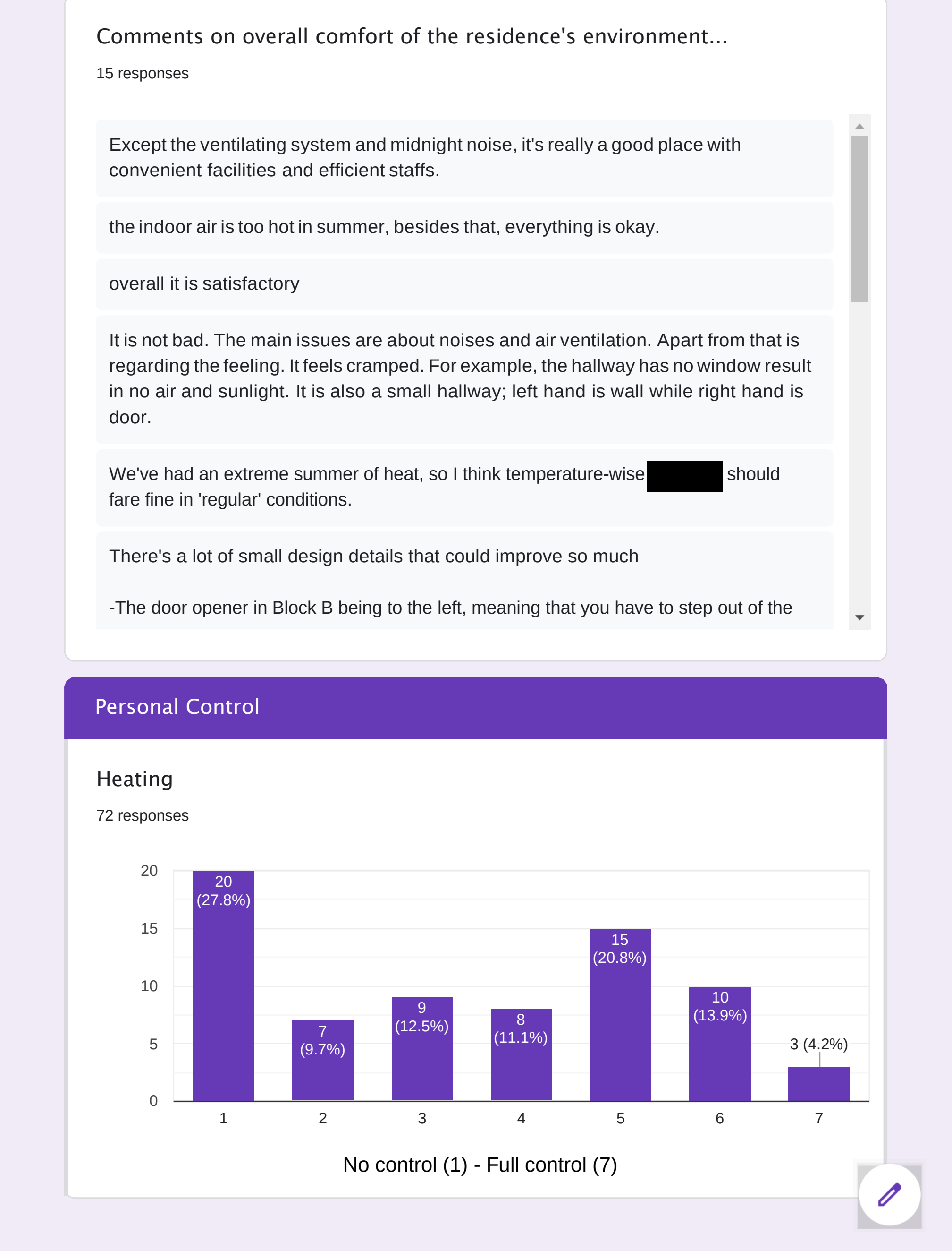
Overall Comfort

All things considered, how do you rate the comfort of the residence's environment overall?

74 responses

[redacted]

[redacted] [redacted]



Comments on overall comfort of the residence's environment...

15 responses

Except the ventilating system and midnight noise, it's really a good place with convenient facilities and efficient staffs.

the indoor air is too hot in summer, besides that, everything is okay.

overall it is satisfactory

It is not bad. The main issues are about noises and air ventilation. Apart from that is regarding the feeling. It feels cramped. For example, the hallway has no window result in no air and sunlight. It is also a small hallway; left hand is wall while right hand is door.

We've had an extreme summer of heat, so I think temperature-wise [redacted] should fare fine in 'regular' conditions.

There's a lot of small design details that could improve so much

-The door opener in Block B being to the left, meaning that you have to step out of the

Personal Control

Heating

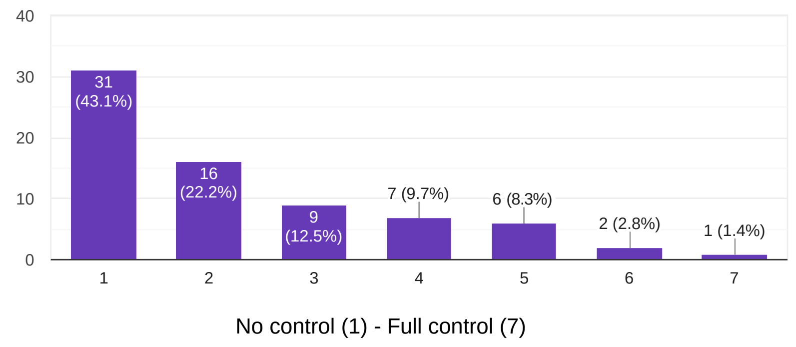
72 responses

[redacted]

[redacted] [redacted]

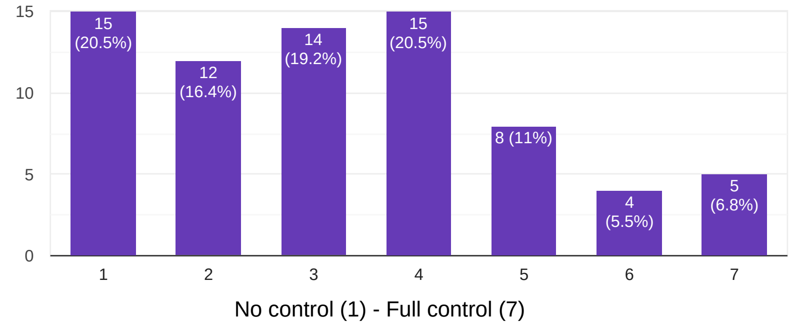
Reducing the temperature in your room (cooling)

72 responses



Ventilation

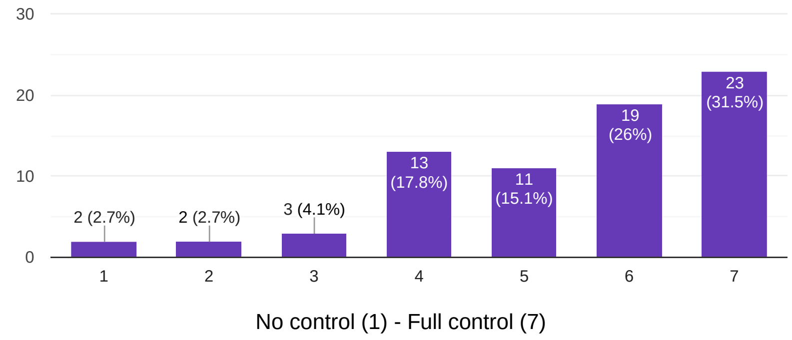
73 responses



[redacted]

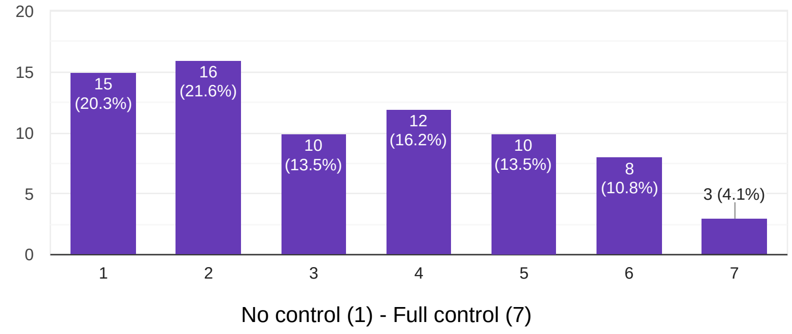
Lighting

73 responses



Noise

74 responses



Comments on personal control...

6 responses

sometimes in summer when it is sunset, the natural light in the kitchen is too much so maybe curtains can be added so that it is more convenient for cooking or it will be so sunny and hot to cook

Heating is a definite plus

Ventilation is alright, but the fan being on is quite noisy. The windows do not open enough to provide enough air flow (perhaps additional small openings at the top can provide more capacity)

It's hard to cool the room, ended up purchasing a fan (which helped immensely to get rid of the 'stale' air feeling)

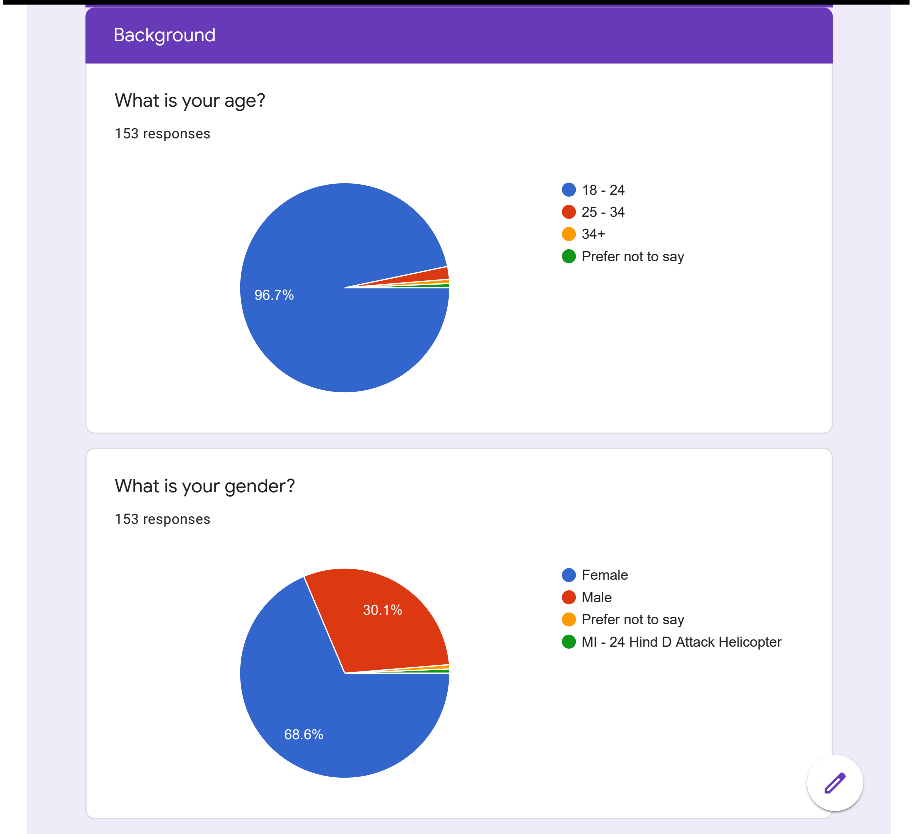
Again, block B's lower levels facing east are quite affected by Block A's blocking.

Perhaps a bit more could be done for noise, rooms next door might fare better, but for rooms that are in 'corners' with another - it seems that the noise travels from the door quite easily into mine. From above as well, the steps can often beh eard

Anything else...?

E.2 CSB Survey Summary Statistics

[redacted]



Background

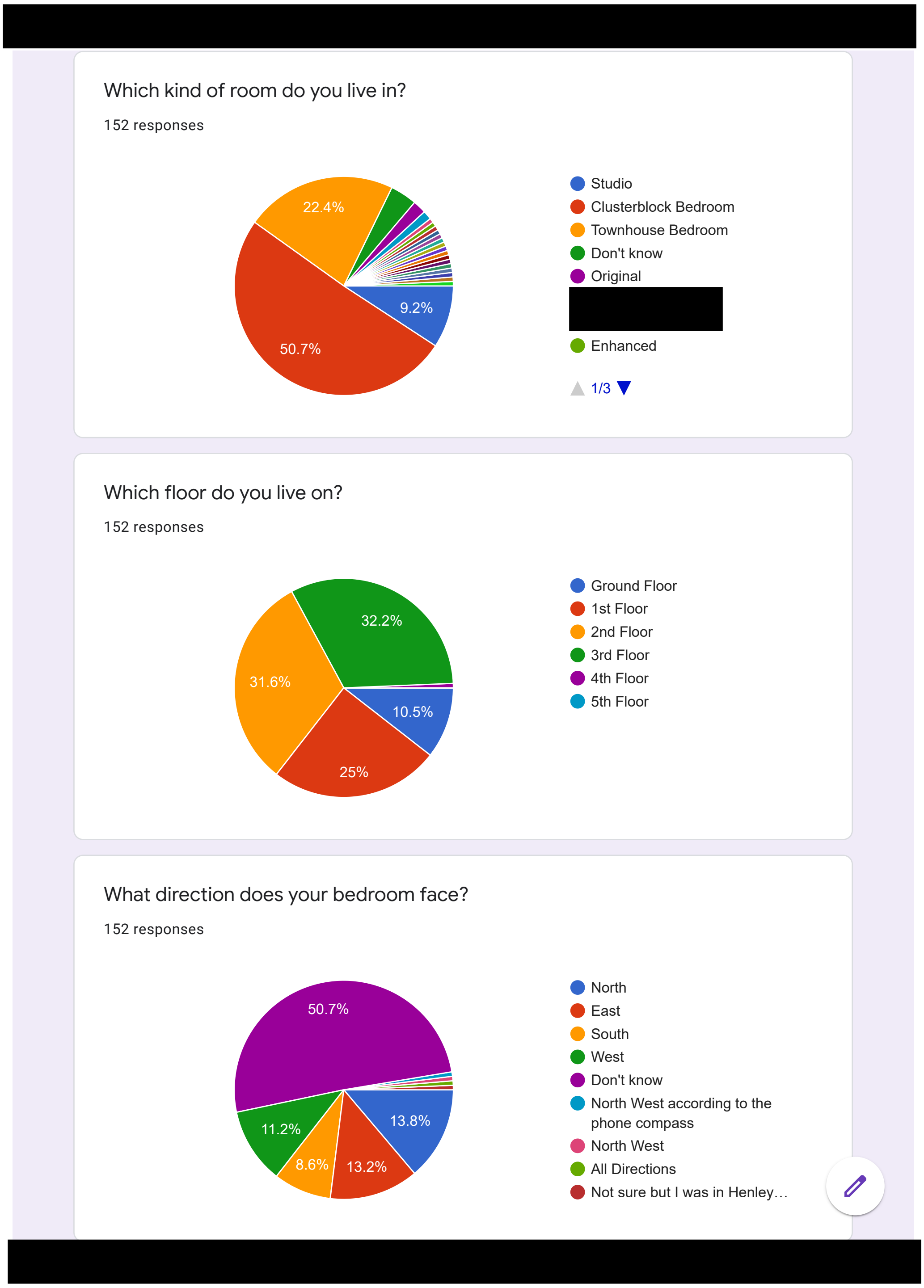
What is your age?

153 responses

What is your gender?

153 responses

[redacted]



[redacted]

Which kind of room do you live in?

152 responses

[redacted]

Which floor do you live on?

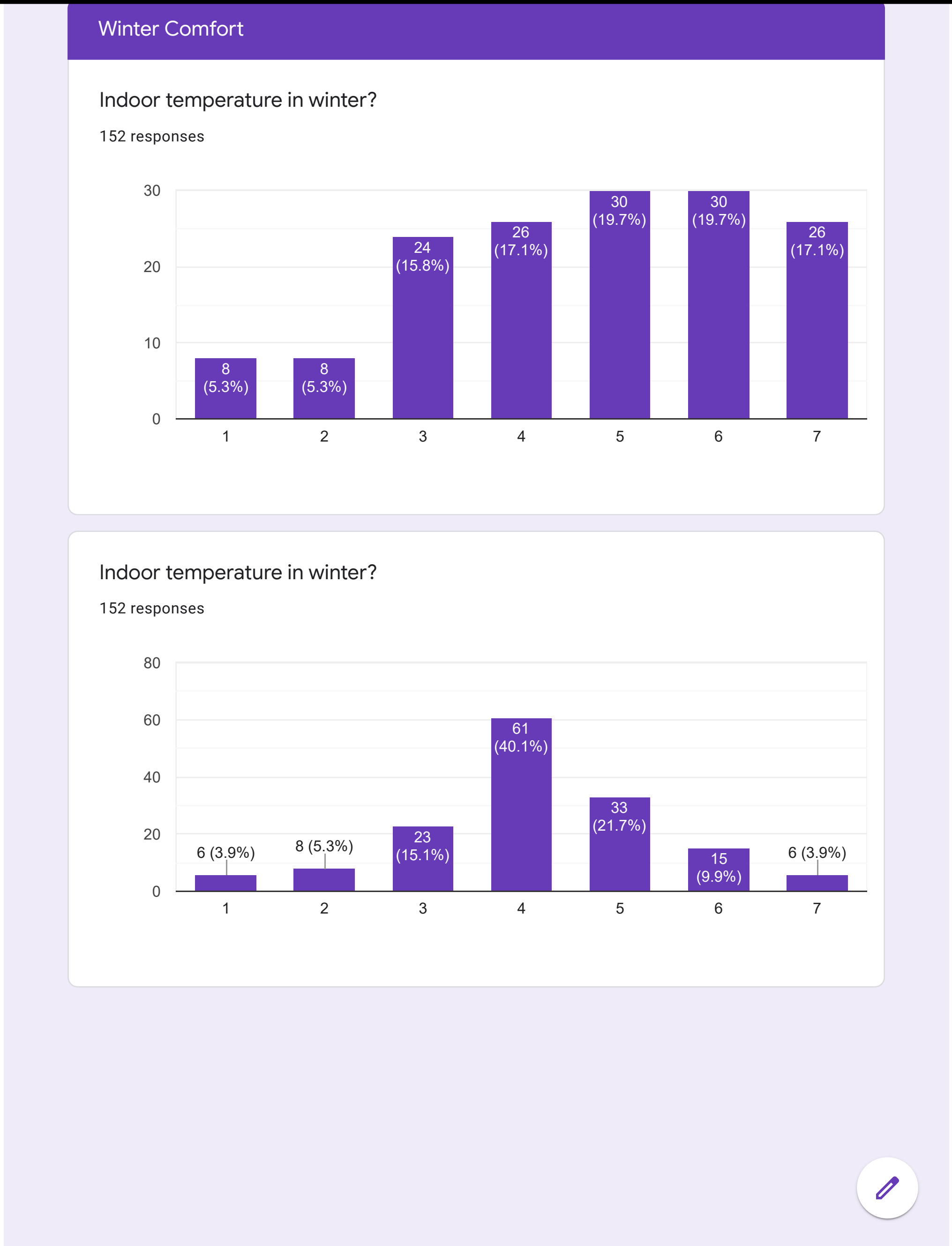
152 responses

What direction does your bedroom face?

152 responses

[redacted]

[redacted]



Winter Comfort

Indoor temperature in winter?

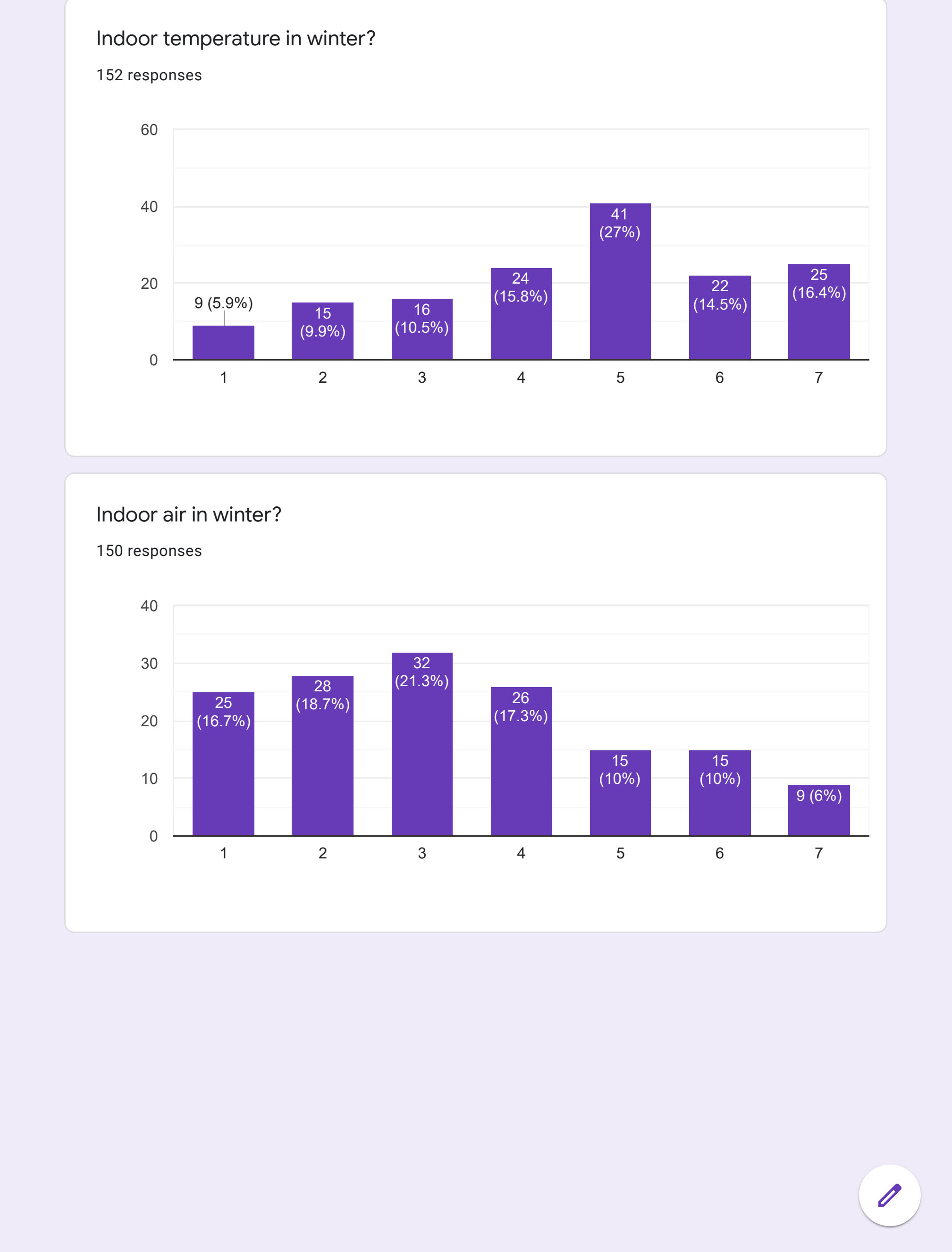
152 responses

Indoor temperature in winter?

152 responses

[redacted]

[redacted]



Indoor temperature in winter?

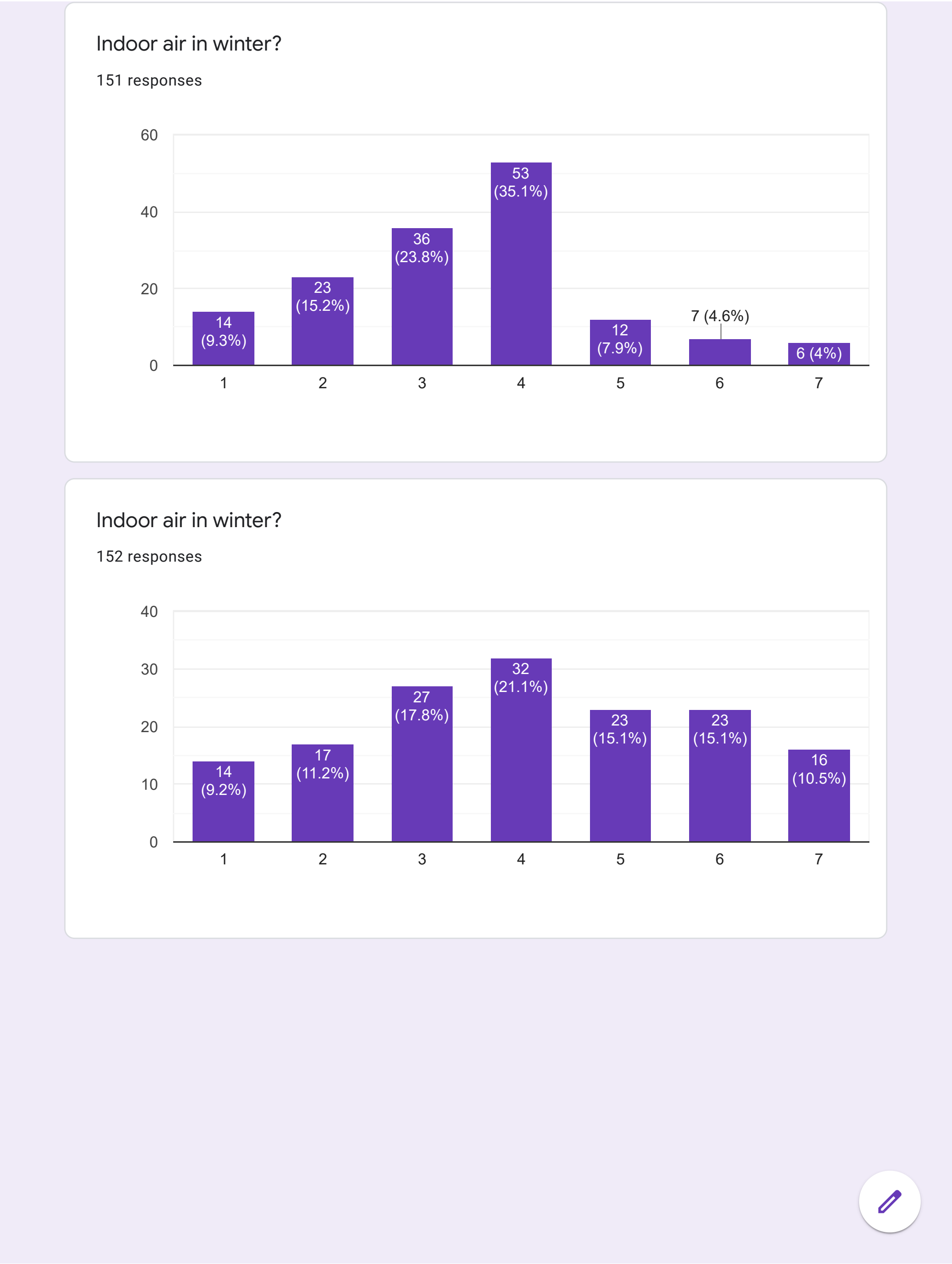
152 responses

Indoor air in winter?

150 responses

[redacted]

[redacted]



Indoor air in winter?

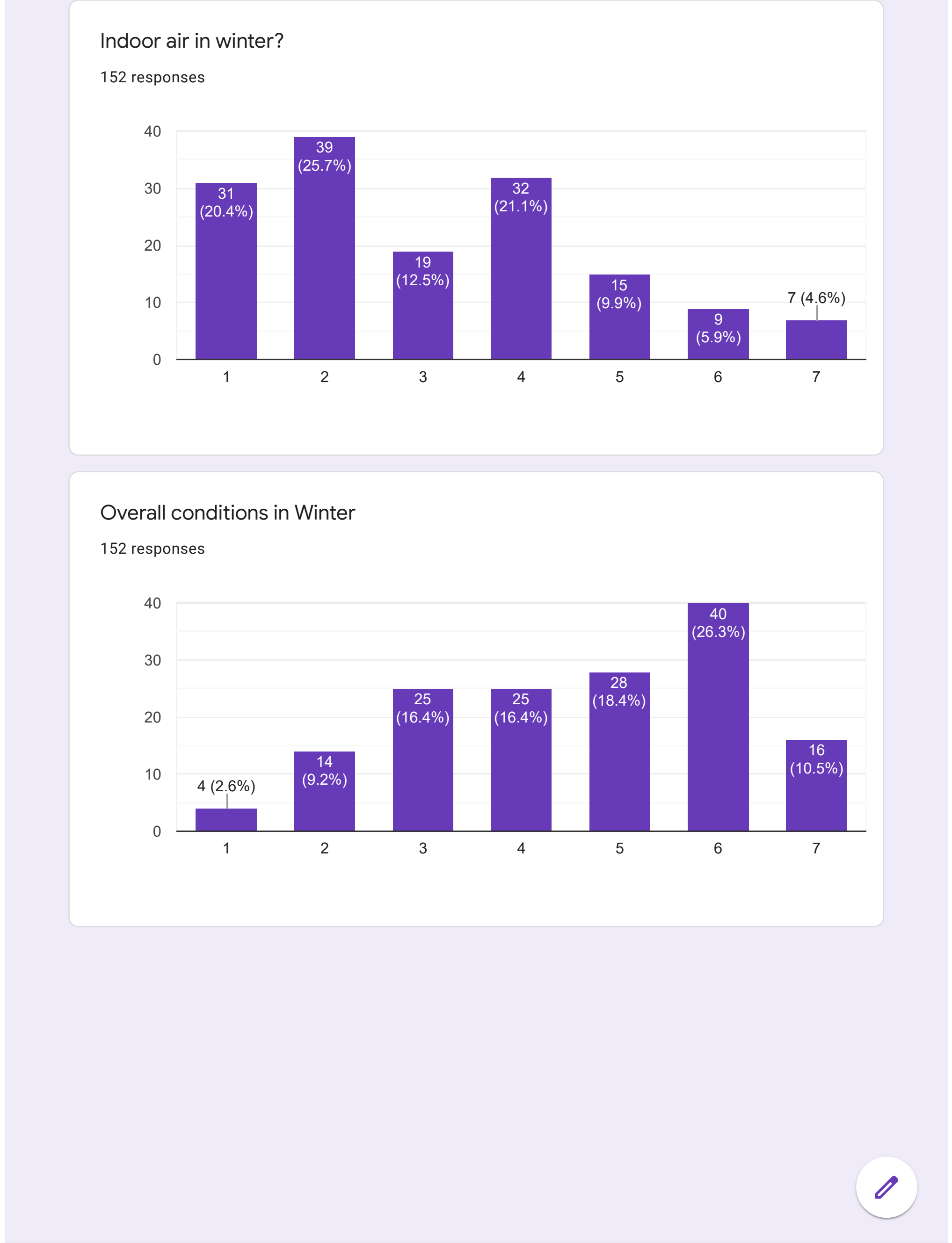
151 responses

Indoor air in winter?

152 responses

[redacted]

[redacted]



Indoor air in winter?

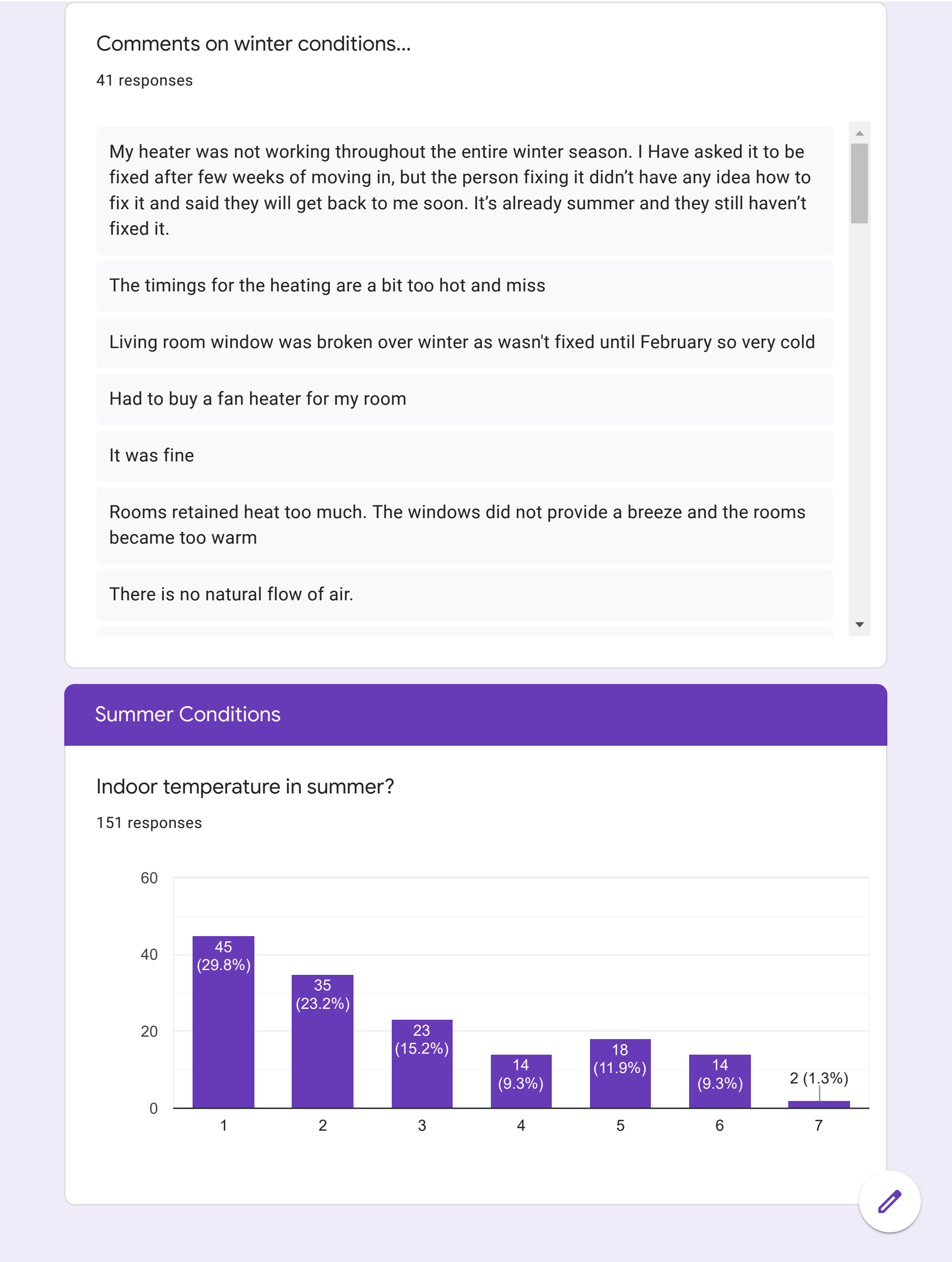
152 responses

Overall conditions in Winter

152 responses

[redacted]

[redacted]



Comments on winter conditions...

41 responses

My heater was not working throughout the entire winter season. I Have asked it to be fixed after few weeks of moving in, but the person fixing it didn't have any idea how to fix it and said they will get back to me soon. It's already summer and they still haven't fixed it.

The timings for the heating are a bit too hot and miss

Living room window was broken over winter as wasn't fixed until February so very cold

Had to buy a fan heater for my room

It was fine

Rooms retained heat too much. The windows did not provide a breeze and the rooms became too warm

There is no natural flow of air.

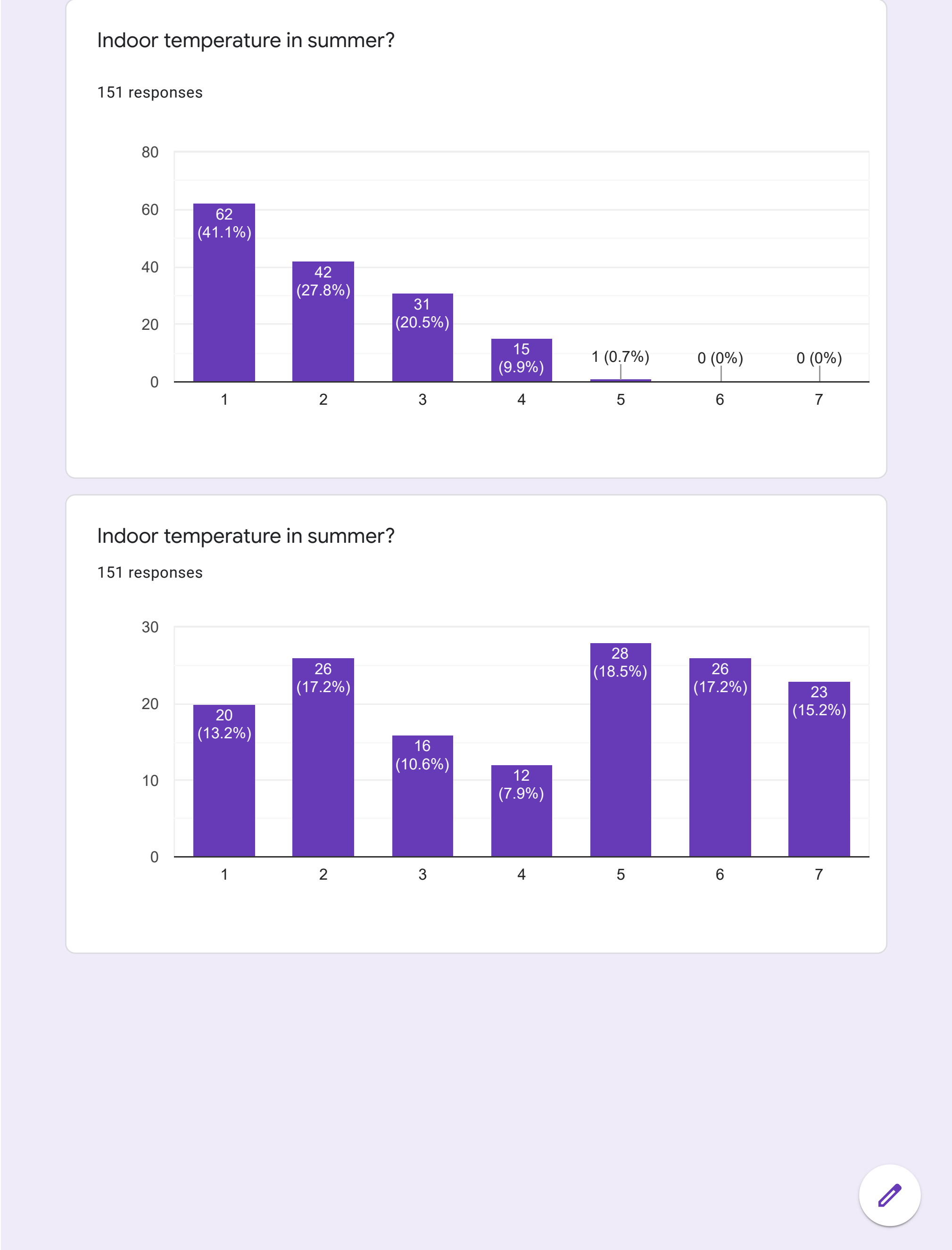
Summer Conditions

Indoor temperature in summer?

151 responses

[redacted]

[redacted]



Indoor temperature in summer?

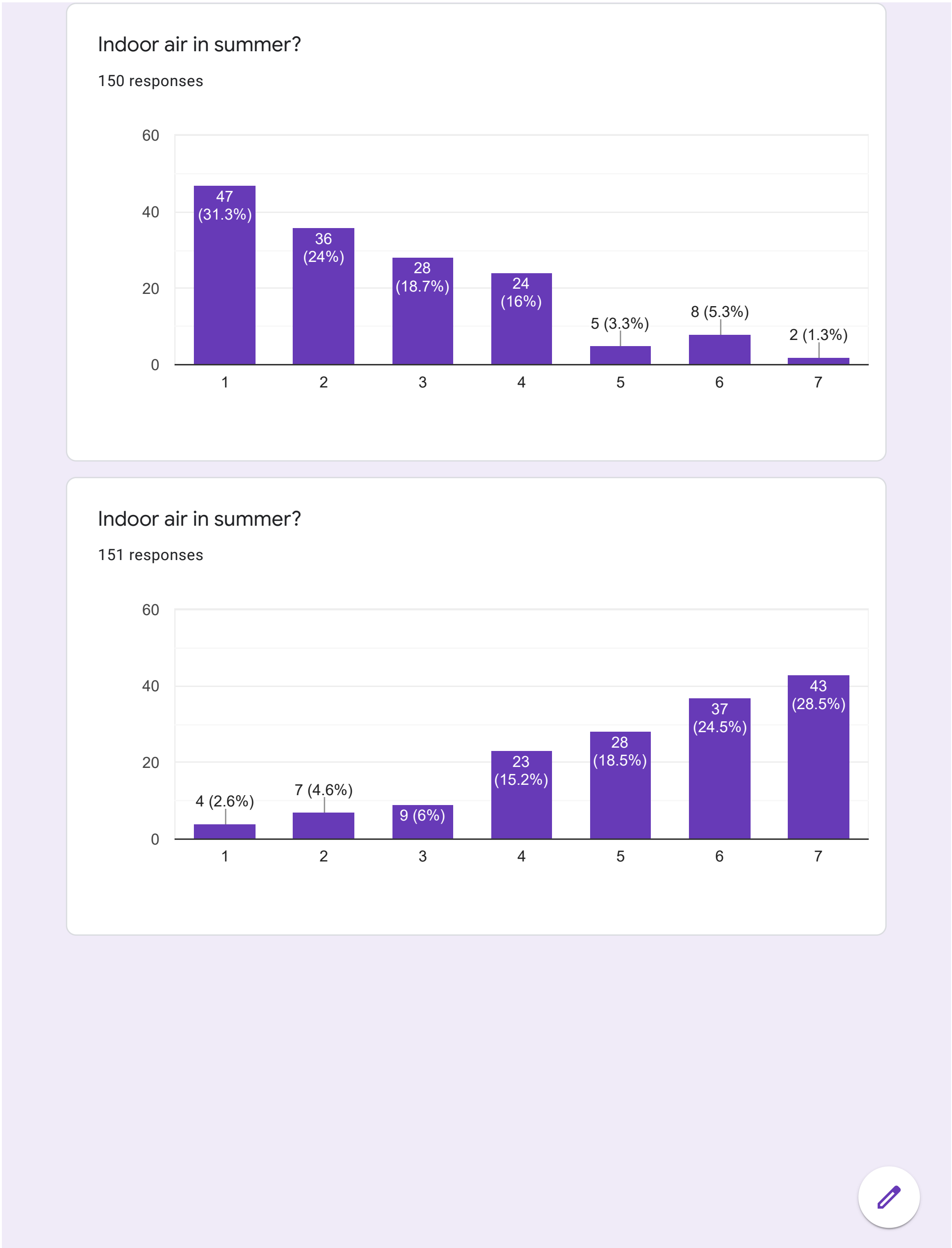
151 responses

Indoor temperature in summer?

151 responses

[redacted]

[redacted]



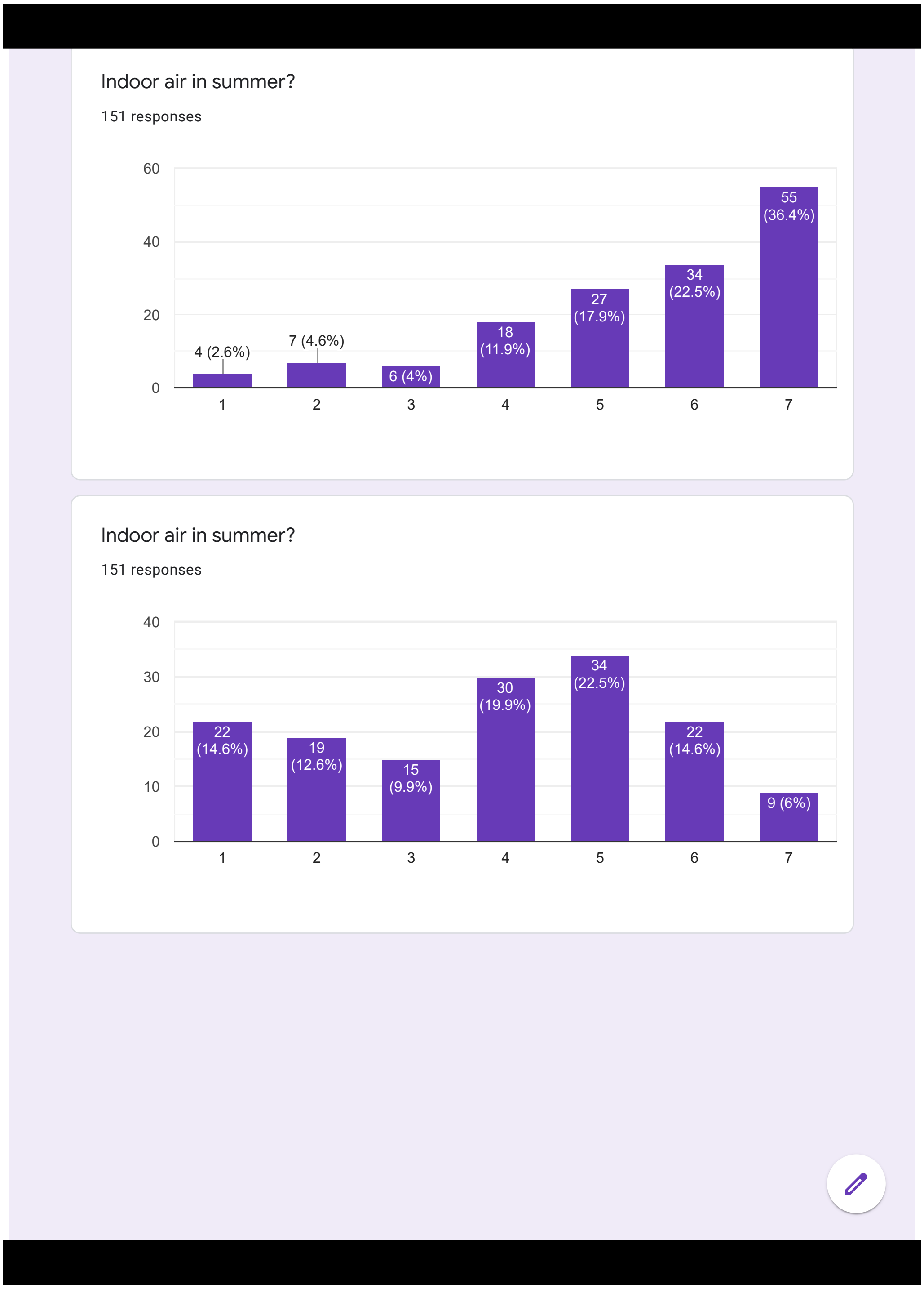
Indoor air in summer?

150 responses

Indoor air in summer?

151 responses

[redacted]



Indoor air in summer?

151 responses

Indoor air in summer?

151 responses

[redacted]

Overall conditions in Summer

151 responses

Comments on summer conditions...

51 responses

The rooms are unbelievably hot and the windows can only be opened a fraction of an amount.

Heating still came on during peak heat and off when colder in evenings

Again, it was fine

Unbearably uncomfortable

Far too warm. No ventilation even with the windows open.

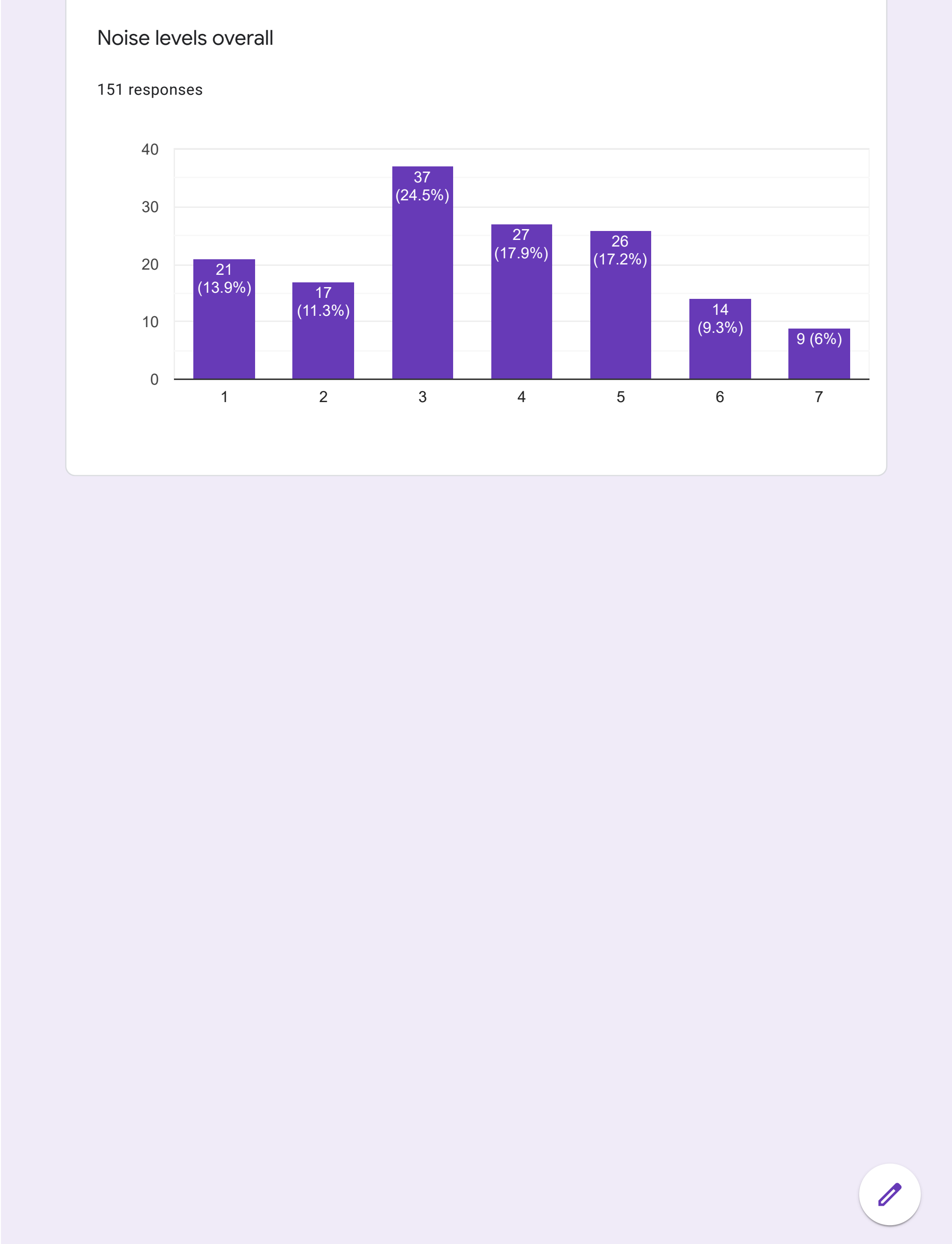
Natural flow of air as bathroom "extractors" and windows do not provide appropriate ventilation.

No air flow in the flat, window barely opens, really really stuffy and way too warm

It can get quite hot in the summer because the windows don't open fully so it's very hard to get cooler air into the block

[redacted]

[redacted]

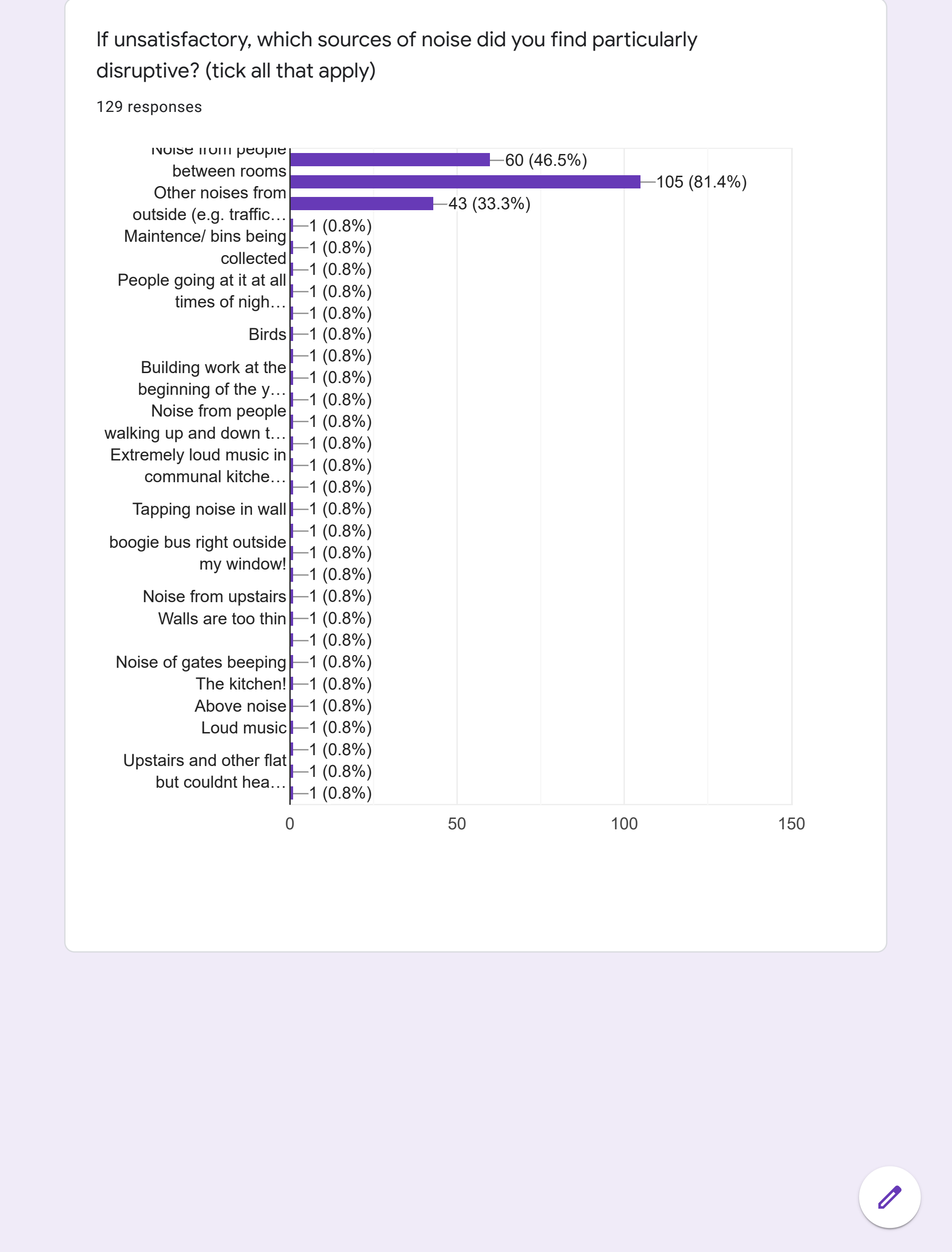


Noise levels overall

151 responses

[redacted]

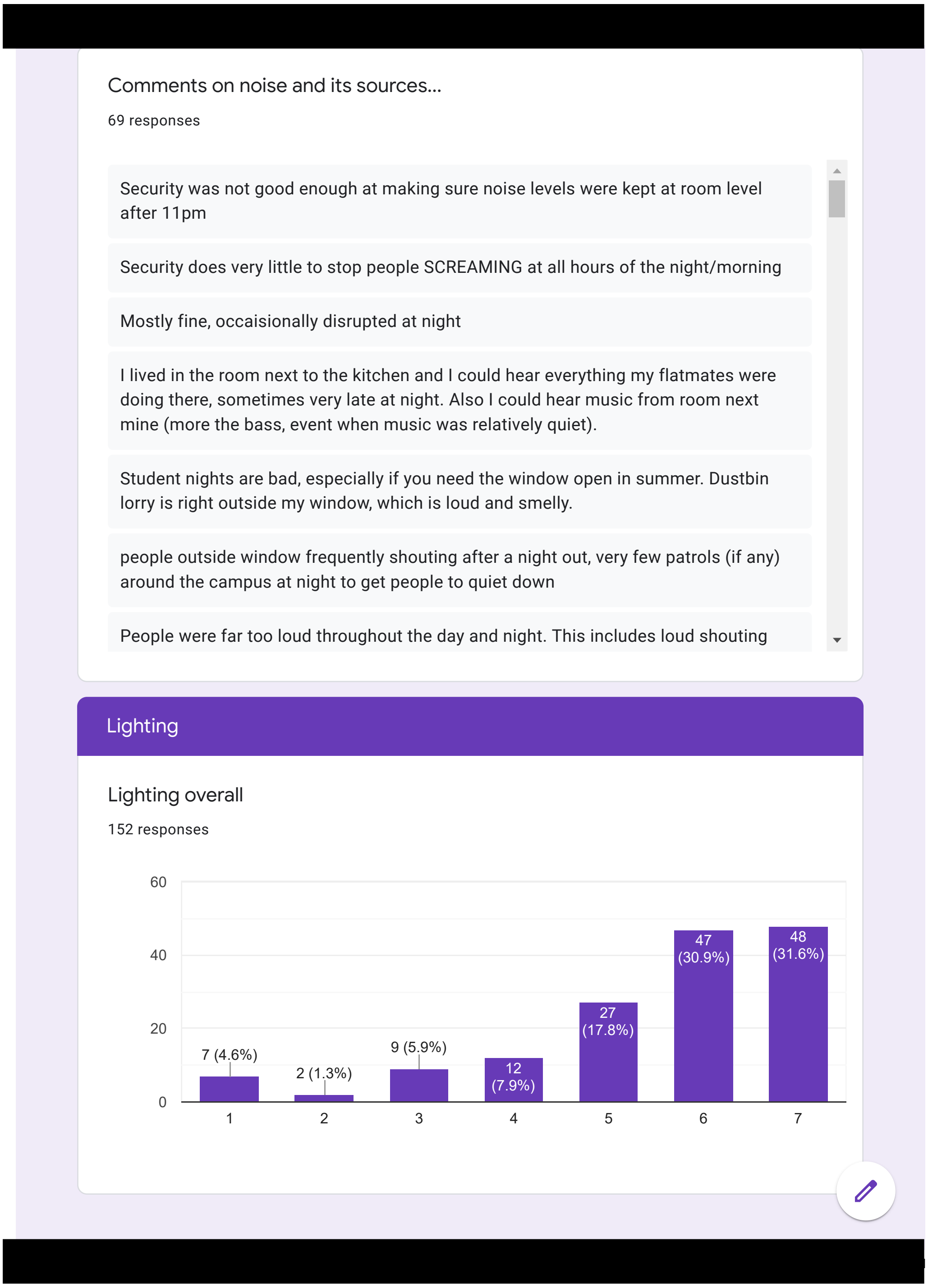
[redacted]



If unsatisfactory, which sources of noise did you find particularly disruptive? (tick all that apply)

129 responses

[redacted]



[redacted]

Comments on noise and its sources...

69 responses

Security was not good enough at making sure noise levels were kept at room level after 11pm

Security does very little to stop people SCREAMING at all hours of the night/morning

Mostly fine, occaisionally disrupted at night

I lived in the room next to the kitchen and I could hear everything my flatmates were doing there, sometimes very late at night. Also I could hear music from room next mine (more the bass, event when music was relatively quiet).

Student nights are bad, especially if you need the window open in summer. Dustbin lorry is right outside my window, which is loud and smelly.

people outside window frequently shouting after a night out, very few patrols (if any) around the campus at night to get people to quiet down

People were far too loud throughout the day and night. This includes loud shouting

Lighting

Lighting overall

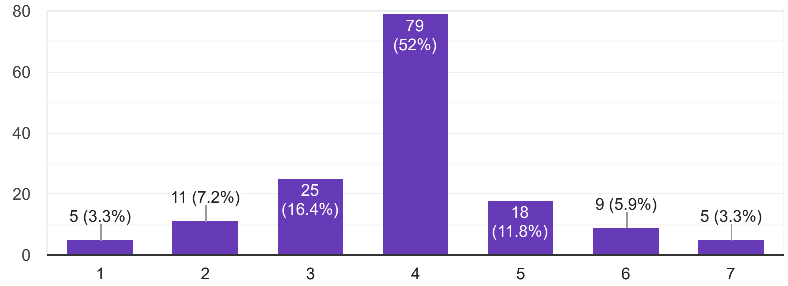
152 responses

[redacted]

[redacted]

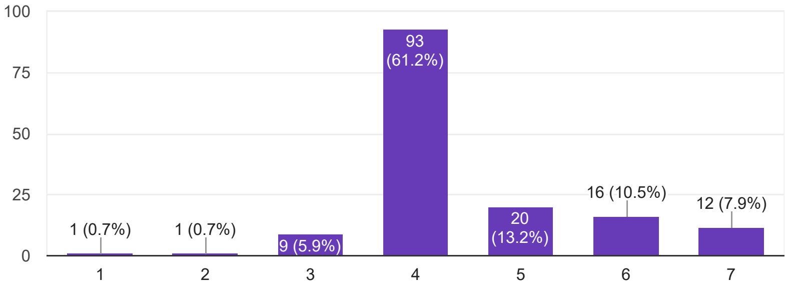
Natural Light

152 responses



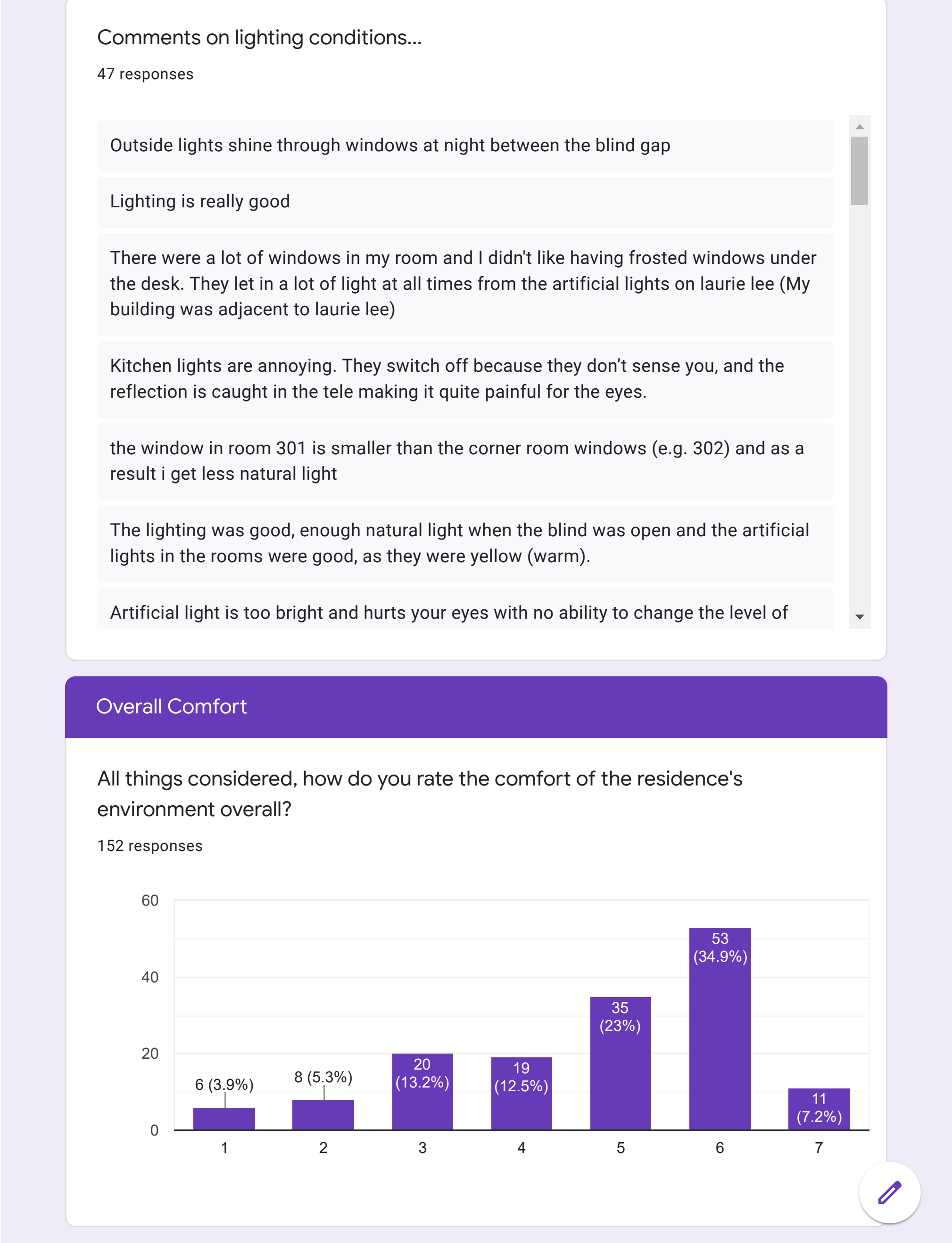
Artifical Light

152 responses



[redacted]

[redacted]



Comments on lighting conditions...

47 responses

Outside lights shine through windows at night between the blind gap

Lighting is really good

There were a lot of windows in my room and I didn't like having frosted windows under the desk. They let in a lot of light at all times from the artificial lights on laurie lee (My building was adjacent to laurie lee)

Kitchen lights are annoying. They switch off because they don't sense you, and the reflection is caught in the tele making it quite painful for the eyes.

the window in room 301 is smaller than the corner room windows (e.g. 302) and as a result i get less natural light

The lighting was good, enough natural light when the blind was open and the artificial lights in the rooms were good, as they were yellow (warm).

Artificial light is too bright and hurts your eyes with no ability to change the level of

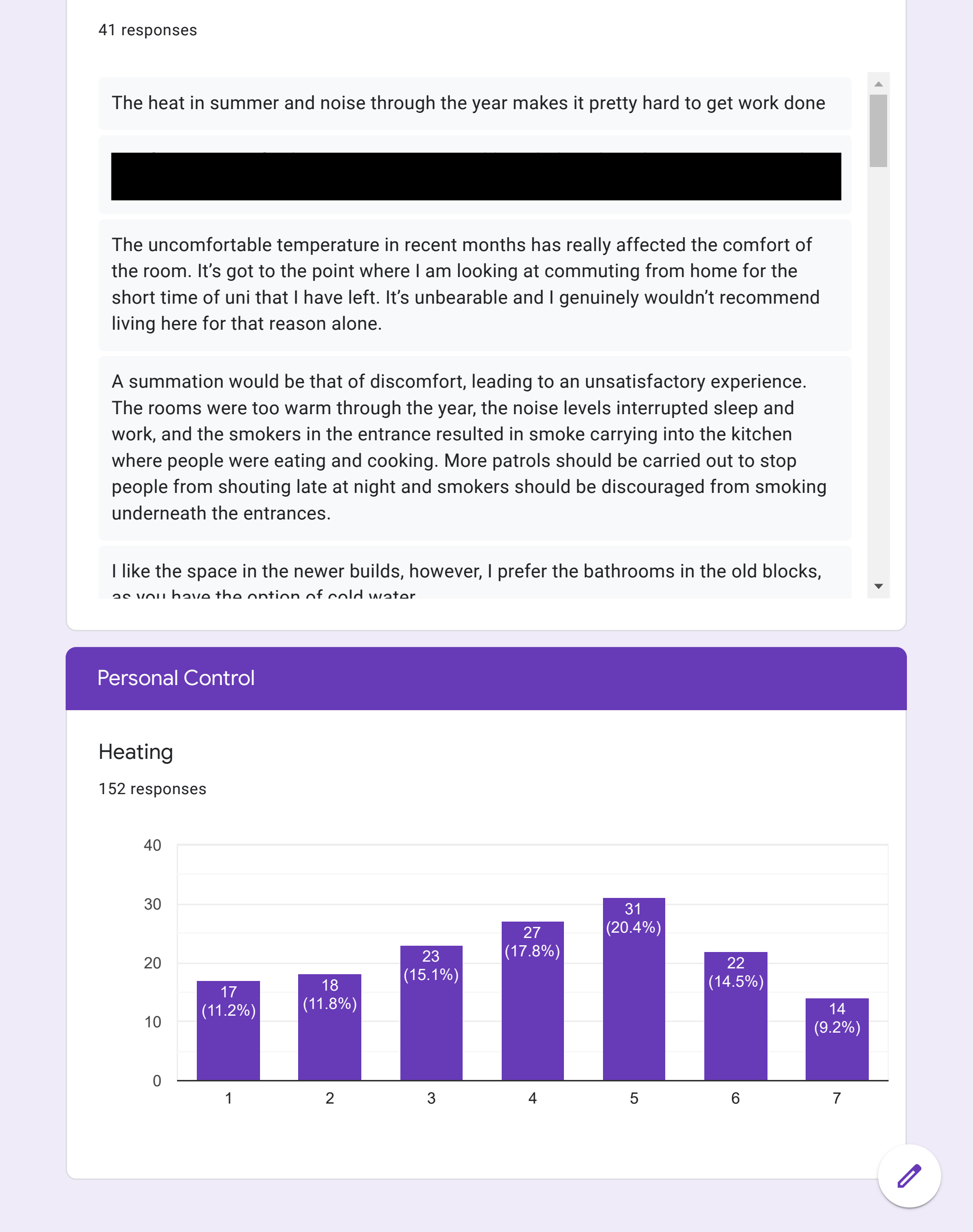
Overall Comfort

All things considered, how do you rate the comfort of the residence's environment overall?

152 responses

[redacted]

[redacted]



Comments on overall comfort of the residence's environment...

41 responses

The heat in summer and noise through the year makes it pretty hard to get work done

[redacted]

The uncomfortable temperature in recent months has really affected the comfort of the room. It's got to the point where I am looking at commuting from home for the short time of uni that I have left. It's unbearable and I genuinely wouldn't recommend living here for that reason alone.

A summation would be that of discomfort, leading to an unsatisfactory experience. The rooms were too warm through the year, the noise levels interrupted sleep and work, and the smokers in the entrance resulted in smoke carrying into the kitchen where people were eating and cooking. More patrols should be carried out to stop people from shouting late at night and smokers should be discouraged from smoking underneath the entrances.

I like the space in the newer builds, however, I prefer the bathrooms in the old blocks, as you have the option of cold water

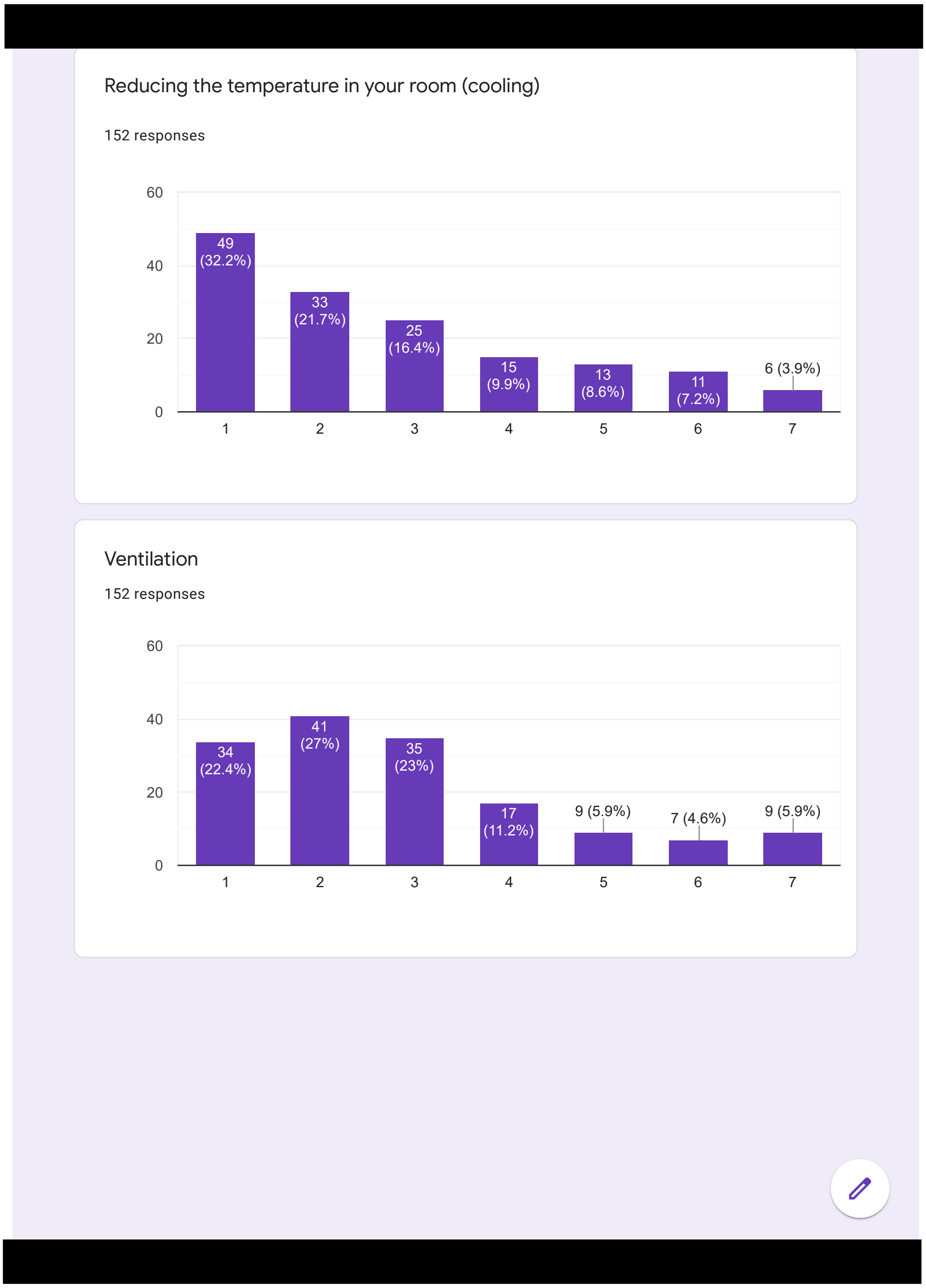
Personal Control

Heating

152 responses

[redacted]

[redacted]



Reducing the temperature in your room (cooling)

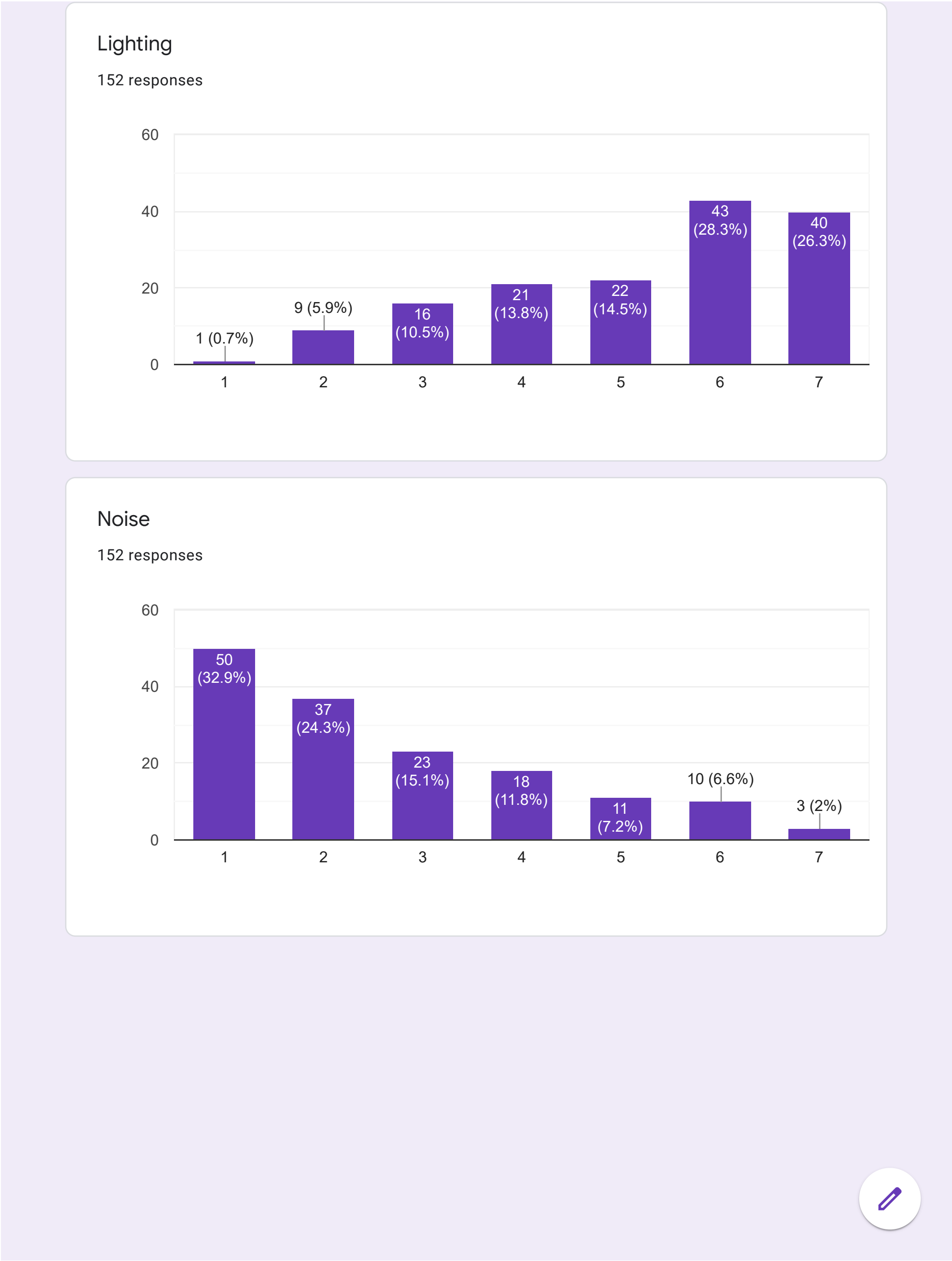
152 responses

Ventilation

152 responses

[redacted]

[redacted]



Lighting

152 responses

Noise

152 responses

[redacted]

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