An occupant-centric assessment of the building performance gap in low utilisation, higher education facilities

By

Stephen Oliver

A dissertation submitted to

Department of Architecture

University of Strathclyde

In partial fulfilment of the requirements for the degree of

Master of Philosophy

September 2019

Abstract

Seminal literature advocates that the occupants of buildings are the real consumers of energy, not the buildings. While this is a helpful philosophy for design and retrofit analysis, it is not entirely accommodating of operational building energy demand. An optimistic amendment would suggest that it is the needs of people that consume energy rather than buildings, for nondomestic buildings at least. However, needs in operation are not guaranteed to correlate with simulation, and servicing of needs is not bound to the real occupant presence. The presence of the people, whose needs exist in a given discrete space is not a prerequisite of energy consumption. In broader terms of occupancy, the observation is absent from the nature of consuming services' relationships with occupants and the activities that drive the second-order interests. That is, what constitutes as needs of one occupant is not necessarily equivalent of identical needs of another. These factors cause great concern for retrofit decision-making and invariably make a significant contribution to the building performance gap. Given the presumption of needs' role in building energy consumption, it appears that the industry must revise its current definitions of what constitutes as an occupant and how efficiency is measured. After all, an ideal system is still inefficient, if its operation has no utility.

Further and higher education facilities are notably sensitive to these concerns. Where the assumption that needs exist in design models is known typically to deviate by 73% in teaching spaces, in the United Kingdom. However, they are also uniquely equipped for stabilising their utilisation through strict class allocation planning. The difference in utilisation when mapped to zones in EnergyPlus can profoundly affect how a simulated building behaves. These changes to simulated behaviour can redefine the retrofit solution space. Without strict heating management through registration of periods of nonzero density presence to a building management system, over two-thirds of needs do not exist. This study aims to demonstrate the severity of the presence simulation gap and provide a case for heat management as a precursor for conventional retrofit analysis. It also aims to determine whether gaps exist in the current occupant ontologies.

A registration system-led occupancy modelling tool for EnergyPlus is developed to explore divergence from standardised and real utilisation to simulated behaviours under

known conditions. The tool is tested through two virtual cases under different building states by assessing real-world utilisation of the teaching spaces for two years' weather data and six Schedule-Climate scenarios. Three retrofit options encompassing heating management, lighting and boiler replacement are simulated and presented under each Schedule-Climate scenario. All results form building energy modelling are considered in terms of emissions, net energy and operation costs. Retrofit results are assessed using discounted cash flow analysis at the Green Book suggested discount rate. The entire solution space is procedurally generated by a bespoke library which integrates EnergyPlus and data analytics tools.

The experimentation results show the severity of the presence and presence-bound scheduling simulations gaps. It is shown simulated heating energy demand is dependent on latent gains to the extent that when heating schedules are decoupled from presence as per the real world, retrofitting lighting will have an adverse effect on building energy performance. The results proceed to explore the underlying relationship between heating and lighting energy demand, occupancy and net building energy demand. This is demonstrated through presentation of disaggregated internal gains and determining the ratio of energy consumption to net energy demand for combined lighting and heating. The experimentation results are concluded by presentation of result from constant-efficacy lighting retrofits from eighty Schedule-Climate scenarios. Referencing the low utilisation from the registration system and out-of-design presence, the discussion proposes how measuring efficiency in terms of met needs has merit in the higher education sector. Findings from the literature review and consideration of the heterogeneous utilisation is used to explore several new ontologies which bridge the gap between virtual and real occupants.

The thesis which is themed on a previous publication proposes a philosophical framing of energy consumption in low-utilisation buildings. It makes several suggestions for future research ultimately concluding that retrofit analysis should focus on robust mediocrity over simulated optimality of proposals.

Acknowledgements

I want to thank my supervisor Dr Pour Rahimian for his mentoring throughout my study and creating an invaluable development experience. It was an incredible opportunity to learn from him. I would also like to express my deep gratitude to Maureen Eisbrenner – Director at arbnco, and Karen Ramage – Operations Manager at arbnco for guidance and support throughout the last eleven years.

I wish to thank arbnco for funding and supporting the study. I also thank them for the opportunity to explore energy in the built environment. I would also like to thank the arbnLabs team for sharing their diverse knowledge.

A special thanks to Saleh Seyedzadeh for feedback on this research and the pleasure of collaborating on other projects. Our work has been a highlight of my study.

Finally, thanks to my family for being supportive and making life worthwhile.

Declaration of originality

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date: 16/10/2019

Related publications

- Oliver, S. (2019). "Communication and trust: rethinking the way construction industry professionals and software vendors utilise computer communication mediums." Visualization in Engineering 7(1)

Literature review used to provide a core understanding of the social science behind human-computer relationships and computer personalities. The content provides the social case for section 2.7 – Computers as pseudo agents.

- Oliver, S. Pour Rahimian, F (2018 "Are computers agents? Considering the implication of classifying computers as occupants on energy consumption and proximity-as-utility equipment scheduling" Proceedings of *Creative Construction Conference 2018*

An extended version of the 2.7 – computers as pseudo agents literature review presented at Creative Construction 2018. This paper extends the section to include the computer ethics considerations and links the social and physical characteristics of devices.

- Oliver, S. Seyedzadeh, S. Pour Rahimian, F. (2019) "Using real occupancy in retrofit decision-making: reducing the performance gap in low utilisation higher education buildings" Proceedings of 36th CIB W78 Information for Construction Technology Conference

A paper and conference presentation of the finding outlined in sections 5.2 and 5.4 of the results in this thesis. The presentation was used to present the animated Schedule divergence to demonstrate the claim that presence beliefs are a greater contributor to consumption than behaviours in low utilisation buildings.

Glossary of abbreviations and terms

Abbreviations

ABM	Agent-based modelling
ASHRAE	American Society Heating, Refrigerating and Air-Conditioning
BMS	Building management system
BRUKL	Building Regulations United Kingdom
CASA	Computers as Social Actors
CFD	Computational fluid dynamics
CIBSE	Chartered Institute of Building Service Engineers
CO2	Carbon emissions
DCF	Discounted cash flow
DNAS	Drivers, Needs, Actions and Systems
DSM	Dynamic simulation modelling
EPC	Energy performance certificate
EU	European Union
HMS	Heating management system
IAQ	Indoor air quality
IDF	EnergyPlus input file
IEQ	Indoor environmental quality
IUC	Intelligent unitary controller
L2B	Existing nondomestic building regulations
LCE	Low Carbon Economy
LTHW	Low-temperature hot water
MEES	Minimum Energy Efficiency Standards
NCM	National Calculation Method
NDBSCG	Nondomestic Building Services Compliance Guide
NDEPC	Nondomestic EPC
PMV	Predicted mean vote
POE	Post-occupancy evaluation
PrOE	Pre-occupancy evaluation
PRS	Private rented sector
R-BMS	BMS retrofit method
R-HVC	Heating system retrofit method
R-LIG	Lighting retrofit method
SBEM	Simplified Building Energy Model
SCL	Smart controllable load
SHOCC	Sub-hourly occupancy
SMG	Space Management Group
SQL	Structured query language
UK	United Kingdom

Terms

Nonzero-density presence	Period where building services are active, and occupants are present
Presence	The state of a zone having occupants whether physical or abstract
Pseudo agent	An occupant which is not a human
Schedule-Climate	A term describing a simulation scenario with Scheduling and climate components which may not contain parts of the default NCM 2016 occupancy scheduling and climate
Utilisation	A function of real and design density presence
Zero-density presence	The state of a zone having no physical occupants but active services

List of tables

Table 3-1 R-LIG lamp-luminaire cost data 90
Table 3-2 R-LIG activity-level costs for the case study 92
Table 3-3 R-HVC kW boiler cost lookup 94
Table 3-4 R-BMS head equipment and smart controllable load cost data 95
Table 3-5 R-BMS case study costs 95
Table 4-1 NCM activity database bindings for case study zones 107
Table 4-2 Heating, ventilation and cooling systems in on-site 108
Table 4-3 Domestic hot water system on-site 109
Table 4-4 External envelope construction properties 111
Table 4-5 Internal partition construction properties 112
Table 4-6 Internal load-bearing walls construction properties 113
Table 4-7 Flat roof construction properties 114
Table 4-8 Raised floor construction properties 115
Table 4-9 Single glazing construction properties 116
Table 5-1 Schedule-Climate end use and emissions 119
Table 5-2 Classroom Schedule scenario lighting demand: kWh per annum 142

List of figures

Figure 2-1 Literature review summary 28
Figure 2-2 NCM database teaching space weekday schedule 66
Figure 3-1Quantitative research design tree (credit: Amanda Szapkiw) 78
Figure 3-2 Retrofit simulation process 87
Figure 4-1 Case study model preparation and translation process 103
Figure 4-2 DesignBuilder representation of the case study building 105
Figure 4-3Case study activity floor plan 106
Figure 5-1Schedule-Climate base model simulated performance 119
Figure 5-2 Example Schedule set membership and cumulative presence plot 124
Figure 5-3 GH813 Schedule set membership and cumulative presence plot 125
Figure 5-4 GH816 Schedule set membership and cumulative presence plot 125

Figure 5-5 GH817 Schedule set membership and cumulative presence plot 126
Figure 5-6 GH818 Schedule set membership and cumulative presence plot 126
Figure 5-7 GH863 Schedule set membership and cumulative presence plot 126
Figure 5-8 GH898 Schedule set membership and cumulative presence plot 127
Figure 5-9 Schedule source day set membership 129
Figure 5-10 Schedule scenario presence summary 130
Figure 5-11 Register and NCM schedule comparison: Days per month 130
Figure 5-12 Weekday presence hours distribution overview 131
Figure 5-13 Heating mismanagement overview: Hours per classroom 134
Figure 5-14 Classroom latent gains by Schedule set membership 135
Figure 5-15 NCM and registration system expected gains error: Monthly 138
Figure 5-16 NCM and registration system, degree-day adjusted expected gains error: Monthly 139
Figure 5-17 Schedule-Climate scenario net energy comparison with NCM-2016 144
Figure 5-18 Annual carbon emissions by Schedule-Climate scenario 145
Figure 5-19 Schedule-Climate running costs estimates compared to NCM-2016: Ten-year projection 147
Figure 5-20 Schedule-Climate scenario running cost estimates: Pre-installed and retrofit groupings 150
Figure 5-21 R-BMS discounted payback rates: Discounted at 3.5% 151
Figure 5-22 R-BMS discounted payback rates: Unadjusted head equipment costs 152
Figure 5-23 R-HVC Discounted cash flow projections for Schedule-Climate scenarios 153
Figure 5-24 R-HVC Discounted payback grate 154
Figure 5-25 Constant efficacy retrofit Schedule-Climate simulated running costs 155
Figure 5-26 Constant efficacy retrofits simulated carbon emissions 155
Figure 6-1 Identified real-world occupant ontologies 168

Contents

Abstract………………………………………………………………… 02

Acknowledgements……………………………………………………… 03

Declaration of originality…………………………………………… .04

Related publications…………………………………………………... 05

Glossary of abbreviations and terms………………………… 07

List of tables…………………………………………………………... 08

List of figures……………………………………………………….... 08

1 Chapter 1 - Introduction 14

1.1 Background of the study 14

1.2 Purpose of the study 18

1.3 Research gap and motivation for study 19

1.4 Aim and Objectives 20

1.5 Overview of research methodology 21

1.6 Scope of the study 22

1.7 Structure of the thesis 24

2 Chapter 2 – Literature review 28

2.1 Introduction 28

2.2 Energy efficiency and the built environment 30

2.2.1 General contribution from buildings 30

2.2.2 Significance of building operational phase emissions 32

2.2.3 Reporting uncertainty 33

2.2.4 Growth in consumption and emissions in the UK 33

2.2.5 Legislated commitments 34

2.3 Retrofitting and building lifecycle emissions 34

2.3.1 UK efficiency policy and operational phase retrofitting 34

2.3.2 Lifecycle consumption and innovation trade-offs 39

2.4 Interior design preferences, building energy performance and occupant comfort 42

2.4.1 Furnishings and non-isothermal heat transfer 42

2.4.2 Lighting design, harvesting, controls and ergonomics 43

2.4.3 Colour and textures....46
2.5 Occupants 48
2.5.1 Behaviour 49
2.5.2 Psychology 53
2.5.3 Physiology 56
2.5.4 Adaption level theory: Acclimatisation is not ethnicity 58
2.5.5 Gender and sex 58
2.6 Occupancy profiling 59
2.6.1 Overview....59
2.6.2 Utilisation vs simulation accuracy....60
2.6.3 Stochastic scheduling 62
2.6.4 Agent-based modelling 62
2.7 Schedule calibration and energy efficiency 64
2.8 Extant literature on university scheduling 65
2.9 Computers as pseudo agents 66
2.10 Summary 70
2.11 Conclusion 72
3 Chapter 3 - Research methodology....73
3.1 Introduction....73
3.2 Research Philosophy 74
3.2.1 Philosophy 74
3.2.2 Approach 75
3.2.3 Strategy 76
3.2.4 Design 77
3.2.5 Justification of in silico research design 81
3.2.6 The virtual case study design....82
3.2.7 Summary 83
3.3 Literature review approach....84
3.4 Defining and modelling the virtual case study model....85
3.5 Development....86
3.5.1 Integrated retrofit analysis environment design 86
3.5.2 Retrofit options and cost models 87
3.6 Scheduling 96
3.6.1 Schedule Data 96

3.6.2 Scheduling strategies....96
3.6.3 Translating occupancy schedules 97
3.7 Data Analysis....99
3.8 Summary 100
3.9 Conclusion....101
4 Chapter 4 - Virtual case study building energy model 102
4.1 Introduction....102
4.2 Overview....103
4.3 Geometry and zoning....104
4.4 Zone classification 106
4.5 Heating, ventilation and cooling systems 107
4.6 Domestic hot water 109
4.7 Lighting....109
4.8 Envelopes and glazing....111
4.9 Building Climate Data 117
4.10 Conclusion....117
5 Chapter 5 – Results and Analysis 118
5.1 Introduction....118
5.2 Building energy performance 119
5.3 Classroom scheduling....123
5.3.1 Understanding the schedule overlap plot 123
5.3.2 Utilisation overview 124
5.3.3 Utilisation and dependent consumer demands....131
5.3.4 Lighting and net energy demand....142
5.3.5 Heating management....144
5.4 Retrofit results....148
5.4.1 Non-domestic building service compliance guide VS R-BMS heating management retrofit analysis....148
5.4.2 HVAC heat source and BMS retrofits....152
5.4.3 Constant-efficacy lighting retrofits 155
5.5 Conclusion....158
6 Chapter 6 - Discussion 159
6.1 Introduction....159

6.2 Occupancy’s role in observed performance 160
6.3 Experimentation results 161
6.3.1 Heating system retrofitting and Schedule-Climate scenarios....161
6.3.2 Effect of scheduling on simulated performance and legislated commitments 161
6.3.3 Effect of climate 162
6.3.4 Nondomestic building service compliance guide BMS, operation/simulation calibration and BMS retrofit analysis 164
6.4 Behaviours, devices and wasteful consumption 164
6.5 Occupants 166
6.5.1 Occupant ontology 168
6.5.2 Occupants in the real and simulated worlds 175
6.5.3 Key differences between real and virtual occupants....177
6.6 Needs 179
6.6.1 Do needs have the same servicing demands for mixed occupant roles? 181
6.6.2 Needs as a performance metric 183
6.7 Conclusion 184
7 Chapter 7 - Conclusion 186
7.1 Introduction 186
7.2 Were objectives met? 186
7.3 Contributions to the existing body of research....188
7.4 Recommendations for reducing the performance gaps and optimising decision-making 189
7.4.1 In lieu of reliable utilisation data, simulate poor utilisation scenarios during design and decision-making 190
7.4.2 Start measuring performance as a measure of needs....190
7.4.3 Prioritise building management systems over active service replacements....191
7.4.4 Nomadic occupant planning strategy 191
7.5 Future research 191
7.5.1 Needs as an efficiency metric 192
7.5.2 Occupant taxonomy 194
7.5.3 Absent (ghost) agents....194
7.5.4 Pseudo agents (computers and servicing equipment)....195
7.5.5 External interference....196
7.5.6 Dyadic vs social intimacy in relation to adaptive measure adoption 197
7.5.7 Artificial intelligence 197

7.5.8 Heat recovery (Partial district heating networks) 198
7.5.9 General (Strategic planning and marginal value estimation) 199
7.6 Limitations 200
7.7 Closing remarks 201
Bibliography 203

1 Chapter 1 - Introduction

1.1 Background of the study

During design and retrofit decision-making, designers and analysts have to make decisions based on the background knowledge of the built environment that they have developed over their careers and the results of building energy modelling. However, the former to no discredit of the professionals is a belief system built upon observations from simulations building energy model assumptions. Rastogi (2016) demonstrated in a similar vein to this thesis' focus on occupancy that design and retrofit package development cannot reliably be made using historical climate data. He demonstrated that under different probable climates, the realised building performance is sensitive to climate, to the point where decision-making should no longer be considered an optimisation challenge. Instead, Rastogi suggested that decision-making needs to include assessment of climate robustness. The goal should not be to make decisions which are optimal for the virtual world or a historical climate, but rather decisions which hold up under uncertainty. Operational phase utilisation is not entirely akin to climate concerns as there is a level of determinism in utilisation. While it may not be guaranteed to be consistent for all nondomestic buildings, it at worst has medium-term stability. At best registered historical and planned utilisation.

Janda (2011) discusses the role of education in reducing energy consumption and that occupants' roles with buildings need to be better understood. Summarised by the author as "buildings do not use energy: people do". This paper continues to suggest that a new role of educator may be required to realise built environment efficiency targets. It also makes the salient point that behavioural changes can contribute to greater savings from technological and architectural solutions. They are important observations; however, the paper's focus on behaviours is not entirely encompassing of energy consumption in nondomestic buildings. Unlike residential buildings, nondomestic energy consumption is a second-order interest of the owner, and its utility has an explicit function. It is an important distinction from residential as it reframes energy consumption as meeting the needs of the utilising occupants. Therefore, Janda's summary might first be altered to be framed around "the needs of people do" defining the consumption as having utility and purpose. However, buildings and retrofit design relies on faith that real and simulated utilisation are similar. The latter is often a reasonable assumption though insufficiently represented in design schedules and not necessarily true within certain building types, such as higher education facilities or space-as-a-service letting with 24-hour access. This reliance on presumption and stochasticism are inherently a belief system that is not likely accurate in for low utilisation buildings. These suggest another meaningful extension to accommodate the underlying belief system ingrained in building energy modelling. Considering both amendments, buildings do not consume energy: belief that needs exist to be met does may be a more encompassing statement.

Depending on the function of the building and operating principles, the presumption of presence often viewed as the main source of deviation, rather than the real problem itself. However, divergence from design utilisation patterns is considered by many to be the primary factor in buildings' failure to meet an expected performance (T. Hong *et al.*, 2016; Kneifel *et al.*, 2016; Ridley *et al.*, 2014). Therefore, it is very relevant to higher education facilities, which in the UK have average utilisation rates of 27% (Space Management Group, 2008) and space-as-a-service buildings.

In the case of the latter for example, the Inovo Building in Glasgow owned by the University of Strathclyde is conditioned for twenty-four hours a day and seven days a week, despite typically having a near-zero presence for 12 hours per day. The Inovo building's design schedule is unknown, and it is new. Therefore the building is not likely to undergo retrofit for some time. When a building is older or subject to retrofit, the design occupancy schedules will not coincide with the operation. The divergence means during retrofit and design decision-making, there is the assumption that latent and other internal gains will assist or impede the air tempering system. Ostensibly, agents in that context may be considered employees of the designer or retrofit analyst in that they are expected to share or cause the burden of meeting tempering requirements. There are two important underlying beliefs in this. First, the burden is within an acceptable margin of error were the external conditions used in modelling consistent with the real-world climate. The belief can only be true if the design presence is accurate. Second, and more importantly, that the requirements (needs) exist. As a burden to cooling systems, chiller capacity must offset steady-state gains with consideration for latent and other internal gains. As a general observation, no matter how efficient a system is in design, it is still inefficient in the real world if it is meeting non-existent needs.

Utilisation's role in decision-making does not necessarily increase entropy on all fronts. Corgnati *et al.* (2017) note main active contributions to building energy demand, those that are not implicit of the mentioned belief systems, are adaptive comfort behaviours. Therefore, decreased utilisation though not necessarily mitigating occupants' behavioural contributions to energy consumption, the adaptive measure interaction frequency will decrease. Reduced frequency affects occupant density and the characteristics that, according to Tabak (2009), drive occupant behaviour. Naturally, this reduces the number of unforeseeable behaviours from interdependent services and systems. Behavioural entropy is considered a major challenge for energy consumption prediction which may relieve some concerns (T. Hong *et al.*, 2016; Oliveira-Lima *et al.*, 2016; Zani *et al.*, 2017). In terms of the building, performance gap occupant behaviours were proposed to be the single largest contributor by (Stoppel & Leite, 2014). However, this is a reduction in the solution space rather and therefore, not necessarily a reduction in an adaptive control state. Therefore, it is another belief system tied to one of the more important study areas of occupancy.

Density makes a notable contribution to psychological factors in comfort perceptions and therefore, the likelihood of adaptive behaviours. The perception of agency in adaptive measure control was observed to affect thermal comfort in occupants who were in some way proportional to density (Marcel Schweiker & Wagner, 2016; Yun, 2018). Similarly, H. Wang *et al.* (2018) observed a simple declaration of comfort levels by other occupants could affect perceived thermal comfort, which is inherently bound to psychological distality between agents. In longer terms, adaptation level theory as discussed by Tabak (2009) affects the resting comfort levels for individual occupants. It is inferable from Tabak and implicit of the others that density adaptive and subsequent indirect actions frequency and psychological malleability are correlated with and negatively correlated with density, respectively.

Occupancy in energy modelling puts significant focus on occupants' as components of a closed system mechanically but models rarely if ever consider the drives and interests that lead to their interactions. Occupants are never comparable in the real-world. Whether that be in their own eyes, those of their colleagues in isolation or as collectives or the people who drive their presence, yet designers do not commonly consider these characteristics. Ethically, all needs are equally deserving of being met, but this idealism is neither realistic of human or corporate interests nor feasibly integrated into the design. Even in the eyes of cohabitants the right to comfort or access or relevance to social cohesion in collectives are not guaranteed to be equal. In practical terms, do ancillary staff spending thirty minutes in a stock trading room sparsely have the same right to the same environmental conditions as the standard occupants? Are their needs remotely similar to the primary occupants' and does meeting their needs align with the second-order interests or social personas of occupants who control the environmental conditions.

These are important questions because they create a separation of the individual's needs and intentions from the building services, decoupling occupants from the assumptions of designer and introducing occupant-/energy-ignorant pragmatism and fallibility. Even in contexts such as research in wellbeing effects of retrofitting such as (Juslén & Tenner, 2005; J. A. Veitch & Newsham, 1998) of lighting are ancillary agents ignored. That is not to say they are meaningfully relevant to simulation or decision-making, but they are nonetheless occupants of retrofitted spaces and part of the buildings' socioecological system. In short: while energy consumption strategy is bound to the concept of an occupant, the concepts of a person and operating entity or the nonphysical drivers embodied in their agent representations are not truly compatible with that concept.

The separation of real and virtual occupants is more prevalent in modelling situations than others. In the compliance-led analysis, occupants exist as they are defined as they are in earlier literature "thermal disturbances". They exist to change the thermal state of the building and give purpose to the results, but they are not representative of the real building, purely inefficiencies of the mechanical system. In design and more complex analyses, simulations are calibrated with scheduling methods better aligned with the building's intended use. Accommodations for stochastic nature of utilisation through a novel application of Markov-chains, agent-based models and Random walks replaced standard occupancy schedules. Agent-based modelling introduced greater complexity to building energy modelling. These models represent occupants as individual agents with consumer traits and in some cases, include quasi-social interactions between agents. Occupant wellbeing models have been gaining popularity over recent years considering, interestingly, introducing a more human-centric approach to assessing needs. These presence and needs scheduling philosophies demonstrate progression towards adapting occupant models for human and corporate factors of energy consumption. However, they still frame agents exclusively as components of the space they reside.

Rastogi (2016) demonstrates the uncertainty building sensitivity to climate and reaches the same conclusion that designs should be robust to uncertainty rather than optimal in simulated environments. Occupancy is no different. Through better scheduling and reducing the needs expectations gap will reduce the performance gap and improve operational efficiency. However, scheduling in either real or virtual worlds is to the problems associated with the individual building in the respective world. It is not buildings or people who consume energy but their needs which are not comparable and are independent. Additionally, they are not able to be met with equal effort and if we are honest, treated as equally deserving of being met. In order to design or retrofit buildings with stable performance, the industry must break away from considering occupants merely a set of quantifiable values. Generally, few entities or actions can or should be translated literally into virtual environments. A human counting objects in a virtual room, for example, would use their eyes where the virtual world would reference the entity database.

1.2 Purpose of the study

Retrofit decision-making relies on building energy modelling, which is sensitive to operation and climate (Schedule-Climate). This relationship can change the way the building service interactions of the building and occupants contribute to calculated consumption with simulated energy behaviours as operational presence diverges from design. Without investigating the effect of Schedule-Climates on retrofit options’ energy and monetary savings, any chosen package in conflict with real-world performance. It creates a simulation behaviour gap which changes the consumers' consumption profiles unpredictably, which requires building service schedule calibration to mitigate. Decision-makers cannot rely on standard schedules correlating with real-world and should design for utilisation resilience where no registered occupancy is available. This thesis intends to demonstrate the importance of introducing real-world occupancy schedules to low utilisation building energy models. It also aims to demonstrate why real-world occupancy's absence results in simulation and performance gaps. Using real-world schedules will demonstrate how divergence to real from simulated Schedules cause energy consumption to be counterintuitive standard Schedule simulated performance. Additionally, exploring how the Schedule-Climate scenario's effects retrofit package cost-effectiveness. It will also demonstrate why a gap between expected and realised needs is the source of the problem.

A second drive for this thesis is to frame needs as the primary consumer of buildings rather than the buildings themselves or the occupants. Even in the purely numerical context of simulation, nondomestic building occupants do not mindlessly consume energy. Furthermore, service installations are designed to meet needs which are presumed to be present. These services are not guaranteed to ideally fit the needs of the occupants or hold value under operational conditions. Furthermore, using thermal comfort as an example, the needs of one agent or type of agent are not equal to those of another regardless of equality of preferences. This thesis also explores needs' role in energy demand and considers where existing models and design philosophies fail to represent the real-world. Using the observations, it offers potential remedies for the resulting issues.

1.3 Research gap and motivation for study

The UK's compliance-led energy efficiency assessment and retrofit decision-making criteria are ignorant of the real-world fixtures and building utilisation. England and Wales especially, use a standardised relative performance system where requirements are not based on absolute improvement but rather, simulated performance relative to a service-augmented variation of the building energy model. Regardless of the specific legislated requirements, the standardisation of occupancy schedules and service schedule binding inherently conflict with the intent of the legislation which can only be exacerbated as utilisation decreases. The problem extends to what is considered the occupied period with no accommodations for operation outwith design scheduling.

Embodied emissions have little representation in the legislation, certainly none for existing nondomestic buildings. However, they are fundamental to the realised emissions reduction from service lifecycles. As is discussed later in this thesis, no matter how efficient a new system is in technicality, it is still inefficient if it is rarely utilised. Similarly, utilisation of a service needlessly is still an inefficiency. Granted, if energy is going to be consumed wastefully a more efficient system is desirable, however, decisions based on manageable waste are inherently poor.

Gupta and Gregg (2016) hypothesise service management, namely heating, is an untapped solution to mitigating problems with the simulation gap and building inefficiencies, suggesting manual intervention by staff could be a solution. While they identify this problem, they did not find related literature nor a meaningful method of proving the concept. Rastogi (2016)'s work on climate sensitivity demonstrates why robustness of design under uncertainty is important which is an underlying premise of this thesis and numerous works have considered utilisation's effect on consumption. However, few attempts have been made to reconcile low utilisation and no previous works were identified which considered calibrating the simulation-based real-world presence.

The motivation for this study is bound to these complaints about the conflict between compliance-led decision-making and real-world building performance, including the NDBSCG retrofit modelling guidelines for heating systems. It sets out to demonstrate the severity of the conflict and fill and identify gaps in the literature which further impede the decision-making process. Existing compliance-led

1.4 Aim and Objectives

This thesis aims to demonstrate the simulation gap and therefore building performance gap resulting from use of standardised occupancy schedules and occupancy-bound servicing assumptions. It also aims to propose an extension to current agent ontologies such that occupants in the real world are comparable to those used in decision-making processes.

Objective 1: Carry out a critical analysis of the current literature surrounding occupant behaviours and the characteristics that drive their interactions with each other and buildings.

Objective 2: Develop a methodology for integrating real-world registration system data with EnergyPlus such that its effect on simulated performance may be considered. The framework will include a building management system (BMS) modelling feature which enables representing efficient conditioning system management.

Objective 3: Investigate the effect of managing the building's heating system with a BMS to and assess its relation to standard energy model behaviours and how performance metric match up against assumed presence rules.

Objective 4: Describe the characteristics of occupants which do not have prominent exploration in the literature and identify classifications which may have significance for future occupancy researchers. The objective includes production of an argument for why needs are a useful metric for measuring operational performance.

Objective 5: Describe the simulation results concerning building servicing energy consumption and occupant contributions to the perceived needs of utilised spaces. Doing so will demonstrate the extent to which heating management plays a role in shaping simulation results and whether it should be a precursor to retrofit analysis further.

1.5 Overview of research methodology

The research in this thesis required critical analysis of the literature, development of an integrated retrofit analysis environment, creation of retrofit application and cost methods for EnergyPlus, acquirement and translation of scheduling and construction data, and over 200 EnergyPlus simulations. The critical analysis is achieved by searching the literature based on keywords related to building physics, occupancy, psychology, biology and sociology. The literature was then collated into subsections considering each and their relation to one another. The retrofit analysis environment was designed and built are bespoke libraries and a common workspace structure. Data from the University of Strathclyde's Estates department was used to identify the characteristics of the case study building and formed the foundations of the base building energy model. A scheduling methodology is created for introducing real-world occupancy and extended to enable representation of a BMS system in EnergyPlus. Retrofit measures are designed by investigating the structure of the EnergyPlus IDF model and identifying which properties and objects represent the relevant building characteristics.

The integrated environment is used to generate the solution space for the retrofit packages and an additional set of constant-efficacy lighting retrofits. Results are interrogated using the discounted cash flow evaluation method and intermediary schedule data clustered using a library designed for another project. Finally, the results and literature review are used to discuss gaps in the literature and the significance of the simulation results in terms of simulation and performance gaps.

1.6 Scope of the study

The research presented in this thesis is not a historically validated end-to-end study. It exclusively integrates idealised registration system utilisation for teaching spaces in the case study building substituting individuals' physiological properties with NCM standards. The case study buildings and energy performance calculation results are exclusive as per the deterministic configurations for EnergyPlus. Where possible, building service information has been substituted in from the design schedules of retrofits. However, the design schedule sparsely contained details that were relevant to the dynamic simulation model.

The following list outlines the study limitations:

- Occupant sex distribution for each class: An ethics application was produced for this study. However, the controversial nature of utilising such information outweighed the value of its introduction to the model, especially given the idealised nature of the schedules.
- Idealised scheduling, student absence: The study does not consider absence from students in any form, including the midterm dip in density mentioned as feedback from a building physicist. This information is not consistently available across all departments and classes.

- Idealised scheduling, class cancellation: The study does not consider class cancellations.
- Use of standardised scheduling for office spaces: This study intends to focus on teaching spaces, and the university does not track the utilisation of office spaces. It may be possible to infer the Boolean state of occupant presence for these zones from the utilisation rate, the designation of spaces to staff and researchers and/or monitoring of lighting power states. However, this is neither relevant to the study, nor is it in the scope of the requirement for the degree.
- Meter reading validation: This research does not include verification of results via comparison to or calibration with meter readings from real-world operation. Though desirable, it is not necessary to demonstrate the significance of the results even with the previous caveats on idealised use of real-world regarding absence and cancellation. The difference in utilisation between standardised and recorded utilisation is demonstrably significant enough that no scenario exists where the schedules become comparable.
- Rastogi (2016) demonstrated how the unpredictability of climate changes could affect the performance of conditioning systems. He wrote an algorithm to probable future climates generator to demonstrate why robustness-led design is critical. However, this study is limited to two weather schedules.
- Ancillary occupants' schedules are discussed but not integrated with the Schedule-Climate scenarios. These would have some effect on results though its significance is low during the experiment, and it is not the primary focus of discussion on their contributions.
- Wellbeing is an emerging area of interest in commercial building operation where the ecosystem adapted with automatic and/or manual control measures to improve occupant comfort. While these considerations are important, feedback-controlled environment quality adaption is not readily supported. No lighting automatic lighting controls are present, heating system outlets have no central controls, and the glazing is inoperable. Therefore, wellbeing considerations are discussed in the literature review but absent during experimentation.

1.7 Structure of the thesis

This chapter describes the background and purpose of this study and what it aims to achieve. It outlines the aims and objectives that drove the research design and implementation. The chapter proceeds to summarise the research methodology in succinct terms to give the reader an idea of what they can expect from chapters three and onwards. It also sets the scope of the study in terms of which related features were omitted from the experimentation and offers justification for omission. It concludes by providing an overview of the remaining chapters of the thesis and what the reader can expect to find within them.

Chapter 2 explores the extant literature on occupants and related research from indirect research areas, including the characteristics that constitute being an occupant. It reviews psychological, physiological and social traits for affect occupants' relationship with the building they reside. It also questions whether some literature result misattribution. It includes an investigation into other factors of built environment performance gaps from national to building levels. Additionally, it considers reviews lifecycle emissions' contributions to the overall energy efficiency of buildings which is absent from legislative requirements though should be critical to design. Lifecycle emissions are important, particularly in mitigating the disingenuous attribution of 8% of emissions to cement, or 70% emissions to 100 companies. These are both true, but it is rarely noted that the emissions are not mindlessly activities nor are the emitters the consumers of the end product.

Chapter 3 describes the research methodology of this research used to meet the aims and objectives outlined in this chapter. It begins by outlining the characteristics of the literature considered for the critical analysis of the extant literature and why the primary focus was not on existing scheduling techniques. It proceeds with an overview of how the virtual case study data was translated and modelled into a form which was appropriate for the research and relatable to building energy performance legislation. A summary of the development process of the integrated retrofit analysis environment used for simulation and data interrogation. In the development subsection retrofit options and cost methods are described along with how the related data attainment. The chapter proceeds with an explanation of the scheduling data obtained from the university's Estates department and the features that led to the Schedule-Climate scenarios set. Where Schedule-Climate scenario is used to describe the Schedule source and strictness, the Climate used and the presence or absence of heating management. The chapter also touches on why an ethics application was created for physiological characteristics of the occupants but not pursued. The chapter concludes with an overview of the data analyses methods used to produce the results.

It also describes the philosophy behind the research discussing why the research, which is a form of positivism, may be considered logical positivism. The chapter proceeds to summarise the deductive nature of positivist research. A summary of what research strategy is and why the research fits the top-level category of quantitative research. It then describes the principle of research design for quantitative research and how this led to the classification of less common experimental classification of in-silico. It concludes with a logical justification for the in-silico classification

Chapter 4 describes in detail the case study building and the virtual case study model. The chapter provides an overview of the history of the building and the state of building regulations at the time of construction and the resulting poor envelope thermal performance. It proceeds to describe the process of converting the geometry from an IES model created for an EPC to a DesignBuilder model which is zoned appropriately for the scheduling methodology in this research. It proceeds with discussion on zone classification and how that is used to bind the NCM database to the EnergyPlus model, which is ignorant of the NCM at point of exporting from the interface. The following sections describe the building service systems present in the building and which are present in the building energy model. The chapter concludes with a summary of impetus for using multiple climates during experimentation as per findings from Rastogi (2016)'s doctoral thesis on building sensitivity to climate.

Chapter 5 presents the results from experimentation. In this chapter, the reader will find discussion on the overall building performance as-built under the different Schedule-Climate scenarios in terms of energy performance and operational costs. The section highlights inconsistencies between expected metric relationships based on standardised, high utilisation scheduling and real-world scheduling. It ends the section commenting on how real-world scheduling calibrates the energy model and how the absence of heating management results in inefficiencies that would be misattributed to inefficient systems during retrofit analysis. It proceeds with the most significant feature of this thesis, a breakdown of impact on the classroom scheduling on the standard and realised utilisation. In this discussion, the reader will find details on presence expectations, utilisation with the Space Management Group's utilisation function, disparity in heat gains from internal and external sources and discussion on lighting energy's relation with net energy demand. The section concludes with a discussion on heating management's effect on simulated results and business-as-usual running costs compared to the 2016 climate, NCM schedules Schedule-Climate scenario. This section will make it clear why Rastogi's work is so important and how this thesis integrates with his work. The chapter concludes with a discussion on the retrofit options considered changing the classification of heating management to a retrofit and a distinct methodology from the accepted heating efficiency credits method described in (Government, 2013). The results are used to demonstrate why the R-BMS modelling strategy is an important change to the current methodology. The section concludes with the presentation of 80 constant efficacy lighting retrofits grouped into 8 per Schedule-Climate scenario.

Chapter 6 explores the research from the literature review and experimentation stages. The chapter opens with a discussion on the experimentation results in terms of the literature and current retrofit analysis legislation. It demonstrates the relationship with the literature and supports the hypotheses about calibration and operational inefficiencies. The chapter proceeds with discussion on how occupants are currently classified and discussion on the disconnect between virtual and real occupants' roles and interactions with the building. Here the reader will find proposals for new classifications of occupants which fill gaps in the modelling process and may enable a more realistic and less ideological approach to assessing energy efficiency. The proceeding section discusses inequality in needs-based consumption, noting that the method of meeting the needs of one occupant role is not guaranteed to work for other roles. Additionally, debating if all needs deserve to be met. The chapter proceeds with some proposals for improving real-world operation, energy modelling, and evaluating energy efficiency in buildings before concluding with a summary of the findings from the literature review.

In the case of the latter, the reader will find discussion focused on the unpredictability of occupant behaviours and separation of psychological, physiological and social drivers for occupant behaviours.

Chapter 7 concludes the thesis with an outline of the thesis' contents and what research outcomes. It proceeds by describing the limitations of the research primarily that outwith the experimentation results the discussion topics were to complex to fit the scope of this thesis. The chapter continues to provide an extensive list of future research opportunities. The proceeding section summarises the fulfilment of the aims and objectives. The chapter concludes with closing remarks from the author and offers an amended version to Janda (2011)'s famous "buildings do not consume energy: people do".

2 Chapter 2 – Literature review

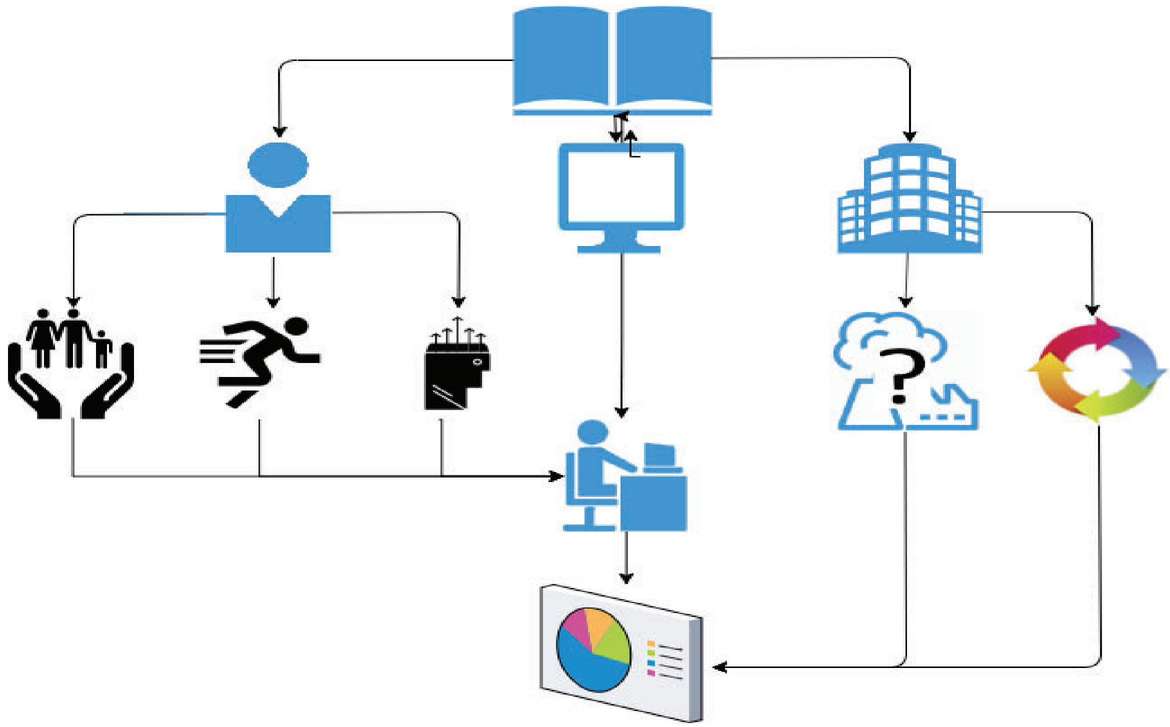


Figure 2-1 Literature review summary

2.1 Introduction

Building energy consumption is largely a function of the occupancy patterns except for ancillary emergency service maintenance services and parasitic consumption from other perpetual systems. It is the interactions with services and equipment, and in many cases, the presumption of presence that drives energy consumption. Understanding occupancy is fundamental to effective energy efficiency retrofitting where utilisation can define whether a measure is critical to operational performance or just an expensive checkbox exercise for compliance. University buildings, for example, have notably low utilisation (Space Management Group, 2008) which inherently conflict with generalised schedules. It may lead to situations where retrofit options seemingly ideal on paper are wholly redundant in operational contexts, and lighting retrofit savings cannot be realised. If the affected zones are only in use a small fraction of the assumed utilisation. Conversely, 50% of building energy consumption has been observed to occur during periods of inoccupancy (Gandhi & Brager, 2016; Gunay *et al.*, 2016).

In order to better understand how the challenges faced by in retrofitting strategy design, their implications and the crucial role occupants play in determining their success this chapter reviews several important areas of the literature to develop an understanding of the current state the built environment lifecycle performance. It proceeds with consideration for how occupants during design, renovation and operation contribute to the energy performance of buildings and how why the industry struggles to model their presence and absence accurately. It continues with the collation of the characteristics that define occupants and their interactions to determine where the existing literature falls short when designing agent-based modelling systems. Figure 2-1 outlines the structure of the literature review and its classification of the human, technological and built environment concepts. Human covering social, physical and psychological, technological covering social science in computing, and built environment, the uncertainty in existing nation-level reporting and lifecycle emissions.

The chapter begins by reviewing general building emission estimations in the United Kingdom (UK) and to a lesser extent, Europe (EU), discussing contention with the uncertainty and lack of consensus in the attribution of emissions to buildings. It proceeds with discussion on the significance of operational phase emissions before finally touching on consumption growth and legislative commitments in the UK. This chapter proceeds with an overview of embodied emissions hinting at the relationship between realised and expected retrofit environmental return on investment.

The chapter continues with discussion on how interior design may affect energy performance and occupant behaviour, how they relate to the way occupants interact with control measures and why interior design deserves greater focus from researchers looking at real-world energy efficiency. It begins with a discussion on furniture mass and location before progressing on to how it relates to visual discomfort and adaptive thermal comfort. Finally, the discussion extends to the fringe area of colours and textures and discussing whether they merit greater consideration during design and retrofit strategy selection in both psychosocial and building physics contexts.

The proceeding section reviews the definition of an occupant in several contexts as outlined by the built environment research and attempts to fill the gaps through reference to research from other disciplines including psychology, physiology, sociology, ethics and neurology. Additionally, it aims to describe topics which are present in the literature but do not have disambiguated descriptions — specifically, adaption level theory's perceptual hypothesis in terms of first and second-order interests.

It then touches on probabilistic schedule techniques which have become popular over the last twenty years. First, it describes the most commonly used model also used in compliance modelling, standardised schedules followed by a summary of stochastic scheduling before ending with a summary of agent-based-modelling.

The chapter concludes with discussion on why computers should be considered a form of agent in agent-based models.

2.2 Energy efficiency and the built environment

In Europe, up to 80% of existing will still be in use in 2050. By then the European Commission expects to reduce carbon emissions by 90% of 1990 levels - 80% in the United Kingdom (A. Marshall *et al.*, 2017) through 90% reduction in building emissions - requiring retrofitting of 80% of useful floor space in the EU-27 countries (Vilches *et al.*, 2017). The target is monumental given existing stock's contribution and the relatively low introduction of new builds which will improve over time but are far from commonly net-zero in theory or practice. There are many interconnected challenges faced by industry professionals, including institutional, organisational, market and behavioural. However, given the necessity for vast retrofitting, they are all bound to the efficacy of actioned retrofits. Each option needs to be appropriate for the target building, which can be estimated through simulation but not proven. Therefore, confidence in the simulation model is paramount to the value of both pre-occupancy and post-occupancy evaluations of a given strategy in both new build design and retrofitting where the gap between theory and practice the building performance gap or energy performance gap has 30% estimated savings potential from closing (Corgnati *et al.*, 2017; Pelenur & Cruickshank, 2012) alone.

2.2.1 General contribution from buildings

Buildings contribute 30 – 45% of all primary energy consumption in developed countries (Z. Chen *et al.*, 2015; T. Hong *et al.*, 2017; Yan *et al.*, 2015) typically being referenced as closer to 35% - 40% for western nations. Roughly 20% attributed to non-domestic buildings. In terms of nondomestic building-related emissions, this equates to 12% to 19% of total energy industry emissions. In the United Kingdom variance in this estimation is dependent on the source of information with estimates typically between 17% to 19% (Department for Business\, 2017; Lawrence & Keime, 2016; Parker *et al.*, 2017). However, it appears that the government is not entirely reliable as a source. Committee on Climate Change (Committee on Climate Change, 2016) estimates that heating and hot water contribute 40% of the United Kingdom's energy consumption alone which is equivalent to their previous entire energy consumption estimates.

Interestingly, the literature for American non-domestic buildings suggests that its estimated emissions are the same as the United Kingdom's government estimate at 12% (Martani *et al.*, 2012). In the United Kingdom domestic energy consumption is estimated to contribute 29% of total energy consumption (E. Marshall *et al.*, 2016) which given the significant contribution to building energy consumption 60% to 70% suggests a greater dependence on direct fossil fuel consumption, speculated based on the government's carbon emissions conversion factors. On a broader scale, developed countries contribute an estimated 70% of global emissions (Wu *et al.*, 2017). However, it is worth noting that developing countries have increasing emissions intensity as industrialisation grows. Since an estimated 42% of these countries have no energy standards (Gobbi *et al.*, 2016), this will result in their contribution increasing until they legislate or incentives energy efficiency. In reaction to the significant contribution to energy consumption from buildings, the European Commissions has established a long-term commitment to reducing building sector emissions by 88% to 90% (Cecconi *et al.*, 2017). The target reduction seems unrealistic at least in the United Kingdom given existing building stock life expectation and poorly scoped minimum energy efficiency standards. Unless there is a massive shift to green energy, the target is not practical. It would be in the interest of European nations to research the practicalities of aiming for this target focusing on new build rate and their relationship with construction and servicing system innovations.

2.2.2 Significance of building operational phase emissions

Carbon emissions from buildings during the operation phase are estimated to contribute 30% to 45% of global annual anthropogenic carbon. In terms of greenhouse gas emissions, carbon emissions associated with buildings are estimated to contribute 19% of all anthropogenic emissions (Giesekam *et al.*, 2016). However, according to US Environmental Protection Agency greenhouse gas emission estimates, carbon emissions account for 65% of all anthropogenic greenhouse emission (United States Environmental Protection Agency, 2017) suggesting a level of disparity between estimations.

In the United Kingdom operational building phase carbon emissions are typically estimated to be between 30% and 37% of total annual emissions (Brady & Abdellatif, 2017; Brøgger & Wittchen, 2018; Committee for Climate Change, 2013; Department for Business\, 2017; HM Government, 2011). The term “typically” is cautiously used for these references as there is a worrying disparity between those and statistics published by the Department for Communities and Local Government (DCLG). DCLG estimates heating alone to contribute 40% of national carbon emissions contributions (DCLG, 2017a). However; Committee for Climate Change (2016). appear to remain consistent within the context of this statistic attributing 20% of national carbon emissions to heating and hot water Despite the heating estimate there seems to be more consensus when discussing subsection specific estimates suggesting between 12% and 19% for non-domestic buildings with lower estimates from the government and upper from the literature (Lawrence & Keime, 2016; Parker *et al.*, 2017), and lower estimates of 17% and upper of 27% (Hamza & Gilroy, 2011) for domestic. In terms of heating, the literature appears to support further the 20% estimate where 46% of UK final energy demand has been attributed to heating with 82% attributed to gas-fired systems (Chaudry *et al.*, 2015). A rough conversion using UK emissions factors, treating non-gas consumption as electric ignorant of in other fossil fuels, returns a rough supporting estimate between 17% and 21% based on (DCLG, 2013) and (BRE, 2013) respectively. Nonetheless, both literature and government bodies and departments stress the significance of building carbon emissions contributions to gross anthropogenic greenhouse gas emissions and the necessity for reductions.

2.2.3 Reporting uncertainty

Estimates seem to indicate a lack of consensus in contributions or calculation methodology. The source reputation and maturity of the field of study indicates that the disparity is likely epistemic rather than agnotological or a symptom of indolence. Kundzewicz *et al.* (2018) stress agnotology is an important consideration before utilising any climate data. Although part of the issue may be attributable to a need for retroactive word sense disambiguation (WSD) as superficially highlighted by(Arskey & O'Malley, 2005). Machine learning is being used in an attempt to rectify this issue but faces challenges of its own that may limit its effectiveness(McInnes & Stevenson, 2014).

The disconcerting aspect of the lack of consensus is that these estimates are the basis for justifying research significance. Although there is indisputable value and importance in reduces identified regardless of which bound is used in a study. It may suggest that cross-disciplinary assessment of environmental strategies can be subject to the similar issues discussed in pharmacology regarding significance testing (D'Errico, 2009). Additionally, broader concerns with reliability and uncertainty (Rocchetta *et al.*, 2018). In more dogmatic terms the adage "garbage in, garbage out" moderately applicable and is inherently has social and economic costs (R. Y. Wang, 1996) which is a strong case for scrutiny in the context of Low Carbon Economy 2050 abatement strategies put significant weight on building emissions reduction with specific focus on introduction of low carbon heat; although it is worth noting that in this instance the government attributed this aspect of the strategy based on the generally accepted emissions contribution estimate referencing 38% (HM Government, 2011).

2.2.4 Growth in consumption and emissions in the UK

Since 1997 UK buildings energy consumption has grown by 49% and emissions by 43% and the energy consumption is projected to grow by 34% in the next twenty years (Albadry *et al.*, 2017). Despite the growth from the building sector, the UK's overall electric consumption declined by 5.4% between 2000 and 2013 *(Kucukvar et al., 2017).* In contrast, overall energy consumption is expected to grow by 7% by 2050 (Dagoumas & Barker, 2010). While not the decrease envisaged by EU policy is a modest increase given that 40% of UK buildings that will exist in 2050 are yet to be built. Arguably, energy consumption is moot. Instead, focus show primarily on GHG emissions reduction; however, lifecycle emissions, including those outwith direct building emissions are likely somewhat proportional to energy consumption.

2.2.5 Legislated commitments

The UK has committed to reducing its national greenhouse gas contributions by 80% through domestic reductions compared to 1990 levels (E. Marshall *et al.*, 2016). Note: the paper appears to reference the Energy Act 2008 erroneously. The Climate Change Act 2008 Part 1, Section 1(1) ratified the commitment setting a preliminary target of 34% reduction by 2020 in Section5(1)(a) (UK Government, 2008) and introduced into secondary legislation in 2009. The CCC made recommendations for a 60% reduction by 2030 a decade ahead of the EU deadline of 2040, although neither of these targets has been introduced into national law (Climate Change Committee, 2010). While UK target dates are ambitious by comparison on EU 2050 Low Carbon Economy deadlines (European Commission, 2011), their overall ambitions are to meet the minimum reduction in contrast to other nations' commitment to 95%. The EU collectively reduced emissions on 1990 levels by 18% by 2012 and is said to be on target to meet its 2050 targets (Pacheco-Torgal, 2017). However, the same cannot be said for its commitment to increase renewable energy generation by 20% nor its energy consumption reduction targets. However, even with met targets, it must be noted that capacity and production differ making renewables less secure than they appear on the surface. In contrast, overproduction may be balanced. There are novel technologies such as green gas generation from power-to-gas systems which have applications in both heating in the built environment and fuel in the transport sector (P. Lee *et al.*, 2018).

2.3 Retrofitting and building lifecycle emissions

This section discusses strategies and impacts of operational phase retrofitting and trade-offs with lifecycle emissions from the whole building lifecycle.

2.3.1 UK efficiency policy and operational phase retrofitting

Higher energy efficiency is pertinent to achieving EU low carbon economy 2050 performance targets and is considered a "win-win" option encompassing economic growth and public health wellbeing (Pacheco-Torgal, 2017). The UK economy has estimated potential to grow by 0.2% through the introduction of 71,000 jobs in the field of retrofitting. In broader terms, it will reduce energy poverty in residential buildings which will improve occupant wellbeing in all buildings and significantly reduce health service demand. However, it is primarily an indirect contributor to occupant wellbeing and uncertainty in occupant behaviour modelling. That is, this research aims to improve the accuracy of occupancy modelling, and by reducing known epistemic uncertainty which will either improve operational behaviours or at least identify the next modelling challenges.

The EPBD sets out a set of legislative agreements which have been implemented across the EU that describe the process of improving existing building stock and developing new stock. In terms of retrofitting, Article 4 requires the government to define minimum energy efficiency targets for both new and existing buildings. In England, Wales and Northern Ireland these are in the form of the Private Rented Sector Minimum Energy Efficiency Standards (U. Government., 2018)which is essentially a constraint on (from April 2018) to update or re-lease a commercial property or discrete space within and (from April 2023) to continue to lease a property, where the energy performance is modelled at worse than an E rating as per the Simplified Building Energy Model unless the building meets one of a few exemption criteria; namely these criteria are either economic infeasibility of retrofit options or the loss of value that would result from implementing a retrofit.

In Scotland, buildings which do not meet a target based on Section 63 amendments to the SBEM calculation must undergo a set of cost-effective retrofits as set out in Section 63 or one or more which achieve the same or better improvement than the improvement from the applicable prescribed measures. Scotland's Section 63 (S. Government., 2018) is by far an inferior model which results in marginal improvements over MEES however, Scotland's rating system is stricter than that in the rest of the UK. Article 4 requirements also apply to existing buildings where a renovation changes the floor space or increases load on the heating and/or comfort cooling system as outlined in Article 6 and discussed in Part L2B However, the not all the consequential improvements listed in L2B made it into the requirements for cost-effective improvements under the National Calculation

Methodology which is effectively the parent policy of SBEM and rdSAP for residential properties.

The UK's implementation considers simulated emissions exclusive of those from small equipment. Display energy certification were considered which are the operational equivalent, however, they didn't make it into MEES requirements. This appears to be a significant failing in the EPBD implementation given that up to 50% of energy consumption is attributed to small equipment (Gandhi & Brager, 2016; Gunay *et al.*, 2016). 75% of which has been observed to occur during inoccupancy (Gunay *et al.*, 2016). Combined, small equipment and lighting consumption during inoccupancy has been observed to contribute 50% of all building energy demand (Zhao *et al.*, 2014). However, it is worth noting that while SBEM typically attributes around 40% to lighting, the literature observes only 13% to 30% in the literature and the results section of this thesis demonstrate inconsistencies in the definition of occupancy periods. There is significant conflict between operational and SBEM-simulated consumption in that whilst operational is both more relevant and heavily weighted toward inoccupancy consumption, SBEM-based modelling is fraught with the use of defaults and templates which significantly reduces simulation performance. For example, offices, industrial and storage buildings constructed post-2002 would be required to have a lighting efficacy of greater than 40lm/cW (DCLG, 2002). However, template values for CFL, T8 and LED (until SBEM 5.4.b) are 27lm/cW, 30lm/cW and 33lm/cW, respectively, LED is now 50lm/cW (DCLG, 2015). That is, the best lighting template was the lowest permissible efficacy for top-lit activities. In contrast, some required efficiency values are conservative unless supported by an accredited AEC professional's assurance that a greater performance can be achieved such as 0.55W/m² U-Value for cavity wall insulation.

*The following paragraph is a summary is from a PGCert module "Environmental Economics" accepted submission based on the arbnco SBEM database in the arbnConsult platform-as-a-solution.

Nondomestic buildings contribute 18%~ of the UK's carbon emissions with 11 percentage points contributed by the retail sector (Lawrence & Keime, 2016; Parker *et al.*, 2017). Two-thirds of the retail sector is privately rented or 8 percentage points. The SBEM calculation deals exclusively with regulated consumer demand not accounting for I.T equipment, freezers, televisions and other unregulated loads. It is a significant omission since these contribute around 43% of non-domestic operational demand, which leaves 3.44 percentage points. Finally, around 10 – 14% of non-domestic lettable areas are at risk as estimated by the estate performance estimates from arbnco, British Property Federation Retail Therapy event presentation (CO2 Estates, 2013). This further reduced the scope of the non-domestic, private rented sector MEES to around 1 percentage point before considering reductions for the A – E band emissions of the non-compliant F and G rated sites. The sample-set used in this paper necessitates a 30% in index points across non-complaint sites suggesting that this policy emissions reduction in the range of 0.3 – 0.75 percentage points.

UK policies are based on cost-effective retrofitting rather than cost-optimal, which is debatably another failing of the Article 4 implementation. Cost-effective looks for the greatest ratio of cost to return on investment which in the case of MEES is constrained by a net present value greater than zero at year seven. However, it does not consider the lifecycle implications of the retrofit, as does cost-optimal retrofitting (Shaikh *et al.*, 2017). It is particularly a problem when determining whether to retrofit with LED or T5 lighting. In terms of cost-effective retrofitting T5s are cheaper and can achieve similar efficacies as LED. However, LED lifespans can be four times greater than T5s. Additionally, LED lamps have been observed to mimic better the therapeutic qualities of daylight, resulting in wellbeing and productivity returns not achievable from other forms of lamp. Finally, LED has the potential for future technology integration in the form of Li-FI communications through instantaneous state transition capability allowing data transfer through the lighting at practically no additional energy cost (Neves, 2016). In contrast, LEDs have significantly higher embodied emissions than other lamps suggesting that low utilisation may negate the benefits of selecting them over T5s.

In theme with this thesis, one of the main challenges for building owners in choosing optimal or efficient retrofit strategies is risk assessment. Occupant behaviours, presence and practices in managing inoccupancy consumption play a significant role as does weather and even secondary functions of retrofit measures (Shaikh *et al.*, 2017). Climate is also a significant determinate of the quality of a retrofit strategy changing climate will affect a given strategy's annual impact over time. For example, according to Keeran Jugdoyal of Carbon+Sustainability Services, the UK saw a 15% drop in building-related carbon emissions between 2014 and 2015 due to reduced heating demand from a warmer winter (Carbon+Sustainability, 2017). His claim is in no way handled by compliance-based simulation, yet it has a significant effect on heating and thermal insulation retrofit strategy efficiency. However, it is supporting of Rastogi (2016)'s research on building sensitivity to climate.

Eliopoulou and Mantziou (2017) discuss non-energy benefits from architectural energy retrofits which are intertwined with the operation, utilisation and behavioural efficiencies. While these types of benefits should be an important part of the decision-making process, they are not explicitly represented in compliance-based modelling. Take external or internal insulation, for example. Hahm *et al.* (2017) storefront design to be one of the greatest drivers for pedestrian walking route choices. Therefore, external insulation may be an appealing option in contrast to say a remote office where there is little need to increase customer presence or value by effectively gentrifying the area. Similarly, internal insulation is not well suited to private rented sector properties as leases are often based on floor space; however, in public service buildings, this may not be an issue.

The answer as to which type of retrofit a building owner will likely differ depending on the type of industrial professional asked. Current practice typically seems to pass the responsibility on to building service engineers in the best case and worst-case level 4, non-domestic energy consultants which in the case of the former will likely have bias towards mechanical systems and in the case of the latter, a selection based on a magic 8 ball or equivalent low-effort dice roll (this seemingly unfairly assessment of compliance assessors is more tactfully expressed by Strachan (2013) when noting that BREEAM consultants are likewise low fees, are underutilised and the process often turns into a checkbox exercise. However, BREEAM consultants necessitate credibility not required of NDEA assessors). However, an architect may lean towards architectural energy retrofit strategies which encompass the application of novel architectural concepts which have a greater focus on non-energy benefits as discussed in (Eliopoulou & Mantziou, 2017).

Interestingly, in her PhD thesis, Strachan (2013) through interviews with established industry professionals, identifies consensus there is a need for a new retrofit strategy professional.

An alternative to relying on retrofitting existing stock which, due to policy, will not likely get the attention it deserves is reduction through education. Described by Anna Laura Pisello and Asdrubali (2014) as human-led retrofits, occupant awareness of the impact of wasteful lighting and small equipment consumption, and exposure to efficiency-related information can result in up to 14% reduction in consumption. This gap is often referred to as the performance gap. Therefore, it seems logical to suggest that training occupants how to use buildings properly and energy consciously is a potentially massive opportunity for improving energy efficiency in all buildings, not just that of interest to a given owner. In a similar theme to (Strachan, 2013), Ciriminna *et al.* (2016) suggest this is a top-down, cross-disciplinary challenge though their focus is on energy managers rather than a new holistic analysis as suggested by Strachan.

2.3.2 Lifecycle consumption and innovation trade-offs

It is estimated that 80% of building lifecycle energy occurs during the operational stage (Azar & Menassa, 2012). Several small scale studies suggest that the domain of this operational stage energy consumption ranges from 70% to 83% (Gustavsson *et al.*, 2010) and (X. Zhang & Wang, 2017). In both cases the variance may be attributed to the building type, country and construction material where in this case both were residential building In contrast, when the literature is approached with intent to review embodied emissions it becomes apparent that operational emissions estimates are most sensitive to geographic location and generally oversimplified to the point where they are meaningless even at regional level unless design factors are considered

Regional estimates for embodied emissions from several industry-leading institutions as collated in (Ibn-Mohammed *et al.*, 2013) based on 50 to 60-year lifecycles highlight the significant variance: United Kingdom: 37% to 68%, United States and Canada 11% to 50% in one estimate and 9% to 13% in another, Sweden 45% and Israel 60%. Furthering the issue with generalisation of lifecycle emissions but offering an insightful look at the potential for lifecycle emissions through careful selection of construction materials (Y.

Chen & Thomas Ng, 2016) reported up to 30% reduction. In collating average embodied emissions from sources outwith the previously referenced study, they identified a mixture of supporting and conflicting regional estimates for offices. Estimated average embodied emissions in the UK are 30% to 40%, which is slightly lower than previous estimates with lower variance and in the United States 10% to 45% which supports previously referenced estimates.

Through a qualitative investigation where they interviewed 12 construction industry experts, Y. Chen and Thomas Ng (2016) identified the main challenge in encouraging embodied emissions-aware material selection, perceptions of tools for green certification compliance assessment and a superficial but weighted consideration for the project stakeholders. They found that while interviewees unanimously agreed that lifecycle analysis is imperative to assess embodied emissions to understand better understand the lifecycle emissions there was mixed views on the relevance of embodied emissions in quantitative assessment of building lifecycles suggesting that the primary consideration should be operational emissions. Two-thirds felt that modelling tools for assessing green energy certification compliance were accurate. However, only half felt they were satisfactorily complex enough to account for the intricacies of embodied emissions assessment. Some of the literature disagrees with the consensus noting that there can be significant variance between design and actual embodied emissions (Pomponi & Moncaster, 2017) although it does support the necessity from more intricate calculation tools citing the Uk Green Building Council's recognition of the gap. Finally, they suggest that to reach the 20:80 ratio of embodied and operational emissions discussed previously in the work of (Azar & Menassa, 2012). there would need to be a 90% reduction in operational emissions through the adoption of renewable technologies. They conclude by acknowledging the potential for extended green rating tools to make embodied emissions relatable for stakeholders but accept that it is a demanding task assessing embodied emissions in comparison to operational.

Combined with the material industries' reluctance to provide necessary data on indirect material emissions can result in time expenditure that restricts the accessibility of green energy ratings for some building projects. An attempt to quantify the impact of retrofitting buildings in the domestic sector with renewable and high-efficiency technologies and high thermal performance envelope materials is discussed in (Seo *et al.*, 2017). Supporting the concerns about the European's commissions ambitious 88% reduction in emissions by 2050 they have identified that 80% to 90% of operational emissions going forward will be produced by existing buildings, attributing 60% to residential buildings. They have identified several significant opportunities for retrofitting domestic properties focusing on the Republic of Ireland. However, they have identified two areas of concern regarding implementation. As discussed previously with (Y. Chen & Thomas Ng, 2016)'s, the impact of embodied emissions is largely unknown due to the difficulty in obtaining manufacturing and transport data, implicitly supporting (Su *et al.*, 2017)'s work discussed in the proceeding section on the incorporating equipment innovation-aware maintenance contributions to embodied emissions calculations. Chen & Ng conclude the subject by highlighting q the fact that embodied emissions associated with retrofits may negate the achieved operational savings. These points are also discussed by (Ibn-Mohammed *et al.*, 2014). Both sources and brief reference to stakeholder decision-making raises a difficult to legitimately answer the question that will likely be answered subversively by property owners. Do they care about embodied emissions, especially considering existing building retrofits? Ibn-Mohammed *et al.* (2014) also mention the prevalence of demand-driven, mixed-mode ventilation. Demand-driven mechanical ventilation would be an effective solution to the belief-driven consumption discussed in this thesis for buildings in part ventilated mechanically.

Green concrete is receiving greater attention in contemporary literature (Liew *et al.*, 2017; Sivakrishna *et al.*, 2019) as is timber frame structures (Bukauskas *et al.*, 2019). There is opportunity along with the design and implementation of high-efficiency building service systems and high thermal performance material to be conscious of the embodied emissions under uncertain climate and utilisation. This would enable research into the relationship between construction and operational stage energy consumption encompassing material with low production and transport embodied emissions. This research opportunity could highlight the long-term benefits of distributing research funding between embodied and operational energy reduction projects. However, it may be more favourable to consider operational stage innovation where near-zero and carbon-negative building designs could potentially mitigate or negate embodied emissions. Accommodations for this type of research exist lifecycle analysis tool such as that proposed in (Su *et al.*, 2017) includes factors not discussed in this thesis including public and political weighting on the importance of green energy, and atmospheric composition.

Recent studies estimate end of life and disposal related emissions contribute between 5% and 7% making it comparatively negligible to lifecycle emissions (Gan *et al.*, 2017; X. Zhang & Wang, 2017). However, they make a separate observation that doesn't appear to be present in other literature beyond the new build discussion from (Y. Chen & Thomas Ng, 2016). Embodied emissions do not adjust for service and construction retrofitting which they estimate that their inclusion could increase their base estimate of embodied emissions from 17% to 28% depending on the extent of the retrofits in terms of their case studies.

2.4 Interior design preferences, building energy performance and occupant comfort

2.4.1 Furnishings and non-isothermal heat transfer

Interior design preferences can impact building lifecycle emissions, thermal comfort and energy use intensity since fixtures, furnishing and finishes affect the physical behaviours of buildings and their consumers. The research is necessarily sector-specific in many cases given there is a distinction between drives for purchases, commercial for non-domestic and hedonic or consumerism for domestic. There are several universally applicable studies varying in practicality for each sector. Furniture's impact on airflow (Horikiri *et al.*, 2015) is loosely represented in the literature, although it does not appear to be prominent. Consequences of furniture's thermal mass on heating and cooling loads (Raftery *et al.*, 2014b; Wolisz *et al.*, 2015) including layout specific analysis (Mustakallio *et al.*, 2017) has recently become an area of interest including discussion on its implications for simulation. While a relatively new subject for building energy simulation, internal layout and fixture selection will likely make a significant appearance in the literature of the forthcoming years as we work towards further reducing the building performance gap. The non-isothermal nature furnishing thermal mass, for example, may have slight to moderate effects on occupant behaviour cycles such as opening windows in the winter A non-isothermal mass near a window whether drawers or curtains may reduce the conductive element of heat loss resulting in longer open periods which in turn will affect the conductive heat transfer rate of mass within the room and the convective heat transfer rate of proximal masses (Li *et al.*, 2016).

Similarly, layout and active state of virtual insulation (curtains) can both affect the occupants' thermal sensation and preference, and the thermal performance of the room in question. A couple may share a couch which they can position freely. Seating is said to have three significant locations for positioning near the window, near the back wall and in front of the wet radiator. Near the window has best natural lighting, which may be the preference for the occupants but conversely may result in greater perceived thermal sensation during both winter and summer. According to Jeong *et al.* (2016), comfort needs may encourage wasteful heating consumption, especially if the windows are opened. Though again, this ties with behavioural cycles. Positioning the couch in front of the radiator is inherently a poor decision for building performance given the radiant and conductive heat transfers to the furniture rather than the surrounding environment (National Energy Foundation, 2019). Unpredictable effects from interior design are a problem for building energy simulations both in performance and comfort akin to the issue with waste heat from inefficient lighting systems. Though the heat is transferred directly to the environment, it is not readily available to the occupant; a point of contention between amongst the building science team at arbnco.

2.4.2 Lighting design, harvesting, controls and ergonomics

Lighting discussions are applicable to both domestic and non-domestic industries although discussions tend to focus on commercial considerations surrounding comfort-related productivity and energy efficiency (Juslén & Tenner, 2005; J. A. Veitch & Newsham, 1998), and psychological impacts of specific characteristics interestingly suggesting correlating discriminatory perceptions of designs and illuminance levels(G.-H. Lim *et al.*, 2017; Pierson *et al.*, 2017; J.A Veitch, 2001; Wardono & Soelami, 2016). Significant research has been carried out on daylight glare invariably yet often indirectly relatable to furniture layout(Y.-W. Lim *et al.*, 2012) (Dubois *et al.*, 2007; Hirning *et al.*, 2014; Huang & Menozzi, 2014). Discussions on surface reflectance from interior surfaces has made a recent entry into the literature (Farjami & Mohamedali, 2017a; Makaremi *et al.*, 2017) suggesting a necessity for updates to our simulation models and missing considerations for occupants' overall comfort. Abstract design concepts are arguably relevant since people's perceptions are susceptible to influence from various characteristics.

In a similar vein to the probability of computing devices' power state changing to off during inoccupancy, ergonomic considerations for task lighting can result in small but meaningful reductions in ambient lighting demand. Approximately, the change would be equivalent to the power required by the task lighting fixture where photoelectric controls were present, according to (G.-H. Lim *et al.*, 2017).

This is particularly interesting as it highlights the complexity of the relationship between general design, control measures and human behaviour. The savings would be not be realised without the existing design delegating task lighting to a designated fixture, the presence and dimming of photoelectric controls and a lesser extent the ergonomic convenience of tasking lighting controls (Juslén *et al.*, 2007). Noting the latter as less convenient as unlike the other two; it is not exclusively bound to the convenience factor of the control. The user's social relationships (McMichael & Shipworth, 2013) and environmental awareness factor into their likelihood of changing the task lighting power state upon returning to or leaving the task area. A final worthwhile observation on task lighting in factory settings is the impact of controllable task lighting level as highlighted by (Juslén *et al.*, 2007). They identify a weak but significant illuminance level and productivity in factory workers notably identifying an illuminance preference rather than control preference through the noting that dimming speed did not affect the selected illuminance, suggesting that the effect is not purely psychological as is observed with self-efficacy and thermal comfort. However, they note two factors that may blur their results. Firstly, the note that the installation of a new lighting system leads to the increased feeling of importance in the occupant and the Hawthorne effect, the feeling of being cared for and observed can lead to a performance improvement. Nonetheless, their results seemingly demonstrate the benefit of self-efficacy or autonomy. However, unlike thermal preference, it is perceived self-efficacy that is less significant than actual self-efficacy given the consistency in chosen lighting levels. This task lighting control study shows a conflict between energy efficiency and productivity where study participants selected higher levels of illuminance, which results in greater power consumption.

Balancing daylight harvesting, and glare discomfort provides a challenge encompassing technical, purpose, physiological, psychological and social characteristics. Pierson *et al.* (2017) collate literature from 1977 to publication covering the primary aspects of glare discomfort calculation which identifies beyond the seemingly obvious temporal considerations, some general characteristics less obvious relative glare to the occupant's previous environment and task intensity. They conclude by noting interesting psychophysiological characteristics such as cortical hyperexcitability. Perhaps one of the more relatable yet surprising features of discomfort glare perception is the attractiveness of the outdoor environment is occupants are more tolerant of glare where they see interest in their view (Tuaycharoen & Tregenza, 2007).

Tuaycharoen and Tregenza (2007) offer a hypothetical suggesting the impact of view attractiveness and how it may relate to overall harvested light where automated blinds are present noting reduction in view may negate some of the discomfort reduction that would be expected from changing the blinds state. However, although not discussed, this has implications on the value in photoelectric dimming measures, particularly in multi-orientation zones where glare index may significantly differ depending on the orientation of the envelope. Interestingly, following suit with other comfort characteristics, namely thermal comfort, exposure to glare in the environment the occupant has transitioned from affects discomfort though only seemingly only significant in the evening (Altomonte *et al.*, 2016). Finally, (Pierson *et al.*, 2017) identify a direct relation between somatic fatigue in the morning and post-lunch afternoon and discomfort which they interestingly discuss as correlating with caffeine intake. The correlation perhaps indicates the significance of psychophysiological aspects of discomfort. It presents an opportunity for a similar study to M. Schweiker *et al.* (2016)'s study on thermal preferences and sensation in relation to the big five psychological traits, namely neuroticism given self-reported fatigue is "linked genetically to personality,…" (Vassend *et al.*, 2018).

As. with other aspects of occupant comfort, the design parameters for improving visual comfort once in a sensible domain are determined from the occupants' perceived (subjective) comfort rather than the objective. There is a notable impact of perceived self-efficacy and autonomy homogeneity between measurement methods for differing forms of environmental comfort. Interestingly, however, (Tokura *et al.*, 1996) cited by (Pierson *et al.*, 2017) identify no link between visual discomfort and age or gender removing commonly relevant perception-based voting in comfort alluding to greater weight on shared physiological characteristics.

2.4.3 Colour and textures

The common theme from most literature being discussed in this thesis on occupants is the interconnected and subjective link between both the mercurial and steady self, comfort, energy efficiency and productivity. Colour and texture add yet another layer of complexity. They are particularly relevant when discussing occupants' perceptions of comfort where assorted colours invoke differing feelings, moods and affect the way ambient lighting appears on the surface (Haller, 2017; McKimm, 2017; Mikellides, 2017), the latter being present in CIBSE lighting design calculations. There is a verified relationship between colour effect temperature and thermal comfort, referred to as the hue-heat hypothesis (H. Wang *et al.*, 2018). Wang et al. identify contrasting research generally in favour of the hypothesis with a few contrasting studies suggesting insignificance or strictly intellectual (observed but not impacting) effects. However; their research seems to confirm what would be expected, occupants feel more comfortable with warm colours in cool environments and cool colours in warm environments. Perhaps more salient in terms of the subject's inclusion in this section of the thesis was how neutral colours were perceived where the emotional response or feeling associated with a given colour was said to affect the perception of temperature. Black, a depressing rarely used contrast, did not change the occupants' perception of temperature. However, white contrast and violet colours were said to arouse feelings akin to cool colours which they say may explain why white and purple were more satisfactory in warmer environments.

In terms of productivity and proneness to errors, one paper experimenting with offices coloured red, green and white observed greater productivity in zones which were not white, similarly noting that occupants in white zones were more prone to error (Kwallek & Lewis, 1990). However, they recognise that this may be a result of complacency from overexposure to white zones rather than benefits from the alternative colours themselves. They question whether the observed benefits of red zones would persist over time as the colour became less distracting. Another paper experimented with blue and red meeting rooms assessing social cohesion, wellbeing and productivity, observing no benefit from changing colours (de Boon *et al.*, 2013). However, unlike (Kwallek & Lewis, 1990)., de Boon *et al.* (2013) question whether the lack of observed differences is the result of the complexity of testing the hypothesis given the numerous other contributing factors and even if their participants answered honestly, seemingly maintaining their hypothesis has merit despite lack of support. However, they make one observation that may be of slight interest and supportive of their general theme for attributes monitored. The majority of those who said the colour was significant always preferred blue or the reference environment, never red. Although there is little literature beyond these articles directly from built environment journals, it does seem like the colour red was a point of contention in both cases even if participants in the first article were less prone to error and more productive. When combined with the hue-heat hypothesis research it seems there is still belief from the researchers of these two papers there is relevance and evidence to support at least energy performance improvement which maintains wellbeing can be achieved with colour and merits further research. The question is however, can the challenge of successfully isolating colours from other factors be achieved as (Kwallek & Lewis, 1990) suspect is the failing point of their research?

Two final noteworthy mentions stepping away from the social sciences towards building physics is a mention from (Farjami & Mohamedali, 2017b) of the benefits of cool colours and white contrast with smooth surfaces as a means of preventing absorption of solar radiation in interior surfaces which they state is one of the most profitable energy efficiency mechanisms involving rendering. In place of internal absorption, they place weight on night temperature management on external thermal mass and suggest even the application of phase change materials. In this section of the literature review, the importance of this paper shows both social science and building physics research are putting more consideration for interior design. The literature now considers colour and texture, which previously were primarily considered for lighting design considerations only. Secondly, lighting colour temperature has been identified to impact the occupant's perception of thermal comfort were cold and neutral colour temperatures observed to accommodate an increase of 1.25°C and 0.46°C, respectively (Golasi *et al.*, 2019). Though they acknowledge there may be bias resulting from environmental expectations and the PMV was developed using neutral colours their research demonstrates not only does lighting colour affect perception of temperature but may potentially be seasonally adjusted for comfort management.

2.5 Occupants

Every collection of people is diverse with its idiosyncrasies along with those of the individuals of which it is composed. This statement holds for building occupancy. Occupants predominantly make active contributions to the energy consumption and overall behaviours of buildings (Corgnati *et al.*, 2017) through interaction with service controls and adaptive comfort measures such as manipulating thermostats and windows, respectively. Their presence and contributions are all, but entirely stochastic guaranteeing no operational period will be the same and design criteria will rarely if ever be perfectly matched, though the significance of differences varies with activity and utilisation. In fact, discrepancies between actual and designed energy consumption can be as much as 30% in mixed-use buildings (Corgnati *et al.*, 2017).

A relative novel approach to occupancy modelling is agent-based modelling (ABM) which aims to simulate individual occupants beyond the oversimplified scheduling techniques commonly utilised in both steady-state and dynamic simulation models such as SBEM and common or compliance-orientated EnergyPlus modelling. ABM is considered to be capable of modelling the uncertainties of human interaction beyond the standard weighting approach and is claimed to be able to model real human behaviours (Raftery *et al.*, 2014a). Unfortunately, current models are relatively simple, typically failing to include agent characteristics beyond adaptive comfort. This section of the literature review aims to achieve two things. Firstly, it aims to outline what behaviours and characteristics are currently understood about agents and how they are documented and defined for simulation. Secondly, it aims to complement the previous interior design and proceeding computers as agents' section to extend the set of characteristics and observations commonly present in the occupancy literature. The themes covered include cultural, physiological, psychological, sociological and geographical nuances.

2.5.1 Behaviour

Occupant behaviour is inherently one of the most diverse research areas in building energy consumption modelling and assessment impact subject granularity encompassing international (Yoshino, 2013) national (Kucukvar *et al.*, 2017; E. Marshall *et al.*, 2016; Yamaguchi & Shimoda1, 2014), regional within the context of local climate (Oldewurtel *et al.*, 2012) and building-specific (Berg *et al.*, 2017) level environmental, sociological and economic impacts.

Behaviours play a significant part in occupants' impact on energy use intensity and their collective comfort (Guerra-Santin *et al.*, 2016; Liisberg *et al.*, 2016; Tagliabue *et al.*, 2016; Yousefi *et al.*, 2017). It is entirely stochastic and whilst moderately inferable thorough understanding of a given building's purpose and refined with presence and density data, it is considered a significant challenge for accurately predicting energy consumption (T. Hong *et al.*, 2016; Oliveira-Lima *et al.*, 2016; Zani *et al.*, 2017) and a leading influence on energy consumption and indoor environmental quality (T. Hong *et al.*, 2016; Mirakhorli & Dong, 2016; Tagliabue *et al.*, 2016). Stoppel and Leite (2014), referencing work from the author of the first computerised building energy model, suggest occupant behaviours could have a greater impact on energy performance than envelope thermal characteristics. Divergence from predicted and actual behavioural patterns has been attributed as a primary factor in low energy buildings failing to meet expected performance (T. Hong *et al.*, 2016; Kneifel *et al.*, 2016; Ridley *et al.*, 2014). Occupant behaviours research is not exclusive to engineering and architecture with many studies in social science and psychology, medicine, environmental science and energy policy (Antoniadou & Papadopoulos, 2017).

The literature has shown a link between comfort and productivity, wellbeing and economic value (Al horr *et al.*, 2016; Geng *et al.*, 2017; Niemelä *et al.*, 2017; Shafaghat *et al.*, 2015;

Yun, 2018) in terms of economic value and health. Although there is less consensus in the literature with regards to this subject one observation is particularly notable, designers' opinions on the subject tends to be in contrast with the literature indicating a necessity for greater emphasis on psychological influence in AEC education. A subject more relevant to the research presented in this thesis is the link between socio-personal perception, energy efficiency and more broadly the general readiness of occupants for climate change (Felgueiras *et al.*, 2017; Klöckner & Nayum, 2017; A. L. Pisello *et al.*, 2017). Education also being discussed for industry professionals managing facilities as an individual leading through understanding staff and energy use (Ciriminna *et al.*, 2016). Finally, building-specific occupant education has been shown to have great potential for energy use intensity reduction (Berg *et al.*, 2017).

It helps to briefly discuss the obXML file format which was created as a standard framework for occupant behaviour representation in simulation software. It is defined by a four-element ontology, drivers, needs, actions and systems (DNAS) (T. Hong *et al.*, 2016). Drivers are said to be the triggering factors that provoke actions from the occupant or at least the desire to act. Needs are the psychophysiological criteria required for occupants to feel comfortable within the indoor environment. Actions are the results of triggering from drives which involve the occupant interacting with active and/or passive control measures within the environment. Moreover, systems are those control measures, thermostats, windows etc. An example of this ontology's application could be: The occupant must be able to see in an unlit zone (need) therefore they are driven (drive) to engage (action) with the lighting control (system). Drivers are defined by six characteristics, time, environment, event type, habit, spatial and other. Time is the temporal component; the environment is the zonal attributes divided into sub-elements for environment characteristics such as IAQ or illuminance.

The events type covers occupant actions such as going to or waking up from, sleep. Habits are personal vices such as smoking or drinking coffee. Spatial refers to the classification of the environment, residential or office for example. Finally, other constraints cover miscellaneous attributes including the state of having occupants. Physical needs are simply parameter ranges for indoor environmental quality boundaries whereas psychological needs encompass less quantitative characteristics such as privacy. Actions are effectively the equations that define the triggered events from drivers and systems are self-explanatory. Definitions paraphrased from the obXML documentation (T. Hong).

Behaviours can arguably be split into two primary categories, functional and adaptive. The former being related to first-order interests such as maintaining personal happiness through consumerism or relaxation and second-order interests. The latter being inter(A)ctions with control (S)ystems to meet your (N)eeds (D)riven by the state of environmental factors. Referring to the luminaire factory article referenced in the controllable task lighting discussion earlier. A functional behaviour of the occupant is manufacturing luminaires in response to their needs and the adaptive measure is adjusting the task lighting illuminance. Unlike functional behaviours, however, adaptive behaviours can be first or second-order i.e., for one's comfort or for meeting the requirements of the employer. This distinction seems important where adaptive measures optional. For example, thermal comfort can be regulated through clothing insulation changes, changing opening states or changing HVAC settings. In contrast, legislated constraints may not be ignored. Occupants must wear protective footwear in a certain zone, for example. Therefore, it may be helpful to think of second-order adaptive behaviours as constraints and first-order as options.

In terms of long-term adaption, Tabak (2009) suggests there are two adaption types, perceptual and behavioural. Perceptual adaption is effectively considered the application adaptation level theory, the longer an animal is exposed to an environmental characteristic extremity the less they perceive it as extreme. Behavioural is considered habitual, described by Tabak as manipulating the physical environment to reduce unwanted stimuli. Manipulations such as rotating a desk to escape glare or desaturating themselves from external audio stimuli by using headphones to introduce preferred stimuli. A seemingly yet understandably missing theme for the built environment literature regarding adaption is its metacognitive nature. Metacognition is how we decide which model we apply for a given problem, say adding clothing insulation vs adjusting the thermostat for example, before we then adjust the what can be effectively grouped as settings, wearing more or less clothing, higher or lower set point etc. Generalised metacognition is said to have three steps, monitoring for anomalies, assessing the response options and implementing (and monitoring for new anomalies) the chosen solution (Haidarian *et al.*, 2010).

Though it is a bit off-topic to discuss metacognition any further, it highlights a significant factor in behaviour modelling that we currently do not consider. It is not just the environmental conditions, activities and interactions that drive our adaption model selection, it' is a mixture of physical and psychological needs, social cohesion, socio-personal perceptions and a plethora of other characteristics that make up the populous. Additionally, the anomalies that arise from solution may require secondary adaption from either the occupant or other occupants. Opening a window may introduce noise pollution which is not necessarily a concern for the occupant opening the window but those closer to the opening or the draft may change the needs of another occupant such that they are driven to change their clothing insulation level. Although the literature does not cover this subject, it is implied from discussion on nonaction by occupants who are experiencing discomfort and do adapt through non-personal measures. They do so of other occupants being present who would be affected by adaptive measures. (Corgnati *et al.*, 2017). The point is that agents are should be and are of external agent and environmental needs that contribute to their metacognitive process of selecting and adaptive measure.

Tabak (2009) suggests there are four main attributes associated with activities, whether planned or unplanned. The frequency in which the event occurs, the duration of the event, the priority and the location. Depending on the event it may affect any number of systems within the environment, for example, using the printer affects small power consumption and slightly tempers the surrounding environment but unlike visiting the bathroom it does not require traversing zones and therefore does not have the potential of changing the temperature state between adjacent zones which are not adiabatic. Similarly, where lighting controls are present the latter may result in lighting consumption in a zone which is otherwise not illuminated and potentially the activation of extraction systems which persist for some time after the zone returns to a state of inoccupancy.

In summary: The existing literature covers many facets of behaviour in terms of its impact on building energy performance, occupants' wellbeing and productivity and economic value. Additionally, it makes great effort to scope the definition of an occupant, particularly in the case of Tabak (2009)'s work on user simulation of space. However, it seems to fall short when it comes to metacognitive activities and lacks categorisation of nth-order interests. It is unclear the extent to which current agent-based models can accommodate these features, but it seems the theme of personalisation of occupancy profiles from this thesis is not without merit.

2.5.2 Psychology

Perception of self-efficacy or environmental control has been shown to affect the thermal preference and sensation of occupants (Marcel Schweiker & Wagner, 2016; Yun, 2018). Higher levels of self-efficacy or perceived control were associated with greater tolerance for warmer environments with occupant higher neutral temperatures being observed to reduce cooling demand in buildings with air conditioning or comfort cooling where cooling set point was determined by observed neutral temperatures which in the case of Yun's study, increased from 24.3°C to 25.2°C. The same was shown to be true in residential building during winter with higher perceived control resulting in greater tolerance for indoor temperature, ultimately supporting the literature referenced by (Yun, 2018) that notes this effect to be "strictly" psychological. That is, the effect is observed without occupant interaction with the control measures. Another interesting secondary observation from Yun in non-domestic buildings was improved self-reported productivity correlating with perceived control which was statistically highly significant ($P = 0.001$). Supporting Yun's referenced literature observation of 6.3% higher self-reported productivity in occupants with higher perceived control. The secondary observation also identified higher self-reported productivity where there was no opportunity for control in contrast to having opportunity but having low perceived control, suggesting that perceived control is not negatively affected by the availability of control but rather the perceived control over those which are available.

Ultimately, perceived control was shown to have both energy-saving potential and potential to improve productivity (Marcel Schweiker & Wagner, 2016; Yun, 2018).

Perhaps more interesting than perceived self-efficacy, however. The effect of announcing the environment was warmer than expected was enough to make occupants feel warmer according to Höppe (unavailable) cited by (H. Wang *et al.*, 2018).

A recent study (M. Schweiker *et al.*, 2016) considers the impact of psychological traits and perceived self-efficacy on thermal comfort and interaction with environmental control mechanisms, namely, opening windows, closing blinds, adjusting clothing and interacting with ceiling fans. They investigated three of the big five personality traits, neuroticism, extraversion and openness to new experiences to assess how they may affect thermal sensation, likelihood to interact with environmental control measures such as windows and ceiling fans rather than exclusively passive clothing adjustment. They establish a correlation between traits and interactions with environments rejecting the null hypothesis that these have no impact. The following paragraph discusses their observations.

Neuroticism was observed to have a high impact on thermal preference and likelihood to interact with environmental control measures. Interestingly, they found little correlation between the trait and perceived thermal sensation. However, they did observe a higher thermal preference in highly neurotic occupants. The latter is particularly interesting given that neurotic people are more sensitive to stress but experience social anxiety which reduces the likelihood of them attempting to change the environment through control measure interactions, yet this was observed instead as a higher thermal preference rather than unwillingness to interact with measures. However, they were observed to have a higher interaction likelihood of opening windows in contrast to other measures such as blinds and ceiling fans, noted as likely a result of sticking to what they know. Unfortunately, this research did not consider other factors of indoor environmental quality, namely carbon emissions concentration.

Environmental quality may explain neurotic occupants' higher thermal preference and clothing level while interacting with windows. Extraversion not surprisingly was associated with greater likelihood of interacting with the environmental control measures including the passive clothing measure. Interestingly, introverts were less likely to interact with systems but more likely to focus on their perception of the environment thus sharing similar traits to highly neurotic occupants in terms of likelihood of interacting with control measures, however, in contrast, they were more sensitive to thermal sensation. Openness to new experiences was shown to have a significant impact on all forms of behaviour covered by the study. Unsurprisingly, those who had high levels of openness were more likely to interact with control measures. However, they were also more likely to have higher thermal preferences. They were also noted to have curiosity that accommodated greater flexibility in feeling comfortable with changes to the environment.

Perceived self-efficacy seems to be a common contributor to occupants' comfort as observed across each personality trait, the perception that they are in control of the environment. The observation seems to support previously discussed work by (Marcel Schweiker & Wagner, 2016; Yun, 2018) on perceived control and thermal sensation and preference. The features of determining and manipulating thermal comfort have been shown to be applicable to visual comfort in terms of personality traits and self-efficacy, albeit in the case of the latter it seems not strictly psychological in contrast to thermal comfort given the relatively consistent individual test subject preferred illuminance increase. The characteristics discussed in this section and those in the section discussing visual discomfort highlight similarities between the psychophysiological characteristics that affect environmental comfort. However, they show a necessity for more granular information on the environment's populous. Unfortunately, the populous will inherently change over time in unpredictable ways which begs the question of whether there is value in post-occupancy evaluation for building demographics of occupant characteristics which are considered intrusive.

Mood seems important or at least worth considering given (Altomonte *et al.*, 2016)'s inference that glare sensation increases with "better" moods in contrast to typical reduced environmental discomfort from positive characteristics, though they recognise a gap in their data makes this observation uncertain. Additionally, mood has been identified as a factor in clothing preferences according to Sinha *et al.* (2010) whose work while noted to have a small sample size alludes to mood's potential to affect thermal insulation levels in occupants. However, it should be noted that there was no correlation between the revealing nature and positive mood and thermal insulation was not discussed

2.5.3 Physiology

Occupants passively affect energy efficiency primarily related to thermodynamics and biological characteristics; they are often considered purely as thermal disturbances in indoor environments. Latent and sensible gains from occupants are discussed in CIBSE Guide A-2015 (CIBSE, 2015b) Chapter 6-2 which extends the discussion to include any animal in a given zone network, CIBSE AM11 (CIBSE, 2015a) makes reference to guide A in section 5.1 in conjunction with BS EN ISO 7730 when discussing design considerations HVAC loads. ASHRAE similarly published guidance discussing accommodating passive occupant effects in comfort calculations (ASHRAE, 2013) Given the uncertainty and epistemic concerns surrounding occupancy, calculations tend to use the predicted mean vote model to comfort considerations credited to P. O. Fanger AM11 although credited to (Korsgaard & Madsen, 1971, 1973) by Fanger (1973). Although less prevalent than is desirable, some research assesses sexual diversity in physical impact - and psychological perceptions (Elnakat & Gomez, 2015; Permana *et al.*, 2015) although off-topic statements suggest slight bias.

A paper published at the time of writing this (Beltrame, Villar*, et al.*, 2017) has identified different oxygen uptake rates are exhibited in each sex which subsequently will not yet have been considered in this regard. Metabolic CO2 is the second primary area of the physiological impact of occupants covered in (CIBSE, 2015b) 4.2.3 briefly reviewing BS 5925: 1991 emissions and dilution rates and ventilation requirements, Interestingly, noting an issue with monitoring levels shortly after occupancy due to the absence of sedentary CO2 exhalation. Another fascinating aspect of indoor air quality intrinsically linked is occupants' awareness; they have been reported to interaction with ventilation mechanisms in response to CO2 concentration (Ahn & Park, 2016; R. V. Andersen *et al.*, 2009; V. R. Andersen *et al.*, 2009; D'Oca & Hong, 2014; Lai *et al.*, 2009; Yan *et al.*, 2015).

The human body aims to maintain homeostasis responding to external stimuli with allostasis, the process of adjusting to achieve interdependent physical system stability. Indoor environmental quality (IEQ) affects the body's ability to achieve such balance and becomes more or less able to do so under poorer conditions. (Jimin Kim *et al.*, 2018), for example, found that experiment participants were unable to maintain homeostasis when the environment had high a concentration of CO_2. Failure to maintain this resulting in experiencing increased sensitivity to physiological changes resulting from changes in the IEQ. They conclude that poor IEQ can be “particularly dangerous” to hypertensive occupants – those with naturally high blood pressure. In contrast, they found that once CO_2 concentration was compliant with international standards (< 1000ppm) that sedentary activity was not significantly affected by changes. However, ASHRAE recommends levels no higher than 700ppm and according to (Y.-C. Chen & Hsiao, 2014) levels around and beyond 1000ppm cause breathing dysfunction. Other symptoms at >= 1000ppm according to Y.-C. Chen and Hsiao (2014) include suffering dizziness, sweating, disorientation, restlessness and not necessarily physiological but likely of more interest to employers, loss of productivity. They go further to note from the literature that classrooms with low air change rates have been observed to reduce attention, learning rate and memory. It is understood that higher concentration CO_2 results in increased respiratory activity and affects thermoregulation through metabolic rate, respiration and cardiovascular system changes.

Personal health is an understudied research area which is suspected to be due to the intrusive nature of considering the subject. There are a few studies on related subjects assessing Fanger’s PMV with blood pressure (Gilani *et al.*, 2016), and the link between health and thermal comfort in elderly people and indoor environmental quality(Ormandy & Ezratty, 2012). Outwith the occupancy and general building physics research work the impact of areas such as obesity can be loosely inferred from metabolic studies (Hosseini *et al.*, 2016). However, introducing medicine is opening Pandora’s box. While not in the scope of this thesis, there has been discussion on demand-driven ventilation in a recent research paper which highlights an interesting difference in male and female oxygen uptake (Beltrame, Rodrigo Villar*, et al.*, 2017). In conjunction with research on uptake decline through ageing (Hawkins & Wiswell, 2003) further demonstrating the complexity of indoor environmental quality management in relation to physiological and psychological characteristics. One final surprising observation further compounding biological diversity is the effect of medicated contraceptives and increased dryness of the eyes and sex differences in people’s ability to produce saliva (Stenberg & Wall, 1995).

2.5.4 Adaption level theory: Acclimatisation is not ethnicity

The relationship between ethnicity and geographic location has been considered in relation to perceived thermal comfort. Some research has suggested that ethnicity and thermal adaptivity play a crucial role in both contexts. These are potentially linked to environmental quality expectations (Fang *et al.*, 2018; Maiti, 2014; Mishra & Ramgopal, 2015). It is likely that ethnicity is erroneously being attributed or is linked to geographic location with a British study concluding that it plays no role in thermal comfort (S. H. Hong *et al.*, 2009) further supported by a physiology paper on vascular cooling (Maley *et al.*, 2014) which is purely quantitative. Geographic climate is better researched and appears to show significant differences in perceived comfort based on average outdoor climate (Duanmu *et al.*, 2017; Indraganti & Boussaa, 2017; Indraganti *et al.*, 2015; Lu *et al.*, 2018; Maiti, 2014). One paper may reconcile both ethnicity and geographic location suggesting the effect of acclimatisation on thermoregulation is significant (Fountain *et al.*, 1996). Acclimatisation seems to confirm support for adaptation level theory's perceptual component noted by Tabak (2009).

2.5.5 Gender and sex

Attempts have been made to reconcile the influence of demographic and biometric characteristics on the perception of environmental comfort, albeit sparsely in comparison to other areas of occupant research. Biological sex is becoming a hot topic for both energy efficiency(Carlsson-Kanyama & Lindén, 2007; Elnakat & Gomez, 2015; Pelenur & Cruickshank, 2012; Permana *et al.*, 2015) and thermal comfort (Indraganti *et al.*, 2015; Karjalainen, 2007; Nguyen *et al.*, 2012; Nico *et al.*, 2015; Schaudienst & Vogdt, 2017). Biological sex and gender could perhaps benefit from disambiguation in the literature. The term gender used interchangeably has been associated with notable differences in perceptions of IEQ, physiological and psychological attributes used in simulation and inherently social traits which are not well represented in the behaviour literature or current agent-based modelling. Women have a greater capacity to perceive thermal sensation and typically have a higher neutral temperature of around + 0.9 degree Celsius. They have also been observed to be 74% more likely to report dissatisfaction (Jungsoo Kim *et al.*, 2013). However, this is refuted by an earlier paper (Stenberg & Wall, 1995). Stenberg

& Wall additionally note that while women are generally more sensitive to IEQ, men are seemingly more sensitive to individual conditions.

Perhaps more interesting is women experienced sick building syndrome more than men, demonstrating that it is not entirely perceptual. This suggests that IEQ and psychosocial loads to an extent meaningfully and objectively differ between the sexes in terms of occupant wellbeing (Stenberg & Wall, 1995). This is an important observation as it shows that in contrast to much of the existing literature, greater emphasis on engendering non-thermal comfort is important and in line with this thesis' literature review, psychosocial attributes are an important consideration, that is, even if metacognition, as described previously, does not efficiently weigh in socio-personal attributes it may be worth adding focus to it in wellbeing education. Out-of-hours social characteristics were shown to have a meaningful impact on occupants' likelihood of sick building syndrome with some, chiefly marital status and number of children (Stenberg & Wall, 1995).

2.6 Occupancy profiling

Compliance modelling in the UK and many building energy simulations during design use standardised activity-classified schedules to define occupant presence and mechanical system demand. These schedules are not representative of real utilisation but rather generally representative of the building type. While understandably practical for compliance-based simulation, these fall short during the design stage and significantly contribute to the building performance gap. (Kordjamshidi, 2013) consider schedule accuracy to be the most significant feature of building energy simulation's relevance. This section briefly outlines two alternatives that have increased in popularity over the last two decades.

2.6.1 Overview

Where real-world information is available it should always supersede static parameters in occupancy and energy modelling in general (Akhondzada, 2017). However, real-world information is not always available or can be sparse. When this is the case for occupancy, it has been demonstrated extensively that statistical methods result in higher model accuracy.

According to Feng *et al.* (2015), there are four occupancy model levels ranging from building to agent. They suggest a 1st building aggregated occupant count similar to US-DOE's Asset Energy Score model, followed by Space-level and Boolean presence status akin to the SBEM model considering occupants in the same light as equipment, an energy/power density. The 3rd is space and occupant count which best aligns with conventional steady-state and dynamic simulation energy modelling using ASHRAE or NCM occupancy profiles. The 4th class may be best referred to as Agent-based modelling where individual occupants are modelled and tracked; however, the use of the term in this context is purely in relation to the knowledge of individual agents and not the tracking or probabilistic modelling methods. Depending on the context of the model, there is some overlap in their definitions. For example, they consider Yu (2010)'s research on genetic programming for predictive occupant behaviours which achieved 80% to 83% accuracy in the cases studies, to be level 2 since it pertains to a single space and utilisation can only be Boolean with one occupant. However, it is a matter of semantics as to whether this should be considered 2 or as it relates to the behaviours in a single occupant space. Arguably it has many features of their level 4 but it is predictive rather than presumptive. In terms of Feng *et al.* (2015)'s four utilisation model categories, this thesis sits somewhere between 3rd and 4th since it is partially aware of the agents utilising spaces but is deterministically scheduled at a level above the agents.

2.6.2 Utilisation vs simulation accuracy

(Akhondzada, 2017) discusses the three overarching forms for occupancy models, (Akhondzada, 2017) deterministic, probabilistic and stochastic noting from the literature they reviewed and their experimentation that deterministic methods for underperform compared to the others. These models might further be split into two categories, utilisation and behaviour. This distinction is important as it has philosophical on the definition of accuracy. (Z. Chen *et al.*, 2015), for example, designed an impressive stochastic model for generating schedules which was benchmarked on its ability to emulate operational utilisation. While it is better representative of utilisation, that does not necessarily mean it lessens a performance gap. Granted, it may lessen disparity between simulated and operational consumption under certain conditions, it is not necessarily improving prediction accuracy but rather introducing the imperfections that lead to simulated inefficiency. Imperfections and uncertainty are not interchangeable.

Consider the behavioural performance gap which (Corgnati *et al.*, 2017) suggest is up to 30% in mixed-use buildings. By introducing imperfections to occupancy, service and equipment schedules results higher simulated consumption as the model reacts to conditions it wasn't designed for. However, the gap isn't closed through mitigating epistemological barriers but rather, effectively changing a random yet tangibly linked set of values. That is not a discount of (Z. Chen *et al.*, 2015)'s work which is noteworthy, cautionary warning that getting utilisation closer to reality does not equate to closing a simulation or behavioural gap and while it does technically reduce a performance gap, it is not necessarily done so through holistically improving the model.

This can clearly be seen through (Akhondzada, 2017)'s presentation of occupation status and residential utilisation. Needless to say, their data shows that people who are unable to spend the afternoon at home due to work commitments do not often do so. Shifting context back to nondomestic buildings, consider the UK 2006 smoking ban. It cannot be demonstrated how the ban changed bar and restaurant utilisation. However, there is no demonstration needed to assert that by forcing occupants to leave the building to participate in a short activity the operation of entrances changes and therefore, average airtightness. All other things equal, the probabilistic or stochastic models may better mimic utilisation patterns, it is ignorant of behaviours, habitual or enforced.

However, this should not be taken as a true criticism of the models. They introduce decoupling of design and simulation schedules, and form the basis for the more complex agent-based models of the future. They also satisfy better satisfy the underlying concerns of this thesis and (Rastogi, 2016); the real-world and design assumptions are neither in alignment nor persistently inaccurate and therefore design conditions alone are not sufficient for design robustness. The comments in this section are also open to philosophical debate: is accuracy through obscured introduction of imperfection sufficient or is improved accuracy exclusively a function of reducing epistemological uncertainty?

2.6.3 Stochastic scheduling

Personalisation of schedules to individual buildings often involves a complementary stochastic generation method to real-world unpredictability. The process feeds in PrOE and/or POE data covering observations, generalisations and behavioural expectations, as model parameter constraints and localisations and produces appropriately granular probable schedules which better represent the building population than those which would be created through standardised or static input generators. Generally, for design-phase, modelling processes are built around some form of Markov model models (Jia *et al.*, 2017; Yang *et al.*, 2016) at varying temporal-contributory granularities shown to produce relatively accurate results under certain conditions. Alternative probabilistic methods have been employed in achieving similar accuracy. Current modelling technology is expanding into deep learning where researchers are working with Gaussian processes and neural networks, creating heuristic scheduling models which are ideal for operational phase modelling both compliance and control. There is debate in whether they should be included in design or compliance models with the latter including occupants in general given that even if the results appear better under test conditions, they're still not representative of the real building populous. Similarly, one paper questions if favoured stochastic models are necessary demonstrating application of random walks with sufficient accuracy.

2.6.4 Agent-based modelling

This modelling approach attempts to simulate the behaviours of real occupants by creating individual agents (occupants) that interact with the building, known as multi-agent-systems (T. Zhang *et al.*, 2011) . They attempt to identify the triggers (D) for behaviours and quantify the needs (N) or preceding action (A) which lead to the system (S) interaction behaviours of the individual. They tend to be constructed on a reasoned action model which encompasses some of the general observations from the behaviour section, presumed, control and socio-personal beliefs. That is, the belief that an action will change their perception such that their needs (N) are met, the belief that they have control over various measure to manipulate their perception of environmental conditions and the constraints they impose upon themselves based on how they want to be perceived by their peers behaviours (Raftery *et al.*, 2014a). T. Zhang *et al.* (2011) note the opportunity for models to incorporate additional non-agent features such as markets and societies. Typically, agent-based models focus on one significant criterion, in the case of (Y. S. Lee & Malkawi, 2014) this is agents' desire to achieve thermal comfort and in the case of (T. Zhang *et al.*, 2011), drives to interact with electrical equipment whilst maintaining thermal comfort. Though these are inherently separate components given the nature of their study. It is worth noting that though not treating equipment as agents, they create a similar taxonomy of small equipment to that of section 2.7 and treat non-ancillary equipment as more than Boolean-state power densities.

Agent-based models rely on a cost function for determining when a behaviour will occur. In the case of (Raftery *et al.*, 2014a) this function determines which behaviour is most likely to achieve the goal, referred to as goal-based agents. In contrast, (T. Zhang *et al.*, 2011) consider a personality parameter as a probability of the agent to carry out certain energy-conscious behaviours such as turning off a computer during absence from the workstation where higher ranking is associated with more energy consciousness, perhaps cynically from the perspective of this thesis, this should be considered a socio-personal attribute though it inherently a feature of self-identity.

In contrast to part of the discussion in the behaviour section. regarding metacognition, (T. Zhang *et al.*, 2011)'s model admittedly does introduce some of the reflective cognition claimed to be all but entirely absent from agent-based models in the form of learning outcomes. However, it falls short on the metacognitive decision-making beyond reactive learning. That is, whilst learning is achieved by viewing other agents' response to action in addition to how well the action achieved one's goal, it does not accommodate passive knowledge of what is known about other agents regardless of observed response to actions.

Perhaps the most significant feature of agent-based modelling its reactive nature. Its heuristic component allows for behaviours to persist as they are observed to be more effective or cause less controversy. For example, (T. Zhang *et al.*, 2011) observed that solar control measures in hot climates were more important than air movement whereas the opposite was identified in cool climates which can be represented in learned behaviours or predefined in the belief weighting.

Finally, this type of modelling is a supporting case for the extension of this research project into knowing more than the density of occupants present in each zone at a given time. By knowing the planned activities of each agent and their department it should be able to accommodate both dynamic belief weighting and as (T. Zhang *et al.*, 2011)note is sadly absent, location or spatial agent tracking, how they move through the environment. This should have a profound impact on CFD as well as energy performance modelling.

2.7 Schedule calibration and energy efficiency

Implementation of operations-aware service management in the real-world has been observed to have a significant effect on building energy demand and performance. Lo and Novoselac (2010) identify, within the limitation of their model and acknowledgement of climate sensitivity extensively discussed in (Rastogi, 2016), that their case study could realise a 30% saving in cooling energy demand by increasing the cooling setpoint for unoccupied spaces. Parker *et al.* (2017) in their research in linking personal metadata and scheduling models for reducing building equipment energy consumption discuss deviation performance gaps resulting from NCM. They both the broader observation that NCM scheduled models have been observed to underestimate consumption by half and 10% underestimation of heating energy consumption in their model set. Lo and Novoselac (2010)'s previously mentioned research on cooling setpoint related energy reductions is worth further recognition. In addition to the potential 30% cooling, energy reduction identified, they demonstrate the capacity for subzone reductions where their case study considered subzones of an open office. While it is not directly transferable to teaching spaces, it an interesting exploitation of CFD and setpoint control which, since it is open space, can be significantly more responsive through variable airflow rates.

As counterintuitive as it may seem, occupant manipulation (education, legislation, rules etc) may be considered a calibration method. Instead of calibrating the schedules in the BEM, the real occupants are conditioned to behave closer to simulation expectations.

This can be seen in (Jenkins *et al.*, 2019) which identifies significant savings to be made from both forms. The observed 32% in energy load reduction through occupant engagement and 58% load reduction on “dark” days through centralisation of the equipment power states. The former of course is educating the occupants and encouraging energy consciousness, the latter though is effectively decoupling the occupants from their waste. Not too dissimilar how one might consider an occupancy presence sensor’s objective. What is particularly interesting about their work which stands out from the other statistical scheduling is, where others introduce heterogeneity to the schedules, Jenkins *et al.* (2019) regulate the sources of uncertainty.

2.8 Extant literature on university scheduling

Universities in the UK are utilised on average around 26% according to (Space Management Group, 2008). However, this is not reflected in the NCM database which is the foundation of Part L2 energy modelling. Figure 2-2 shows the profile used by the NCM where presence utilisation is 65% and presence during design 100% which is found to be inconsistent in definition and practise in Utilisation overview, however, this is shelved for the moment. Outwith the UK and voluntary retrofit analysis are not bound to the schedules where, in the case of the latter, compliance modelling will only be required at the point of next EPC assessment. This section outlines some extant research on university scheduling for design and retrofit decision-making.

Davis and Nutter (2010) note two case studies which used one-time walkthrough surveys to identify correlation between electric load and occupancy utilisation factors which suggests support for the presence-state bound equipment and lighting service NCM modelling method for university buildings. However, the cited authors concede the survey time and frequency required limits the generalisability of the results, and Davis and Nutter (2010) acknowledge the need for real-world presence density data. They also observe in their architecture building case study 24-hour presence with “occupancy factors” (utilisation) only slightly less than identified (Space Management Group, 2008) during typical operation, though less than half during out of hours. While these are in reference to the full building, they support the contention with NCM scheduling that is prevalent in this thesis, as do their observations on weekend presence to an extent. Surprisingly, they excluded one of their three case study classrooms because “It was not deemed a typical classroom building because, as will be discussed below, no classes were scheduled on Friday.” which is an important feature in this thesis. Nonetheless, their research support low utilisation observations and considerable out-of-design presence.

Davis and Nutter (2010) briefly touch on the premise of this thesis through comparison of registration system data and the occupancy factors they calculated from their survey data. While outwith the scope of this thesis, they also note absence’s effect on observed occupancy. In terms of relevance to this thesis they focus on utilisation rather than presence, however, their observations generally support low-utilisation and out-of-design presence.

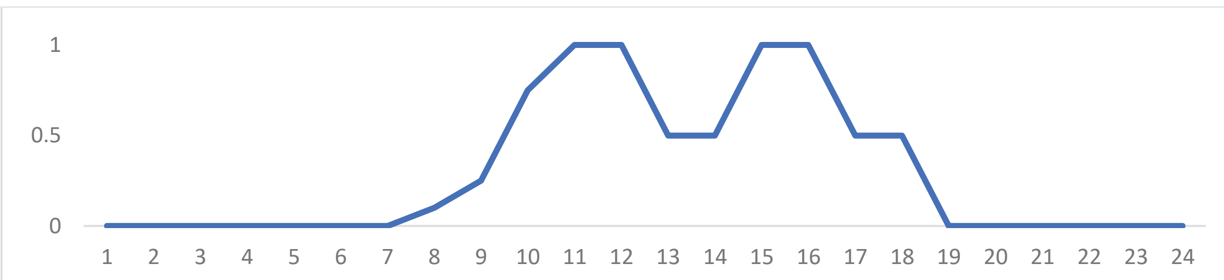


Figure 2-2 NCM database teaching space weekday schedule

2.9 Computers as pseudo agents

**This section is further explored by* Oliver and Pour Rahimian (2018) in their Creative Construction Conference 2018 paper “Are computers agents?”.

Ostensibly, from the planets in a solar system to people in buildings everything is an occupant and ecosystem to some extent. Each are nested and/or interacting, non-stationary systems with their own diverse occupants. Systems are varyingly persistent and prone to traversal through parent systems. Their relationships with other systems and processes can be mutually exclusive or intricately linked, but even those which are seemingly distal can have a persistent knock-on effect on both physical and optimum state definitions. The implied feature is being human is not a prerequisite of occupant status, something which is becoming more prevalent in the literature. Furniture for example, in the form of spatially-represented internal thermal masses (Raftery *et al.*, 2014a) which Li *et al.* (2016) note as contrasting with the existing model assumption of isothermal stability between furnishings and the space. Furthering this, Johra and Heiselberg (2017) discuss the validated relationship between comfort and furnishing, specifically, humidity buffering, and indicate the need for further research into the complex effects of furniture.

Previous building physics research discussed what could be considered the impact of equipment personalities on energy demand with (Jones *et al.*, 2013) identifying an established case for equipment similar to the theme of this article proclaiming “simple workloads” fail to reflect the complexity and variety of user or equipment behaviours. Jones *et al.* (2013) effectively discuss the hardware personalities and identify idiosyncrasies in the form of mixed focus software activity, though they do not consider the relationship between the agent and mediator, the computer. Social science has investigated the effect of perceived humanity in electronic devices on people’s behaviours and perceptions of the world around them (Cliffard *et al.*, 1994; W. Wang, 2017) which is supported by computer ethics literature Deborah G. Johnson and Powers (2008). Nonetheless, scheduling for equipment is still largely proximity-as-utility, aggregated power densities.

The suggestion that some equipment are closer to being occupants than equipment in the conventional sense has in principle been covered previously in occupant activity detection (Ahmadi-Karvigh *et al.*, 2018; Jones *et al.*, 2013) where appliance-level consumption was considered significant to understanding user behaviours. Jones *et al.* (2013) discussing system processes and energy consumption implicitly suggest the impact of idiosyncratic personalities of the machines themselves. Personality seems further supported by Joy E *et al.* (2014) who note agents are not exclusive to a single computing devices or locations and Gunay *et al.* (2016) who identify significant differences in the energy-conscious behaviours of respondents when using differing computer types. Information technology and social science literature makes a contrasting but complementary case for treating computers people and how this naturally manifests in one-way (Klimmt *et al.*, 2006) and two-way (W. Wang, 2017) relationships between people and electronic devices. Similarly, computer ethics research does not consider treating computers as “surrogate” agents a novel idea (Deborah G. Johnson & Powers, 2008).

Computers are distinct in building energy contexts from other equipment in several ways but the most significant is their position between ancillary and non-ancillary stationary equipment where the latter can be managed by smart controllable load (SCL) automation (Martinez-Pabon *et al.*, 2018) and the former’s operational schedule is immutable, refrigerators, routers or servers for example. Computers fall under neither category; user inactivity is not an indication of activity or inactivity of the device, but they are mutable. Additionally, computers and SCLs can have human-mediated relationships both of which can be supported by supervised or unsupervised optimisation (Martinez-Pabon *et al.*, 2018; Robillart *et al.*, 2018). Similarly, computers can dictate conventional occupants’ actions whether actively through delivering information or passively through processing affecting occupants’ activities within a building, although their mobility is dependent on the conventional occupant. The occupant’s behaviours can be guided by the device. Herein lies the problem, non-ancillary equipment, consumption mutability is situational and a product of the relationship between the conventional occupant and the computer. In contrast, services follow rules and adapt, and ancillary equipment consumption is immutable.

Laptops are arguably similar to young children to many building service configurations’ interpretations of an occupant in their ecosystem, differing primarily in the flexibility of shared characteristics. Both passively contribute heat to the parent ecosystem at activity and environment-dependent rates, depend on adult occupants for mobility, not meaningfully able to interact with the parent ecosystem without adult guidance and appear to stochastically exhibit signs of sentience in varyingly significant and consistent forms. In the case of the latter, people mindlessly treat computers as humans (ethopeia) (W. Wang, 2017). In contrast, children do not generate light and computers do not emit pollutants. Nonetheless, they interact with the environment beyond thermal disturbance through interaction with others.

Looking at it from a computer ethics perspective perhaps best alludes to why social personality is important. Discussing surrogate agency Deborah G. Johnson and Powers

(2008) notes the presence of spyware or bots as evidence the idea computers are agents, in ethical contexts, is not novel. The statement supports the observation of Jones *et al.* (2013) on the effect of software on a computer's personality (activity) but its primary relevance to this discussion is defining computers as at minimum, surrogate agents with "second-order interests" akin to the relationship between a lawyer and client. In an earlier article, Deborah G Johnson (2006) explains "… as with human behaviour, when computer systems behave, their behaviour has effects on other parts of the embodied world". This is a critical feature of the proposed reclassification, the effect of their behaviour (personality) does not exclusively reside within the mind of the user, which complements Jones *et al.* (2013) and Wang's energy and social personalities. However, Johnson later highlights computer systems' intentionality is "inert" or "latent" without the intentionality of the use.

People assign humanity to computers whilst fully aware of the absurd attribution. They form relationships which are sensitive to the computer's ability to manage its second-order interests, similar to the way an office worker's employment is dependent on their second-order interest, keeping management satisfied. However, a computer's agency is dependent on the intentionality of the user and therefore is removed when the user and latent intentionality expires. This seems suggests computers are agents during occupancy but not inoccupancy.

Computers share similarities with conventional occupants not quite fitting into any category of equipment, exhibiting similar physical and social characteristics of occupants and developing relationships with the user and world around them. They interact distinctly from other forms of equipment and contribute a significant portion of building energy consumption which was shown to have justification for increasing equipment-occupant interactions modelling precision to software and hardware level. Their contributions to the ecosystem have similarities to young children having dependent mobility and creating a mixture of material and immaterial pollutants causing environmental and social events, arguably with a higher chance of passing the Turing test. That is, the information they transmit to the environment has more utility and capacity to change the environment with greater persistence. Their environment disturbances are also activity-dependent in a manner which is neither Boolean nor reliant on physical or SCL device intervention. Finally, their behaviour is learned from peers though dependent on user intentionality and they can transfer electrical potential and information between environments which, in the case of information does not require spatial proximity.

However, although computers and occupant function are co-dependent in office settings conventional occupants in isolation are independent from computers. Therefore, computers are subordinate to the conventional occupants meaning the stochastic nature of their environmental and social impact do not persist during inoccupancy and effectively are akin to an ancillary device.

The underlying principle of considering computers as more than static sources of disruption and consumption as individual entities sharing characteristics of conventional occupants if only during occupancy is significant and validated by existing research. In terms of inoccupancy it appears the proposal has some merit for filling the absent consumption void of existing proximity-as-utility scheduling however, with computers robbed of agency during inoccupancy there is no necessity for any complex behavioural modelling beyond determining appropriate loads, power state probabilities and durations of inoccupancy. Non-ancillary equipment consumption is predominantly cultural, it is a function of the energy-consciousness of conventional occupants and should accommodate equipment assessment. Jones et al have laid the foundation for the latter with their software.

2.10 Summary

Buildings make significant contribution to the UK and EU’s carbon footprint which needs to be addressed in order to meet Low Carbon Economy 2050 targets. The majority of building that will exist by then have already been constructed therefore the construction industry needs to focus on selecting appropriate retrofit strategies. Unfortunately, current compliance-based modelling does not appear to be conducive to this goal. Seemingly, the only way the 2050 targets can be met is if the industry moves towards models aware of operational consumption and the utilisation of each building. As identified by (Strachan, 2013), there is a need for a new type of industry professional that specifically addresses this problem to avoid the inherent bias of working with designers whether architects or building service engineers and the checkbox exercise approach currently in use needs to be scrapped.

Occupant behaviours were shown to be one of if not the most significant features of operational energy consumption spanning both periods of occupancy and inoccupancy. The current literature covers many facets of the definition of an occupant in psychological, physiological and behavioural contexts in isolation but appears to fall short on sociological and metacognitive considerations, however, agent-based modelling appears to be primed to introduce these features. In contrast to the literature reviewed by Fanger in 1974, discussed by (Schaudienst & Vogdt, 2017), when creating the PMV comfort model there is significant reason for introducing biological sex and gender considerations into models that are not just matters of perception as is commonly suggested outwith (Stenberg & Wall, 1995). However, it is not controversial to say that generally once environmental conditions are within reasonable domains comfort adaption is more psychological than allostasis. That is, occupants' perception of comfort is typically more relevant than objectively meeting comfort needs.

Similarly, to occupants, it seems necessary to consider computers and other forms of non-ancillary equipment as subordinate occupants, not entirely independent relying on the intentionality of some real agent whether proximal or distal. Some agent-based models have addressed part of this issue through equipment taxonomy treating certain equipment as more than Boolean-state power densities (T. Zhang *et al.*, 2011) however, they are yet to be modelled as interdependent agents.

Given current social trends towards discounting psychological, physiological and sociological diversity it does not seem likely that the construction industry will be able to fully utilise occupant diversity outwith research settings, certainly, real-world occupants will not unanimously give up personal information required to create accurate agent representations. Nonetheless, the industry must strive towards creating better representations of individual agents and their collective interactions if it is to cost-optimally achieve the 2050 targets.

2.11 Conclusion

This chapter reviewed the literature concerning built environment operational emissions and how lifecycle emissions. It also considered what it means to be an occupant and how occupants interact with buildings. Discussion on interactions considered adaptive comfort including how these are affected when other agents and belief cues are introduced. The reader should now be familiar with the concepts that will appear in the discussion that consider the ontological and epistemological gaps resulting from excluding these concepts and nuances in real-world roles from building energy modelling.

3 Chapter 3 - Research methodology

3.1 Introduction

Meeting the objectives of this thesis required embarking on numerous theory and practical research activities and strategic design of collation and data interrogation methods. As with any experimental thesis, these challenges may be split into a critical analysis of the literature, data preparation, experiment design and data analysis. This research combined real-world data and building energy modelling in a novel way which required development of a bespoke tool for simulation, BMS modelling and cash flow analysis. This chapter describes the development and design processes used to produce the presented data in Results, the data analysis methods and the approach to critically analysing the extant literature.

In this chapter, the reader will find discussion on the research philosophy and the impetus for the chosen methods and classification of the research. Understanding the established design approaches is an important precursor to designing any research and therefore, these should be explained and justified before progressing to the implementation stages. In this chapter the reader will find discussion on the positivism philosophy behind the research and why it may be considered logical positivism despite logical positivism's contradiction with traditional experimentation. The reader will also find discussion on the research approach and design. Finally, the chapter will explain the characteristics that led to the design's classification as in-silico

The chapter proceeds with discussion on how the literature was analysed and why its focus is primary on sociological, behavioural and physio-psychological aspect to agents and what it means to be an agent. The chapter will enable the reader to understand how the fragmented data was combined and normalised with the standards used to produce the energy models. The reader will also find discussion on the development of the integrated procedural retrofit analysis environment, real-world schedule integration and how the novel BMS modelling tool works. Additionally, the reader will find a discussion on schedule translation and strategies present in the results. The chapter also includes a summary of the data analysis methods used for the results. Finally, a brief note of why the requested data was exclusive of the physiological properties of occupants.

3.2 Research Philosophy

3.2.1 Philosophy

The research in this thesis is ostensibly best described as positivism which is the branch of scientific philosophy that asserts that knowledge is only authentic if it is verifiable, constraining the definition to scientific knowledge.

The experimentation and discussion in this thesis might be better classified as the debatably defunct though fitting for the field of retrofit analysis, logical positivism. The distinction between logical and classical definition is that whilst positivism rejects metaphysics and anything which is either unobserved or cannot be observed, logical positivism also rejects any synthetic a priori knowledge. It is said in this section that the concept is debatably defunct given that the definition supposes that the only meaningful knowledge is that which is verifiable which as Karl Popper identified as contradictory to the definition of the scientific theory which is something that cannot be verified, only falsified by a conflicting observation. However, the statement made by Karl Popper does not hold true in a simulation model where falsifiable theories and observations can be considered axioms rather than theories. That is, building physics is constructed around well established and tested models outwith wellbeing which are still susceptible to falsification, but in dynamic simulation models these theories are immutable axioms. Their isolated models will persist regardless of extension of the simulation model even if the interactions between these interconnected models evolves. The author considers classification as logical positivism rather than positivism to be helpful in reinforcing the separation of the real and virtual worlds, and its rejection of synthetic a priori knowledge for several reasons beyond the axiomatic nature of simulation models.

- Retrofit strategy performance, regardless of how well defined the parameters of the simulation model and engine, cannot be presupposed with a priori knowledge. That is, unless a building is entirely vacant, disconnected from the electricity grid and not utilising fossil or renewable secondary fuels, natural gas or biomass for example, there is no way to predict how the impact of the strategy globally or locally.

- Retrofit strategies when combined do not always if ever match result in a linear estimated performance change through aggregation of their impacts in isolation, instead falling into potentially two other categories: diminishing and complementing returns.
- The concept of an occupant in any simulation model is to an extent is a categorical idealised entity (agents) rather than comparable to real occupants whose presence, activity and system interactions are as much a function of individualism as they are socio-personal (driven by desired perceptions and conformity).

The experimentation in this research and subsequent discussion is considered wholly to reside in and relate to, the virtual world. Its potential for calibration of real-world retrofit decision-making for education facilities is not without value but it would be disingenuous to say that the experimentation was shaped by anything other than a rudimentary understanding of the models, virtualisation of building services and sensitivity to occupancy. Therefore, it is maintained that whilst it is not controversial to associate physics-related research to positivism, this research is fittingly described as logical positivism in a virtual world.

3.2.2 Approach

The positivist method is broadly defined as a deductive approach or deductive reasoning which is concerned with constructing hypotheses through utilisation of existing theories to design a model that enables testing the hypotheses of the researcher(s). Deduction is essentially identifying expected patterns and testing against observations made in the research, aiming to assess the validity of the propositions and premises of the underlying research subject.

Deduction is considered to have several advantages over inductive research, described by Jacob Bronowski as "…a blend of speculation and insight… which cannot be formalised", which are arguably reduceable to findings loosely generalizable causal relationships through quantitative research. Secondary benefits of deductive research are the abundance of research outlining the underlying theories and its capacity to have strict deadlines not reliant on asynchronous data collection from third parties. Finally, it is generally considered low risk in the sense that hypotheses though not necessarily generalisable can be accepted or rejected within the scope of the study.

This thesis aims to demonstrate the severity of the simulation and implicitly the building performance gap arising from failure to integrate real-world utilisation or calibrate heating scheduling assumptions. It achieves this through the application of deductive reasoning using data collected by the Estates department of the Strathclyde University which owns the case study building and integrating it with a moderately accurate (not quite Part L2A BRUKL compliance verification but closer to that than would be identified through survey for Part L2B compliance assessment. Through reviewing the literature, it was identified that the existing definition of occupants in traditional energy models, activity-density defined disturbances or persistently categorized agents, should be rejected. These data and rejections were applied such that the nontrivial impact of occupancy scheduling in a deterministic virtual world which do not reflect the real-world application of calibration or retrofit strategies but explain the seemingly anodyne inference that should be part of any retrofit decision-making.

3.2.3 Strategy

A research strategy is a generalisation of the applied method in conducting the research. Strategy can be broadly split into three categories, quantitative, qualitative and mixed-method. Quantitative research is based on measurable data and statistical analyses using numerical comparisons, depending on your philosophical beliefs surrounding the nature of your research, this purely objective (positivist) or mixed with subjective characteristics (post-positivist). Qualitative research deals with subjective measurement and inference from the perspectives of participants or other non-measurable properties related to the hypotheses, the primary focus of interpretivism. Mixed method approaches integrate both qualitative and quantitative methods, favoured by pragmatists.

The quantitative method is ostensibly rigid and devoid of subjective inference or uncertainty dealing exclusively with measurable numerical (discrete or continuous) and/or categorical (discrete bounded) sets, verifiable within the constraints of the models describing the current understanding of related theories. It is based on deductive reasoning and objective analysis of field, laboratory and/or simulated results. Though it does not deal with subjective data it may be proceeding a qualitative study and therefore may be driven by bias from researchers. Similarly, representation of statistical results is not determined procedurally which may result in the introduction of bias from the researcher(s).

3.2.4 Design

Research design is considered the framework which the research is built upon defining the data collection and analysis methods. It is the structure created by the researcher(s) to reach the objective of the experimentation to reach conclusions on the hypotheses. The process serves to primary purposes, it formalises the process used in the research supporting reproducibility and enables to researcher(s) to remain consistent with the agreed structure of the process. It accommodates prioritisation of the subprocesses involved in the research. There are three categories which can broadly be split into two overarching parent classifications, experimental and non-experimental designs:

Experimental design is the process of identifying how adjustment of independent variables affects the results in a given model. Experimentation aims to identify causal and/or correlating events. For example, the cooling setpoint can affect the thermal comfort of occupants and in adaptable environments, the relationship may be reversed.

Non-experimental design refers to the process of research with immutable independent variables. It is often used to identify non-causal relationships, variables which are related but not interdependent. For example, in contrast to the experimental design example, the cooling set point and solar gains affect thermal comfort but at least in steady-state models, there is no causal relationship. That said, thermal comfort is a function of both all three forms of heat transfer, conductive, convective and radiant which may suggest that agent-based models could see a causal relationship between the intensity of radiant gains for occupants near glazing; radiant heating is said (in warehouse environments not necessarily glazed, to lower the acceptable set point for comfort) to lower the necessary heating set point.

The three categories cover individual and group-based quantitative methods. Despite falling under the quantitative branch of research methods, some of these share similarities with qualitative studies, namely the immutability or persistent nature of independent variables. However, these retain their quantitative status through assessment of measurable data and numerically quantifiable variables or in the case of descriptive research, do not seek to assess variables. Figure 3-1 shows the hierarchy of quantitative design methods.

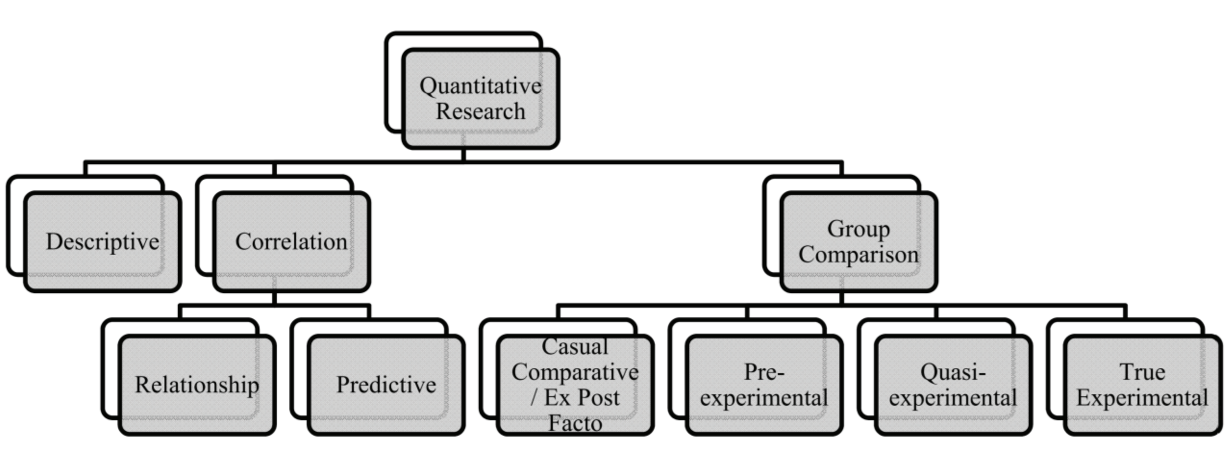


Figure 3-1Quantitative research design tree (credit: Amanda Szapkiw)

Descriptive: This type of research model does not attempt to identify a causal relationship between variables and as such have no independent or dependent variables. Instead, this type of research model attempts to gain an identify problems which are not entirely apparent for further research analysis using an alternative research model. This contrast from qualitative non-causal relationship identification through objective measurability. For example, does maintaining the setpoint temperature always meet your comfort expectations is non-causal since thermal comfort (within an acceptable domain of temperature near the setpoint) does not necessarily correlate with the setpoint temperature whereas, is X amount of units of natural gas sufficient to maintain setpoint temperature for a given week in winter sufficient is a causal relationship since all other things equal (window state, equipment gains etc) the units required to heat a given can be described by a mathematical function. This type of research model falls under two categories, longitudinal and cross-sectional alternatively labelled survey or observational.

They differ by their temporal characteristic where the former is carried out over a period of time whereas the latter occurs at a single point in time.

Correlational: This type of design is used to investigate the extent in which two or more variables relate without necessarily identifying a causal relationship. Similarly, to descriptive models this type of research does not manipulate variables associated with the study and as such is often considered observational. These studies can include prediction and/or relationship analyses. The former considered a predictor and criterion study whereupon the researcher(s) attempt to identify where an individual or set of variables can predict the value of another. Relationship studies are interested in how the relationship between two or more variables is constructed not necessarily seeking to identify causal relationships.

Group comparison: This deals with research identification of causal relations through grouping the participants such as medical trials where an attempt to quantify various properties or prove the efficacy in groups where all other things considered are equal. Obviously, in the real world, this cannot be achieved however, it is possible to create conditions which are sufficiently comparable such that the impact of independent variables can be attributed to the change of dependent variables. When determining whether causal relationships between variables exist the results must meet at least three of five criteria.

- An empirical association which can be observed and is quantifiable. Typically demonstrated through statistical analysis, these associations confirm that the relationship is not merely coincidental or by chance.
- Time order is a seemingly obvious criterion for acceptance of a causal relationship. This simply means that it must be demonstrated that for all confirming groups the order in which the dependent variable and independent variable change is such that the independent variable consistently changes first. It is worth noting that this criterion alone rejects cross-sectional studies as a means of identifying causal relationships since you cannot identify the order in which the variable changed if there is no time component.

- Non-spuriousness is proof of the isolated relationship in the sense that it is not attributable to other factors or otherwise not genuine. For example, an occupant opening a window during winter with the heating system is a causal relationship since the change in window state changes the heat transfer rate between the internal and external environment. In contrast, the presence of an occupant increasing the internal gains from equipment is spurious since, as discussed in section 3.6 (Are computers agents?) computers have similar characteristics to conventional occupants stemming beyond being Boolean-state power densities having their own personalities and second-order interests. Even in scenarios where this equipment is always-on, both the device's personality and latent intentionality of the occupant affect its contributions to small power heat gains. A simple example made be an occupant doing computational demand calibration of hyperparameters of a machine learning model only to leave the zone during the computationally expensive training period. Therefore, the relationship is spurious.

The two additional criteria are not necessary for proving a causal relationship, however, are can significantly strengthen the explanation of the relationship.

- The causal mechanism is the regularities of events that can bring trigger the causal relational change confirmed by the first three steps. Using the example underlying presumption for the spurious example in criterion (3). Were the device contributions caused related to the occupant's and work in machine learning, then the mechanism might be the occupant's first- and second-order interests. They need to provide for their family thus have a career (first-order) and they design solutions to problems faced by their employer (second-order).
- Context is in what conditions does this cause have an effect. Causal effects occur in larger contexts outwith the research is itself. As suggested in 3.6 all processes in the physical universe occur within nested ecosystems, however not all ecosystems are relevant to causal relationships. For example, occupant activity for occupants of non-domestic buildings who take lunch will change around early afternoon as they take lunch is a causal relationship whose mechanisms are desire

to eat or take a break from work and its context is when they are working and in the case of the UK, where their workday is greater than four hours long.

The research in this thesis might be considered as either descriptive or experimental depending on how you classify the modelling process. The difficulty in classifying the research design in this thesis is that it is in effect a quantitative environmental impact assessment which is not constrained by the uncertainty or non-deterministic nature of the real world. Since it exists in a virtual world the models can be considered individual buildings sharing internal and external physical characteristics in spatiotemporal superposition, yet their operational configurations may change in service efficiency/efficacy, state control and utilisation. Finally, its definition of quality is measured objectively in terms of emissions improvement and return on investment rates. It is ultimately designed to be descriptive but when extrapolated to the real-world it answers, “what if?” questions which are the fundamental property of the simulation or “in silico” research design pattern. In contrast, the number of actual simulations, warmup demand neural network notwithstanding is low for the research design pattern.

3.2.5 Justification of in silico research design

This research aims to prove the hypothesis that failure to integrate real-world schedules and decouple occupancy from heating schedules results in a significant simulation gap and inherently, a building performance gap. In doing so it aims to justify the proposal that occupancy schedule calibration and heating management should precede conventional retrofit decision-making. It also sought to frame the results as similar to Rastogi (2016)’s. Discussion does breach the virtual/real-world barrier the research design is non-experimental in the virtual world since it incorporates immutable temporospatial superposition for non-living entities. Though it may be considered experimental since superposition of living entities and nonancillary equipment are mutable, and its ecosystem is neither passively nor actively muted. In short, it will demonstrate a causal network exists in the virtual world which is not generalisable to the real world but supports the case for future research in site-level, non-linear regression retrofit simulation model networks. Informally, a collection of regression models for each building on-site which interdependently estimate site energy performance in different configurations, namely varying occupancy patterns. In the end, the research strategy associated with this thesis was classified as in-silico or simulation experimentation as it best fits the "what if?" investigation carried out in the virtual world.

3.2.6 The virtual case study design

The functional simulation and inherence of the building performance gaps resulting from epistemological uncertainty and presence-bound tempering are ignorant of individuals are represented in the experimentation. This means the study is experimentation is purely quantitative and therefore can be classed as positivism which removed the need for consideration of perceptions. However, positivism is less rigid than desirable and incongruent to the case presented in this thesis. Instead, the research was themed on logical positivism, the militant form of positivism which is said to be invalid in the real world. It is nonetheless, compatible with simulated worlds which are essentially cellular automata when the environment's rules are deterministic and predefined prior to experimentation, it's a black box and model configuration source data verified. The result is the characteristics of the environment can be described as literal truths.

The significance of further constraining experimentation to logical positivism from positivism is it reduces to a single, question with only two possible, definite answers: Does the model produce outcomes which are consistent with the physics of the environment and accordingly, produce different results depending on whether heating is presence-bound? If yes, then the functional simulation gap exists and must translate in some form to the building performance gap unless the model (EnergyPlus) is an ineffective tool for simulation. If the answer is no, then EnergyPlus is likewise ineffective. By constraining the research in such a way as to follow this philosophy the results may be claimed as precisely accurate. They are simply sub-features of the ternary property that defines the outcome, the direction of change between paired Schedule-Climate scenarios which occurs in a deterministic environment. The definition of the research from Case Study to **Virtual** Case Study to reflect the nature of the philosophy and nature of the model.

The Occupant ontology component of the research discusses objectively-defined classes for occupants in relation to their roles in building operation and one another and is therefore not outwith the constraint of logical positivism. However, the approach may better be considered inductive. Not all proposed classes were expected prior to the literature review and in the case of the Dyad, their absence from extant research brought them to attention.

3.2.7 Summary

This section discussed the selection of the logical positivism research philosophy and it's the characteristics of the simulated environment that enables the otherwise deprecated philosophy. It describes the deductive approach taken to produce results and summarises the collated data. The discussion on the approach also expressed the benefits of the self-contained nature of its purely quantitative deductive nature, reducing the need for third-party production of data to the initial registration system and design plans request to the University of Strathclyde's Estates department. It proceeds with an overview of the research strategy's hierarchal structure starting at the split between qualitative and quantitative methods. It concludes strategy discussion noting that while it inflicted by an authority paradox as postmodernism is, the description and presentation of its results are still inherently bound to the bias of the research team.

The section progresses with differentiation of experimental and nonexperimental design methodologies. It notes how some representations of the test environment may in some ways be considered nonexperimental, namely steady-state, where real-world causal relationships are not integrated. The section proceeds to highlight loose similarities between certain quantitative and qualitative methods. Its design discussion concludes with an overview of the three subbranches of the quantitative research design structure, descriptive, correlational and group. The section concludes with a brief justification of the in-silico description of the research design by noting the temporospatial superposition of simulation models and the output data's source being exclusively the virtual world.

3.3 Literature review approach

This thesis assessed the performance gap in nondomestic buildings where energy is consumed explicitly to meet the needs of the occupants. Therefore, critical analysis of the literature attempted to identify sources of uncertainty from the top down. This involved investigating first national-level reporting and measurement conflicts which lead to misreporting or misinterpretation of built environment energy consumption. Lifecycle emissions play a significant role in the overall energy performance of buildings, yet it is a mitigating factor in legislative requirements. To understand lifecycle emissions' relevance to building lifecycle energy consumption a review of construction and end-stage of the building lifecycle was undertaken. These form basis of discussion on realised return from retrofitting beyond private monetary benefits and assumed energy performance improvements.

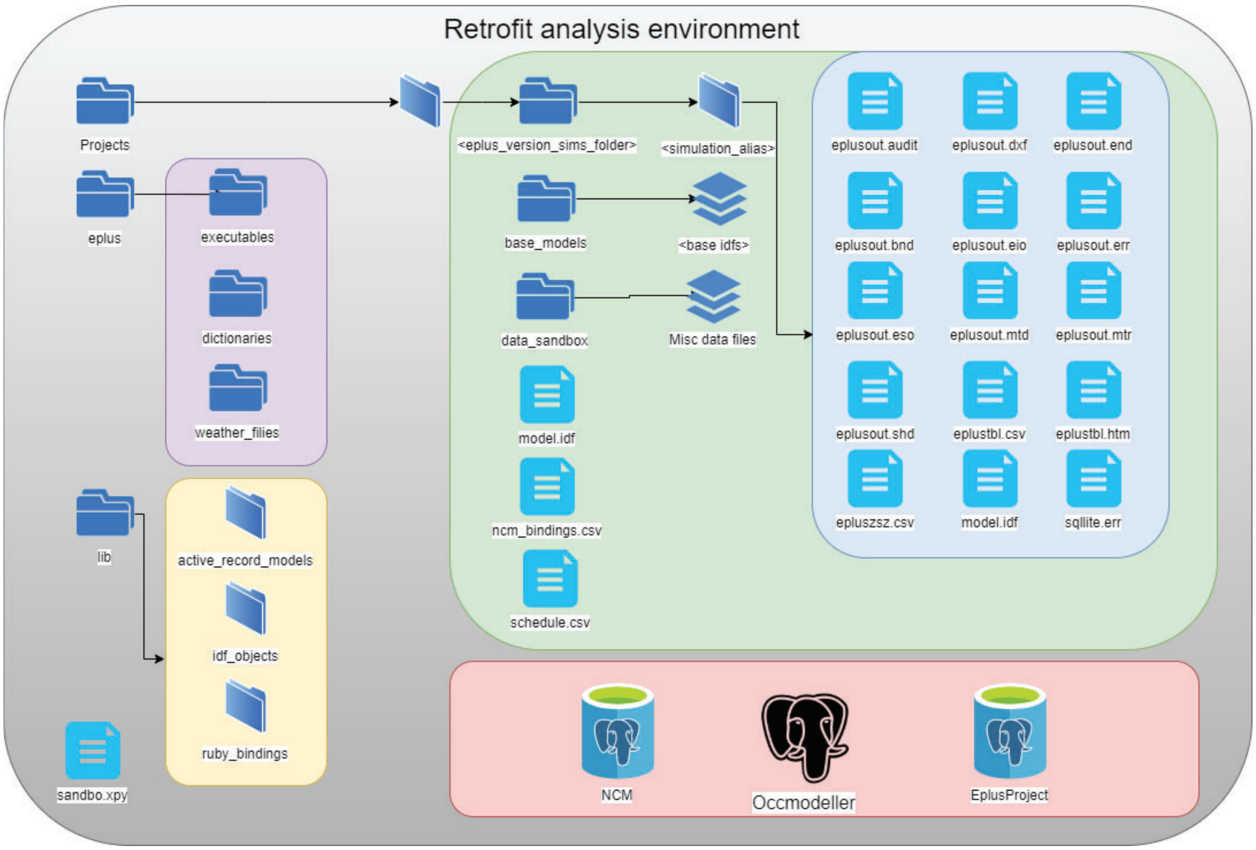
The experimentation in this thesis is novel and its application of real-world utilisation in a low utilisation building being absent from the literature which was the driver for the proposal. The results and discussion do discuss utilisation which is represented in the literature in the form of stochastic and agent-based models, and short-term prediction using autoregressive machine learning. However, the primary talking point in this thesis was the conflict between standard scheduling and idealised heating in building simulation and real-world unmanaged absence, referred to as zero-density presence throughout the thesis. Therefore, it did not make sense to target utilisation literature in great detail since it has probabilistic and autoregressive estimation have little relation to deterministic scheduling or zero-density presence. Instead, it was decided that a more fruitful approach would be to collate and discuss the ontology of agent taxonomy. What does it mean to be an agent and why does agent heterogeneity impose limitations on modelling accuracy and the extent a real-world agent can be represented in a virtual environment. In the case of the latter, it can be said that there are few real-world things or functions which can or should be literally translated into software. To that end, the literature was searched primarily using tags associated with sociology, psychology and physiology. The subjects were then analysed in terms of their effect on building operation and internal, social and environmental perceptions of the individual and collective agent.

3.4 Defining and modelling the virtual case study model

The virtual case study was constructed from various data sets retrieved from University of Strathclyde's Estates department and gaps in the building physics properties populated with properties from the NCM database. The first step was to create a base building energy model from the existing As-built energy model used for the EPC and the floor plans which contained the space-related data. An investigation into the building's history was also carried out to explore why the envelope thermal properties are extremely poor by modern standards, even those for Part L2B compliance. This was a complicated process with numerous data translation processes. The Virtual case study building energy model describes the process in detail.

3.5 Development

3.5.1 Integrated retrofit analysis environment design



The experimenting stage used several bespoke libraries for scheduling and post-processing. Handling building energy models and interactions with EnergyPlus was delegated to the library written specifically for this research, EplusProject::StrathIDF. This library extended the ePPy library from the Python common libraries which provides functions basic interactions with EnergyPlus models. This extension was later named StrathIDF. Broader project handling of was accommodated by the EplusProject library which was written for this research. There is no common description for the type of project though it may be best considered an integrated procedural retrofit analysis environment. Integration denotes the integration of the database, EnergyPlus and abstraction of interactions between the two. Procedural retrofit analysis denotes the algorithmic approach to modelling and simulation which spawns the solutions spaces discussed in

Data analysis automatically from several lines of code without researcher involvement. Finally, workspace denotes the structure of the environment. A significant part of procedural retrofit analysis parsing, simulating, tracking and caching building energy models. This requires binding reference and project databases and scoped repositories. Scoped repositories either persist as in the project's repository or are ethereal and exist only during the process which is anything in the processing directory.

Interactions with simulation results were handled using the postprocessing modules of the EplusProject library, EplusProject::ResultsViewer and EplusProject::::Economics. These modules simply parse the outputs of simulations into objects which are designed for procedurally translating results into meaningful data or passing to other libraries. Interactions with intermediary outputs for clustering such as internal gains and presence were delegated to the OllieMl::RegressionDataSet class. The class creates an inline database with typical SQL functionality through object model equivalent commands. It was responsible for all results presented in Classroom scheduling.

3.5.2 Retrofit options and cost models

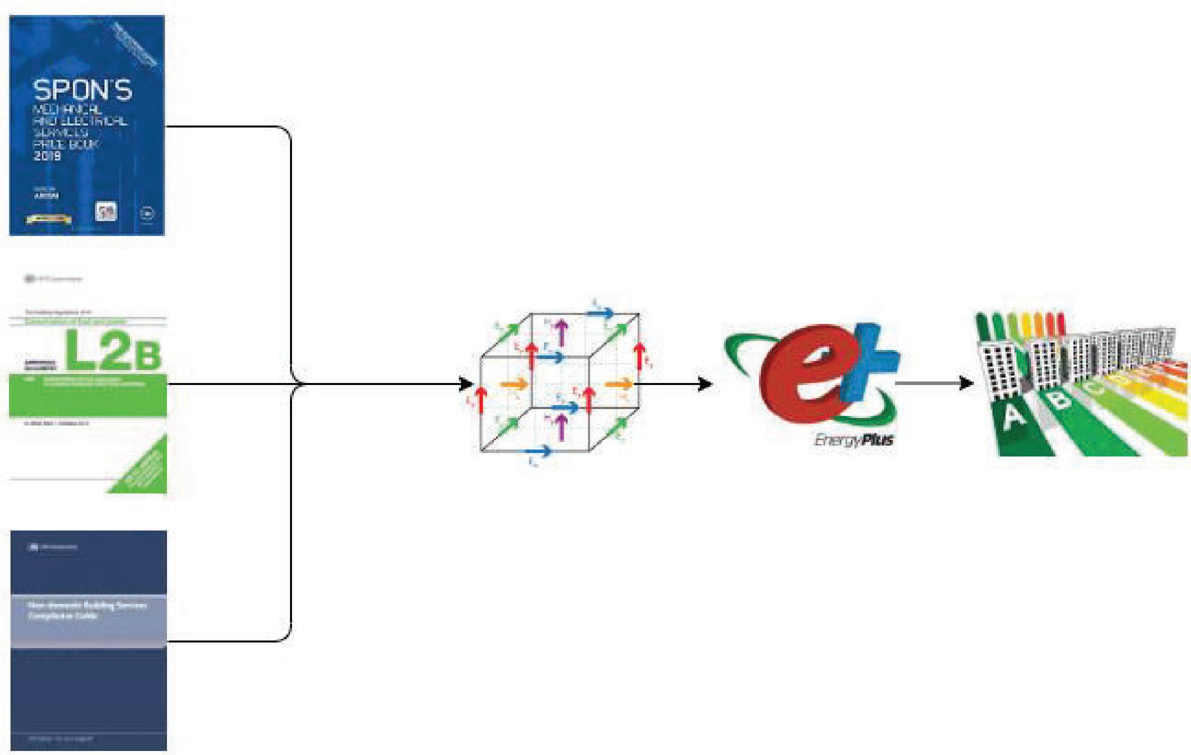


Figure 3-2 Retrofit simulation process

This thesis considered the individual and compounded effects of retrofitting the virtual case study with one or more of three retrofit measures.

1) Installation of high-efficacy lighting. Referred to as R-LIG. This retrofit is discussed in two types of scenario, standard and constant efficacy upgrades. The former represents the design described in R-LIG whereas the latter represents a set of lighting retrofits where all zones are upgraded to use lighting systems with equivalent efficacies.
2) Replace the low-temperature hot water heat source. Referred to as R-HVC.
3) Installation of a Building management system for the LTHW boiler, configured with the registration system occupancy data. Referred to as R-BMS. The associated system is referred to as a heating management system or HMS in this thesis to distinguish between full BMS and heating-only management.

All three fall under different taxonomies of retrofit strategy, lighting improvement, HVAC replacement and control measure subsequently required their respective cost model. The concept of exemption-through-design is critical to the decision-making process and touched upon in the conclusion. However, at this point, it only needs to be mentioned that a cost model for procedural retrofitting is not an attempt to remove human design or labour from the pricing process. Instead, it is to reduce the number of, and intensity of, efforts to price retrofit strategies. To that end, it was necessary to identify data and methods which could be used to estimate retrofit costs for a given model and retrofit specification. The following data was obtained, and methods created which fit the specification for the retrofits within the scope of the efficacies/efficiencies of their respective real-world components. These methods whilst not determinants of the costs which will make it to the bill of works fit the requirements of demonstrating MEES exemption before reaching the design stage. The methods presented in the proceeding sections would be acceptable for MEES regulation 28(3) exemption application. However, these methods are not necessarily appropriate for analysis of complicated building systems. Retrofit analysis lends itself to nonlinear evaluation considering features beyond cost and energy performance, particularly sensitivity analysis. Static costing methods based on (SPON's, 2018) are declared and delegated by the cost information via dependency injection. This enables variable costing analysis by interacting exclusively with the database than the code itself. Figure 3-2 outlines the flow from reference material to generating the solution space and finally producing the results.

3.5.2.1 R-LIG

The lighting retrofit cost model was designed based on the photometrical computation (Lumens method) method documented in the Philadelphia university Electrical Installation lecture 11 online article, adopted to accommodate the spatial information loss which occurs during the translation from the virtual environment to an SBEM building model. The method uses photometric data to estimate the number of luminaires required to light a given environment through lookup using the room index, a simple function of a zone's geometry. Given:

$$N = \left\lceil \frac{EA}{lm.UF.MF} \right\rceil$$

Where:

N = Number of luminaires

E = Target lux level for the zone. Where the target lux level is taken to be the design or "light_lux" value from the NCM activities database as per the binding discussed in 4.2.1.

lm = Total luminous flux from each luminaire

UF = Utilisation factor identified from the luminaire's photometric data

MF = Maintenance factor. The product of the reduction In luminous flux after a certain hours of use(LLMF), percent of lamps which fail on average (for the luminaire type) after the burning hours(LSF), reduction of flux from dirt deposition (LMF) and the reduction in reflectance due to dirt deposition on room surfaces (RSMF). In this study, the function was substituted for a value from the PU lecture note's table.

The UF is identified from the luminaire photometric data through lookup via the room index (k) which is typically given:

$$k = \frac{LW}{(L+W)Hm}$$

Where:

L = Room length

W = Room width

Hm = Ceiling height – work plane height

SBEM does not retain non-volumetric dimensions of zones which prevents the use of the equation in this form. The method was modified to use the zone area (A) in place of room length and width:

$$k = \frac{A}{2A^{0.5}Hm}$$

The luminaires used in this case study were selected manually for demonstration purposes. In the event that this were to be used with a luminaire lookup, the luminous flux of each luminaire considered should be sense checked to ensure its luminous flux is not too intense.

Now that the number of luminaires has been estimated a cost for the retrofit can be determined using the cost per luminaire and time taken to install the luminaire. Note: as discussed in other sections, this function is exclusive of design which cannot be truly devoid of human involvement due to subjective factors, though it may be introduced as an externality to procedural cost-benefit analyses prior to consideration.

Products meeting the criteria for zone activity's design illuminance levels were identified via the Philips product catalogue and priced via lookup of getalamp.com. Installation cost per luminaire were identified from the SPON's Mechanical and Electrical Services Price Book 2018.

Table 3-1 R-LIG lamp-luminaire cost data

	Teaching/office spaces	Other
Product line	Philips CoreLine	Philips LuxSpace
Category	Recessed, panel	Recessed, downlight

Code	RC134B LED27S/840 PSD W60L60 OC	RC531B LED19S/830 PSD
Luminaire efficacy (lm/cW)	123	86
Luminous flux (lm)	2700	1100
Colour temperature (K)	4000	2700
Time performance class @ 50,000 hours	L75	L90
Price (£)	302.80	127.80
Installation time (h)	0.89	0.66
Installation labour cost (£)	31.31	23.23
Annual maintenance saving (£)	6.68	6.68
Location adjustment factor	0.87	0.87

Integrated with the number of luminaires calculation the initial capital cost estimation function for the retrofit in the building's location with the given luminaire is:

$$C = N(Fhl + Lc)$$

Where:

C = Total cost in £

F = Location labour cost adjustment factor

N = Number of luminaires

h = Installation luminaire/hour

l = Labour cost £/hour

Lc = Cost per luminaire £/luminaire

Table 3-2 R-LIG activity-level costs for the case study

	No. luminaires	Labour time (h)	Labour cost (£)	Labour GLA (£)	Unit cost (£)	Gross cost (£)	Net cost (£)
Circulation area (corridors and stairways)	63	41.58	965.90	840.33	8051.40	9017.30	8891.74
Classroom	84	74.76	2340.73	2036.43	16396.80	18737.53	18433.24
Eating/drinking area	4	2.64	61.32	53.35	511.20	572.52	564.55
Office and consulting areas	242	215.38	6743.54	5866.88	47238.40	53981.94	53105.29
Toilet	15	9.90	229.97	200.07	1917.00	2146.97	2117.08
Totals	408	344.26	10341.49	8997.10	74114.80	84456.29	83111.90

3.5.2.2 R-HVC

The cost model for the boiler replacement is significantly less involved than the R-LIG but is sensitive to the simulation model and scheduling associated with the heating system being replaced. The experiments in this research used integrated ideal load calculation rather than separate calculations for sizing though, the calculation process is for load, not consumption and therefore not necessarily bound to a simulation. Instead bound to load input. In this model, domestic hot water does not share the same heat generator as the wet radiator systems which are sized for this retrofit

This experiment whilst assessing occupancy needs to consider not what can be achieved through realistic or intelligent scheduling, but what could be necessary in the future such that duration of missed demand does not exceed targets under any circumstance. Therefore, the pricing method was designed as a function of the seasonal coefficient of performance and the worst-case user "User Des Load (P. Lee *et al.*)" load of all strategies from “eplusout.eio”, not necessarily the building energy model’s default state. The sizing formula given:

$$kW = \frac{Dmax}{SCoP}$$

Where:

kW = Boiler peak load in kW

Dmax = Maximum ideal load from all scheduling scenarios in kW

SCoP = Boiler seasonal coefficient of performance in %/100 (HEAT-SSEFF in SBEM)

The price can then be estimated via lookup of the closest appropriate size range from SPON’s Mechanical and Electric Services Price Book 2018 where size ranged pricing is:

Table 3-3 R-HVC kW boiler cost lookup

Lower (kW)	Upper (kW)	Cost (£)
411	500	15577.47
601	750	17940.27
1151	1250	26092.01
1426	1500	31135.19
1626	1760	37357.70
1900	2050	39147.47
2450	2650	45903.03

All in, the formula for pricing R-HVC is given as:

$$C = CbF$$

Where:

C = Replacement cost in £

Cb = Boiler cost from SPON's pricing lookup in £

F = Location labour cost adjustment factor

3.5.2.3 R-BMS

Being a computerized system attached to local control measures, the cost method for building management systems was designed to be a function of the number of zones it would affect where the number of zone N relates purely to primary spaces, offices and classrooms. The retrofit assumes a schedule-driven BMS which means a cost may be assigned to non-scheduled spaces, but it would not change the simulation results. In the case study, the installation of intelligent unitary controllers is split into two sub retrofits representing all-inclusive primary spaces and teaching spaces only. The case for both is discussed in chapter 5.

The method was reduced to two primary costs associated with BMS installation, a global cost for the management controller and the intelligent unitary controllers necessary to toggle the state of the heat delivery outlets, radiators in the case study. Table 3-4 shows the individual component costs and Table 3-5 the costs for primary spaces in the case study.

Table 3-4 R-BMS head equipment and smart controllable load cost data

Head end equipment (£)	15000
Intelligent unitary controller cost (£/IUC)	500

The cost method is given as:

$$C = Hc + NI$$

Where:

C = Total cost of installation in £

Hc = Global cost for head end equipment (software, computer, commissioning) in £

I = Unit cost for each intelligent unitary controller £

N = Number of primary activity zones to be bound to the head end equipment

Table 3-5 R-BMS case study costs

	No. zones	IUCs (£)	Head end equipment (£)
Classroom	13	6500	15000
Offices and consulting areas	49	24500	
Totals	62	31000.00	
	Gross cost (£)	46000.00	

3.6 Scheduling

3.6.1 Schedule Data

Class registration system data was requested from the Estates department at Strathclyde University. They delivered term time information for academic year 2017/2018 in the form of an Excel spreadsheet. The relevant properties in the spreadsheet represented the string alias of a record's associated classroom, partial time series and duration in minutes, and the room's capacity and utilisation over the period. The data structure used by the Estates team was well suited to the library design and went through no pre-processing prior to utilisation.

Data present but not necessary for this project included information regarding the department and activity taught in the zone. Although not part of the project this information may be used to target departmental inefficiencies whether human or environmental. It is envisaged this information would permit targeting of unintentional wasteful usage by staff/students through collation with metered data investigating consumption during periods of inoccupancy. Alternatively,

3.6.2 Scheduling strategies

The impact of the schedule calibration was the primary theme of the experiments in this thesis. It posited that calibrating utilisation was critical in retrofit decision-making for low-utilisation buildings. Ostensibly, this was under the assumption that a cellular office is a better proxy for a classroom than an open office – therefore subject to inconsistent presence. That is to say, a cellular office's presence may be considered Boolean state when using the standard definition of occupant exclusive of this thesis' proposed Pseudo classification. Currently, however, classroom presence and density in the NCM database is closer to what would be expected of an open office. Using data from the university's class registration system two traditional and two complementary heating management systems (HMS)-extended scheduling scenarios were introduced. These represented the utilisation in the real world assigned during utilisation strategy stage of the Estates' department’s building management process. This process is ignorant of the energy efficiency of the allocated spaces and their buildings. The additional strategies were:

Explicit class scheduling: Only classrooms which are present in the registration system dataset are appropriate fore. If a classroom appeared in the registration system a verbose “Lights” and “People” “Schedule:Compact” was created from the registration system data and substituted in place of the schedule bound to the “Zone” during the DesignBuilder modelling process. However, if a classroom does not appear in the registration system, it is considered an unknown space and its utilisation schedules remain as per the standardised schedules from DesignBuilder.

Implicit class scheduling: Identical to the Explicit scheduling strategy but classes with no registered periods are considered unoccupied. Classrooms which are not known to the registration system are considered to have zero utilisation and accordingly bound to zeroed schedules for “Lights” and “People”.

Explicit- / Implicit-BMS class scheduling: Both Explicit and Implicit scheduling scenarios were bound to the R-BMS retrofit strategy. Standard Explicit and Implicit scenarios were extended to incorporate BMS system behaviours. The extension was achieved through manipulation of heating availability schedules to mimic IUC behaviour schedules based on the related Explicit/Implicit scenarios. However, BMS scheduling is extended to accommodate the preheat requirements into account which required making the heating system available one hour before the change in presence state. The real-world boiler’s capacity could not be ascertained due to its utilisation over multiple floors. Therefore, the default used for level 5 EPC modelling was used.

3.6.3 Translating occupancy schedules

Schedules are created by sorting the schedule by date ignorant of year such that 2018 comes before 2017 for the Through: ## <month> syntax to work. Failure to work with this constraint can result in either a date is missing or overlapping dates error preventing EnergyPlus from processing the IDF. Once sorted by date, grouped by Date and each Date sorted by Start Time. Each Start Time is first given a “Through:”, “For:” and “Until:” statement set defining the previous period of occupancy empty. Grouping is followed by the same collection of for the Start Time + “timedelta (seconds=Duration * 60)”. The value was set to People per area using the Size (number of people) and Area columns. The process ends with one final “Through:”, “For:” and “Until:” value equals zero is added to run through to “31 Dec”.

The resulting hash has the structure is used to create three templates, one for occupancy one for lighting and one for heating availability which was the chosen data structure for mimicking BMS behaviours in EnergyPlus. Where occupancy is not equal, 0 lighting is set to 1. These templates are returned by the zone instance method and then passed individually to the StrathIDF instance’s create object method which creates the new schedule, adds it to the model and returns the object. The name from those is assigned to the occupancy or lighting schedule property of the PERSON and LIGHT objects before being bound directly to the Zone and Light objects. Simulations whose alias contains “_bms_” their synthesised heating availability schedules injected to the model also. Unlike the other two, BMS schedules are extended to include a one-hour zero-density presence entry to represent a preheat period. The preheat period is in line with the default NCM value.

Once this action has been complete zones which are scheduled now have extended, real-world schedules for occupants, lighting and where appropriate heating availability in teaching areas which are not scheduled in the real-world data set now have an empty schedule. The model can now be processed through EnergyPlus with real-world schedules.

3.7 Data Analysis

The analysis in this thesis falls into two categories for exploration of building behaviour and economic impact of augmenting occupancy schedules in the context typically associated with retrofit analysis. The purpose of the chosen data analysis methods is to present the information in an accessible manner. The ethos behind the data analysis was that the graphical representation of data should be immediately accessible to the professional and laity alike. To that end, probabilistic and regression-type analyses are shelved in favour of simple environmental impact assessment methods and media richness-aware presentation. Discussion can on media richness and its role in communication can be found in (Oliver, 2019). The Schedule-Climate scenario and retrofit package solution space and that of each Schedule-Climate scenario with eight constant efficacy lighting retrofits is simulated using EnergyPlus. Results are collated into standard efficiency metrics of cost, net energy demand. Where Schedule-Climate scenarios reference registration system schedules the internal gains and presence profiles for each teaching space were separated into sub-hourly data sets.

Result summaries for base model Schedule-Climate scenarios are collated into a reference set which is then discussed in terms of how they compare to one another and how the efficiency metrics behave with managed and unmanaged heating. Using the discounted cash flow (DCF) valuation method described in Annex 6 of (Treasury, 2013). The base model operation costs are compared to the NCM-2016 Schedule-Climate scenario to demonstrate the impact of scheduling and on business as usual. This is extended to include Climate to demonstrate the overlap between this research and Rastogi (2016)'s work on building climate sensitivity.

Results from the individual retrofits and the constant efficacy retrofit simulations are collated with their related presence, lighting and internal heat gains data using the RegressionDataSet from ollie_ml.rb, a generalised data analysis library for Ruby. intermediary outputs are then grouped by their constituent units to attribute changes to utilisation and lighting and heating use. Heat gains are disaggregated from simulation results to estimate the extent to which waste heat from lighting and latent gains affected the building under managed and unmanaged Schedule-Climate scenarios. Standard retrofits results are focused primarily on DCF evaluation. The reason for this becomes apparent from initial Schedule-Climate scenario discussions and constant-efficacy retrofit results explore these in great detail and divergence between scenarios make them somewhat redundant.

The results from NCM and Implicit Schedule-Climate scenarios are interrogated using the RegressionDataSet to group and intersect teaching space utilisation, gains and external temperatures. These are used to express divergence from NCM and real-world operation in terms of the Space Management Group’s utilisation function, and it is determined the extent to which the function is valid. Data are clustered into different temporal granularities and classifications. The results from NCM and Implicit Schedule-Climate scenarios are superimposed to measure divergence from between the scenarios in terms of presence, heating, external temperature, utilisation and net building energy.

A further analysis of the Implicit and NCM Schedule-Climate scenarios focusing on BMS installation using the industry-standard heating efficiency credits method and the proposed schedule-driven BMS method described in R-BMS development subsection. Results were evaluated using DCF evaluation and discussed in terms of the arbnConsult retrofit engine logic, which is the government-approved procedural retrofit analysis tool.

3.8 Summary

The underlying theme of this thesis is dynamic simulation-led retrofit analysis for low-utilisation, higher education facilities. In order to achieve this, a retrofit analysis environment was created as described in Integrated retrofit analysis environment design. Once the development environment was created the solution space was defined as the powerset of the two Climates, three Schedules and the retrofits described in Retrofit options and cost models. Once the 245 EnergyPlus simulations were complete each simulation’s eio, mtr and eplustbl.csv is interrogated for the relevant energy, emissions, presence and internal gains information. The results are aggregated into common data files before comparisons are drawn between each Schedule-Climate scenario. Where retrofit analysis is included in the results or discuss the results are discount in terms of discounted cash flow analysis (time-sensitive valuation), discounted at 3.5% as is suggested for public projects in the Green Book.

The literature review was carried out to understand the occupancy impact problem space and what drives the interactions between occupants and buildings. To achieve this, the literature was grouped into three categories for human, digital technology and built environment reporting at national-level as outlined in Figure 2-1. The literature's primary purpose was to ensure talking points in the thesis did not conflict with real-world occupancy. It also serves as a platform for identifying non-conventional occupants often ignored by research. The Nomad, ancillary staff occupant, for example, is never referenced in the literature as far as could be identified.

A new plot is created as described in Understanding the schedule overlap plot. The plot is used to demonstrate heterogeneity in Schedule set exclusivity and where the NCM Schedule fails to accommodate the real-world. This is aimed at demonstrating why presence-bound tempering and utilisation estimation are ineffective. In the case of the former, with the aim to demonstrate the underlying simulation gaps presence binding creates.

3.9 Conclusion

This section outlines the research methodology used to meet the objectives of this thesis and expand on existing occupancy ontology. It describes the targeting of literature for critical analysis of existing theory and why existing occupancy scheduling was not at the forefront of the analysis. It also describes how the data obtained from the university's Estates department was translated and incorporated into the virtual case study for simulation. The chapter explains how scheduling registration system data was achieved, and the process also describes the integrated procedural retrofit analysis environment's implementation and explains the novel BMS scheduling tool design. It also describes how the data was analysed to produce the results that form the talking points in the Discussion chapter. The sections in this chapter provide an overview of the research design in a manner which is accessible to those not directly involved in the research and will enable the reader to understand the proceeding chapters.

4 Chapter 4 - Virtual case study building energy model

4.1 Introduction

The experimentation in this thesis focused on occupancy scheduling's effect on EnergyPlus simulation. It required collation of building construction and services data and creation of building energy models for a case study. Floor seven of University of Strathclyde's Graham Hills building was chosen and representative data obtained from the university's Estates department. The data, however, was fragmented in multiple and decoupled formats not appropriate for the experimentation. This chapter outlines the processes in translating collated building construction and service data into an appropriate building energy model for the experimentation in this thesis.

4.2 Overview

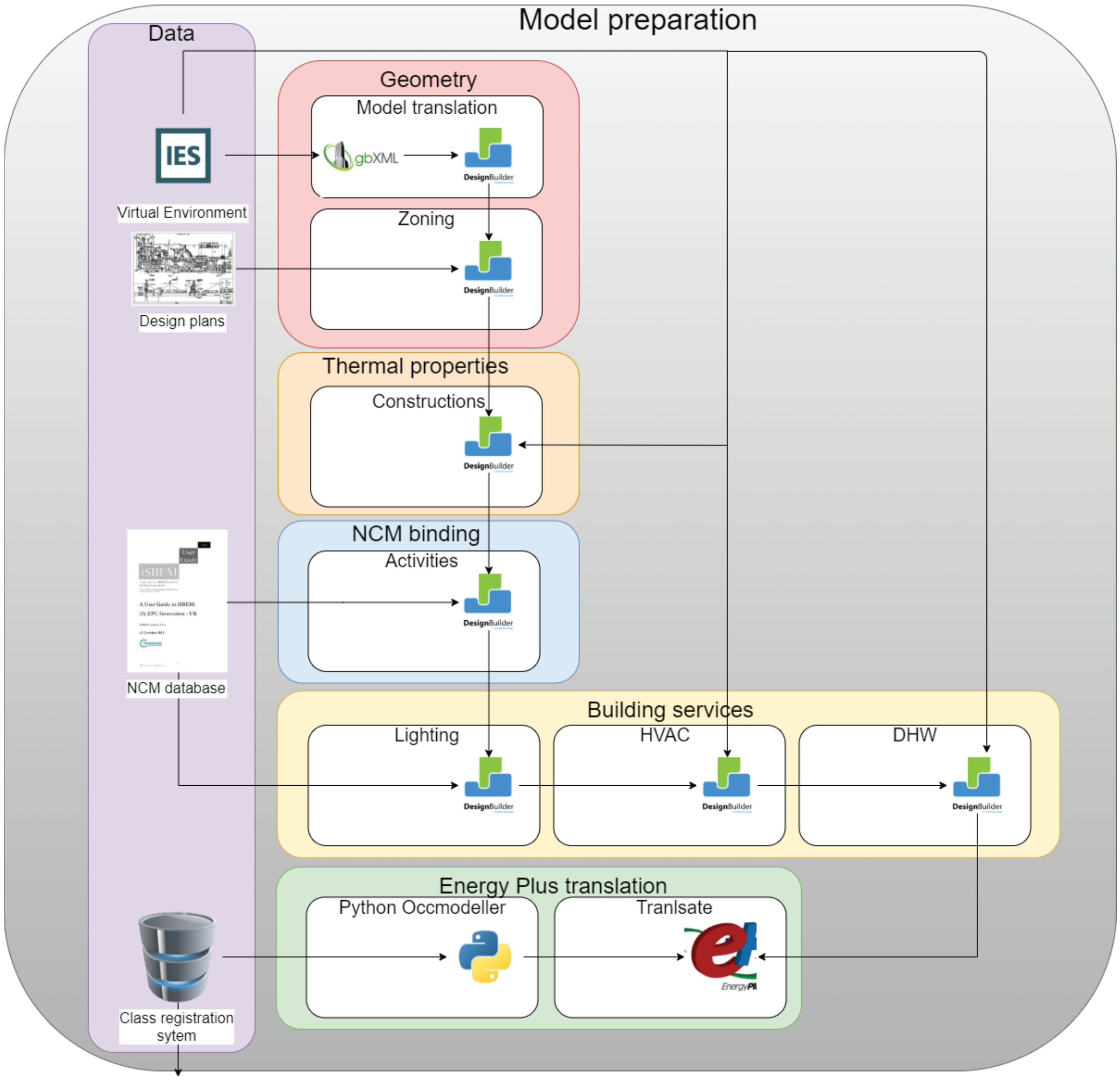


Figure 4-1 Case study model preparation and translation process

The energy simulation component of the research in this thesis carried out on the seventh floor of the University of Strathclyde's Graham Hills building, floor seven. Being an old building, which has been subject of several retrofits over the last twenty years, the data were disparate. Before progressing to the building energy simulation stage, the data which could be identified was assessed to determine the extent which it could practically be utilised. Despite the availability of some data relating to building services, not everything can be meaningfully represented in both simulation engines. Similarly, some forms of input were lost to the existing data such as lighting efficacies or power densities which are difficult to homogenise between simulation engines.

Additionally, as mentioned in the research methodology's ethics data collection section, some desirable data on the demographics of the occupants utilising the teaching spaces were initially of interest but were later discarded from the process. It was decided based on the sensitivity of the information and the privacy concerns surrounding biological demographics. The exclusion was not significantly concerning, though there is a case for its inclusion in future research. Finally, the discussion in this thesis considers the implication of its findings in terms of energy policy in the UK which is dependent on the NCM activities database. The data in which is not readily bound to level 5 energy models nor the attained IES model and therefore required post-modelling binding. This subsection describes the data collected, the homogenisation techniques used to integrate it with both EnergyPlus and SBEM models, and the methods used to bind EnergyPlus to the NCM database.

The required building model was not readily available in a form that could be used for the virtual case studies, requiring combination of an existing IES model, guidelines from the NCM and design plans from the university's Estates department. Experimentation required two models, an SBEM input model and EnergyPlus model. A base model was constructed in DesignBuilder based on the IES model and the information available within it such that both SBEM and EnergyPlus models were comparable. Several additional changes were made to the EnergyPlus model to ensure the NCM values used by SBEM consistently used in EnergyPlus. Figure 4-1 shows the process of translating the original IES model to DesignBuilder and how the external source data is introduced to the model in preparation for exporting to EnergyPlus. This section outlines the translation and preparation process.

4.3 Geometry and zoning

The virtual case study was carried exclusively on the seventh floor of the Graham Hills building and therefore it was not necessary to retain or fill the gaps in the existing IES model for all floors' structural components. However, adjacencies are important features for both EnergyPlus. SBEM is ignorant of adjacency activities though sensitive to adjacency state and presence. Adjacency ignorance results in heat transfer at each step being calculated as the difference between an unconditioned space with assumed conditions, including the outside environment. EnergyPlus is more involved in that it is both aware of the activity or lack thereof of the opposite side of a partition at each step including contributions to the adjacencies passive conditioned state from other zones or the outside. Therefore, both the sixth and eighth floors were retained as were their activities. It should be noted, however, that while SBEM does not consider the scheduling of adjacencies EnergyPlus does. This does not impede the virtual case study, however, in real-world application, it would be advantageous to adapt adjacency schedules where available even if the design project is for a discrete space rather than the whole building.

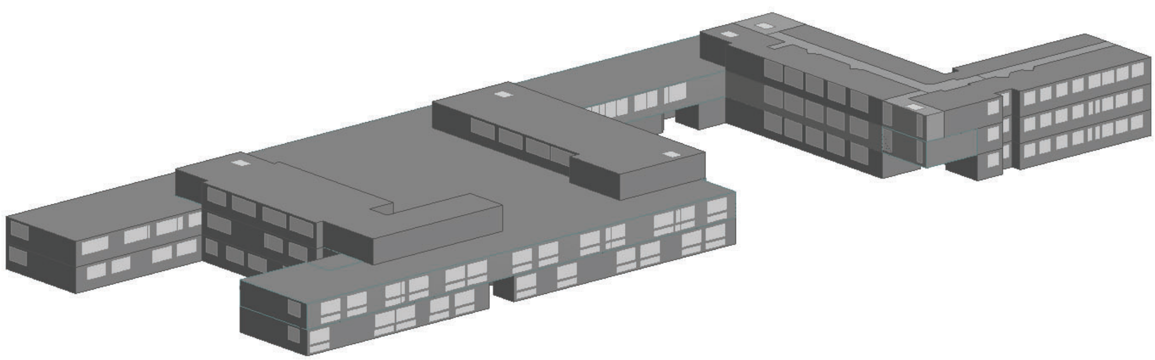


Figure 4-2 DesignBuilder representation of the case study building

The external geometry of the building as shown in Figure 4-2 including individual glazing components was modelled appropriately in the IES model, but internal zoning was not comparable the design plan or registration system labelling, instead explicitly merged by the draughter as is the minimum requirement for Part L2 compliance for which the IES model was created. It raised several problems around integration of scheduling techniques and the binding of data between EnergyPlus, the registration system and the NCM activity database.

The Estates department was contacted to obtain the measured building survey floor plan which was overlaid with the model in DesignBuilder to create the case study zoning as shown in Figure 4-3. Zones were labelled as per the naming convention in the registration system

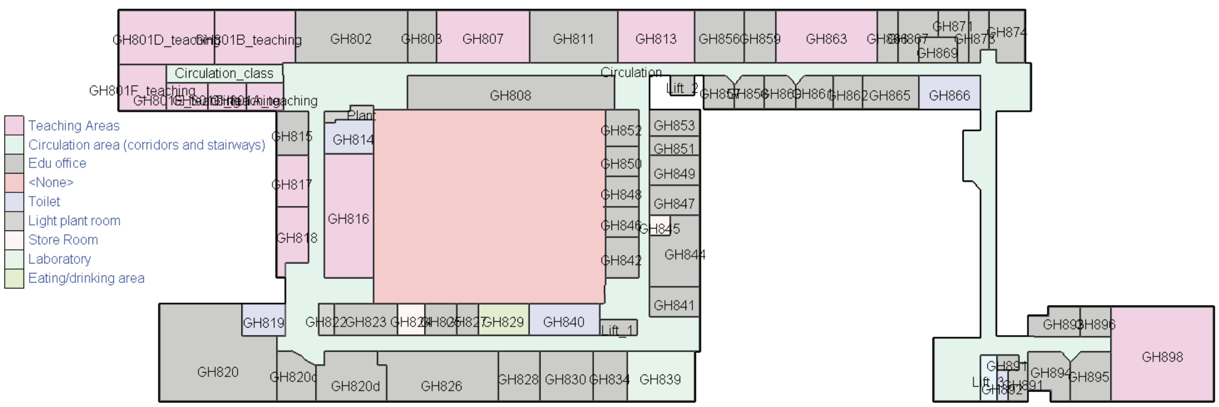


Figure 4-3Case study activity floor plan

4.4 Zone classification

The existing IES energy model was created before the transition from SBEM v3.4.a to 3.5.a and above at which point the NCM building and activity database was reduced and reclassified. Reclassification removed several of components relevant at the time of the IES model's creation, such as a distinction between open plan and cellular offices. Additionally, the IES model's relationship between the NCM "ACTIVITY-NAME" and "ACTIVITY" zone-level properties do not persist when IES creates the building energy model. As a result, the "ACTIVITY" (the value used to reference the activity_types table in the NCM) being set to 1266 (Uni_ClassRm) regardless of the "ACTIVITY-NAME" label. As is discussed in lighting and net energy demand, this property is not only pertinent to the simulation but also required for lighting design watts declaration for zones. Many of the challenges in linking NCM and IDF are resolved in the geometry and zoning section. However, the link to the NCM is not labelled outwith DesignBuilder but a fundamental component of the EplusProject library which prevented an on-the-fly patch on the IES model. The EnergyPlus model was tagged using this method "D1 Non-residential Institutions - Education" as shown in Table 4-1.

Table 4-1 NCM activity database bindings for case study zones

NCM Activity code	NCM Activity ID
Circulation area (corridors and stairways)	1265
Classroom	1107
Eating/drinking area	1269
Office and consulting areas	1284
Light plant room	1277
Storeroom	1279
Toilet	1036

4.5 Heating, ventilation and cooling systems

The seventh floor is served exclusively by a low-temperature hot water boiler fuelled by natural gas and served by wet radiators with thermostatic radiator valves. All zones have natural ventilation except for toilets which have local extract fans. Though the seventh floor exclusively uses LTHW boilers with wet radiators, other floors share several different systems, some of which including cooling and mechanical ventilation. Table 4-2 defines the systems present in the building, including those not utilised by the seventh floor.

Table 4-2 Heating, ventilation and cooling systems in on-site

	Wet radiator	Wet radiator + extra	AHU (boiler)	AHU (ASHP)	Direct electric	Single room cooling	Mitsibishi split
Heat source	LTHW boiler	LTHW boiler	Air source heat pump	LTHW boiler	Local electric	N/A	Air source heat pump
Delivery system	Wet radiators	Wet radiators	Single-duct VAV	CAV (fixed fresh air rate)	Unfanned local room heaters	N/A	Multi-split
Heating fuel	Natural gas	Natural gas	Grid supplied electricity	Natural gas	Grid supplied electricity	N/A	Grid supplied electricity
Seaonal efficiency(%)	82	82	220	82	100	N/A	320
SCoP(%)	73.8	73.8	176	73.8*	80	N/A	254.8
Heat recovery	None	None	Thermal wheel	None	None	None	None
Heat recovery efficiency(%)	N/A	N/A	65	N/A	N/A	N/A	N/A
Heat recovery return temperature(°C)	N/A	N/A	21	21	N/A	N/A	N/A
Thermostatic radiator valves	Yes	Yes	N/A	N/A	N/A	N/A	N/A
Chiller	None	None	Air cooled	Air cooled	None	Heat pump(gas/oil)	Air cooled
System energy effeciency rating	N/A	N/A	2.5		N/A	2.44	2.9
Seasonal system energy efficiency rating	N/A	N/A	2		N/A	1.952	2.3
Nominal energy efficiency rating	N/A	N/A	2.5		N/A	2.44	2.9
Mechanical ventilation type	N/A	N/A	Centralised balanced	Centralised balanced	N/A	N/A	N/A
Specific fan power (W/l/s)	N/A	N/A	2	3	N/A	N/A	N/A
Auxilary energy(kWh/m2@3255hrs)	N/A	1.002	11.16	37.02	N/A	N/A	N/A
Local extract	None	Yes	None	None	None	None	None
Local extract efficiency(%)	N/A	70	N/A	N/A	N/A	N/A	N/A

4.6 Domestic hot water

The building is served primarily by a low-temperature hot water boiler system with storage which is exclusive to the seventh floor. Though not present on the seventh floor there are electric instantaneous point of use systems associated with other zones. Secondary circulation is present in the building. The domestic hot water system does not share heat generation with the wet radiator systems. Table 4-3 shows the properties identified from the IES model and used during EnergyPlus simulation

Table 4-3 Domestic hot water system on-site

Heat source	LTHW boiler
DHW fuel	Natural gas
Delivery efficiency (%)	80
Storage losses(kWh/day)	0.0075
Storage volume(l)	2000
Loop length(m)	100
Pump power(kW)	0.13
Mean cold temperature(°C)	10
Supply temperature(°C)	60

4.7 Lighting

Since the IES model's zoning was merged and the NCM bindings were not retained, the lighting information was not directly translatable from IES to DesignBuilder. It did not persist through gbXML export either. Nonetheless, the "LAMP-TYPE" property for each merged zone was retained in the SBEM input model which enabled introduction of consistent lighting efficacy between SBEM and EnergyPlus lighting. Referencing the SBEM technical guide, the top-lit efficacy for each new zones' related zone lamp types was introduced to the metadata file "./ncm_bindings.csv". The EplusProject uses the file to introduce NCM data to the EnergyPlus model post-DesignBuilder. Binding the data not retained during translation to IDF.

4.8 Envelopes and glazing

Table 4-4 External envelope construction properties

External Wall				
	Layers			
	Material ID: [GPB1] GYPSUM PLASTERBOARD	Material ID: [CBM] CONCRETE BLOCK (MEDIUM)	Cavity	Material ID: [CC] CAST CONCRETE
Specific heat capacity(J/(kg·K))	8400	1000	N/A	1000
Thermal conductivity(W/m.K)	0.16	0.51	0.51	0.51
Density(kg/m^3)	950	1400	1400	1400
Resistance(m^2K/W)	0.0313	0.0196	0.3	0.042
Thickness(m)	0.005	0.01	0.1	0.05
	Surfaces			
	Outside		Inside	
Emissivity	0.9		0.9	
Solar absorptance	0.5		0.55	
	Thermal Performance			
U-Value(W/m^2K)	1.7696			
Thermal mass<CM>(kJ/(m^2K))	17.99			
Mass(kg/m^2)	118.75			
Thermal bridging((W/m^2K))	0.177			

Table 4-4 shows the thermal properties of the external walls extracted from IES. All external envelopes remain without renovation since construction,

Table 4-5 Internal partition construction properties

Internal Partitions (Stud)		
	Layers	
	Material ID: [NCMCBM07] Description: Plasterboard (wallboard) [BR 443]	Material ID: [NCMCBM07] Description: Plasterboard (wallboard) [BR 443]
Specific heat Capacity (J/(kg·K))	1000	1000
Thermal conductivity (W/m.K)	0.21	0.21
Density (kg/m^3)	900	900
Resistance (m^2K/W)	0.0619	0.0619
Thickness(m)	0.013	0.013
	Surfaces	
	Inside	
Emissivity	0.9	
Solar absorptance	0.55	
	Thermal Performance	
U-Value(W/m^2K)	2.605	
Thermal mass<CM>(kJ/(m^2K))	11.7	
Mass(kg/m^2)	23.4	
Thermal bridging((W/m^2K))	0.035	

Table 4-5 shows the thermal properties of the stud partitions which separate spaces where no load-bearing wall is present. These properties were also identified from IES as with those in Table 4-4, however, in the unlikely event they were retrofitted it is unlikely the assessor creating the IES model would have known. EPC surveys only require a glance and selection of representative partitions.

Table 4-6 Internal load-bearing walls construction properties

Internal Partitions (Brick)			
	Layers		
	Material ID: [PLL] Description: PLASTER (LIGHTWEIGHT)	Material ID: [BRI] Description: BRICKWORK (INNER LEAF)	Material ID: [PLL] Description: PLASTER (LIGHTWEIGHT)
Specific heat capacity(J/(kg·K))	1000	800	1000
Thermal conductivity(W/m.K)	0.16	0.62	0.16
Density(kg/m³)	600	1700	600
Resistance(m²K/W)	0.813	0.1694	0.813
Thickness(m)	0.013	0.105	0.013
	Surfaces		
	Inside		
Emissivity	0.9		
Solar absorptance	0.55		
	Thermal Performance		
U-Value(W/m²K)	1.6896		
Thermal mass<CM>(kJ/(m²K))	79.2		
Mass(kg/m²)	194		
Thermal bridging((W/m²K))	0.169		

Table 4-6 Internal load-bearing walls construction propertiesTable 4-6 shows the thermal properties of the load-bearing internal envelopes.

Table 4-7 Flat roof construction properties

Flat Roof				
	Layers			
	Material ID: [CLT] Description: CEILING TILES	Cavity	CavityMaterial ID: [CC1] Description: CAST CONCRETE	Material ID: [F/B] Description: FELT/BITUMEN LAYERS
Specific heat capacity (J/(kg·K))	1000	N/A	1000	1000
Thermal conductivity (W/m.K)	0.056	N/A	1.13	0.5
Density (kg/m³)	380	N/A	2000	1700
Resistance (m²K/W)	0.1786	0.17	0.0885	0.01
Thickness (m)	0.01	0.8	0.1	0.005
	Surfaces			
	Outside		Inside	
Emissivity	0.9		0.9	
Solar absorptance	0.5		0.55	
	Thermal Performance			
U-Value (W/m²K)	1.7034			
Thermal mass<CM> (kJ/(m²K))	3.8			
Mass (kg/m²)	212			
Thermal bridging (W/m²K)	0.17			

Table 4-7 shows the thermal properties of the building's flat roof. It should be noted, however, that this is not the only roof envelope which is essentially external in the model. The model has considerations for heat transfer to zones excluded from the simulation results.

Table 4-8 Raised floor construction properties

Raised Exposed Floor			
	Layers		
	Material ID: [SCP] Description: SYNTHETIC CARPET	Material ID: [SC] Description: SCREED	Material ID: [CC] Description: CAST CONCRETE
Specific heat capacity(J/(kg·K))	2500	840	1000
Thermal conductivity(W/m.K)	0.06	0.41	1.13
Density(kg/m^3)	160	1200	2000
Resistance(m^2K/W)	0.833	0.122	0.0885
Thickness(m)	0.05	0.05	0.1
	Surfaces		
	Inside		
Emissivity	0.9		
Solar absorptance	0.55		
	Thermal Performance		
U-Value(W/m^2K)	0.7976		
Thermal mass<CM>(kJ/(m^2K))	70.4		
Mass(kg/m^2)	260		
Thermal bridging((W/m^2K))	0.08		

Table 4-8 shows the thermal properties of the internal floors. These floors are not underground or at surface level and therefore better classes as “floor or ceiling” in DesignBuilder. However, since heat transfer to zones not included in the simulation results is accommodated, these are to an external surfaces to the extent that their heat losses and gains are to and from the external environment.

Table 4-9 Single glazing construction properties

Single Glazing		
	Layers	
	CLEAR FLOAT 6MM	
Specific heat capacity(J/(kg·K))	8400	
Thermal conductivity(W/m.K)	1.06	
Density(kg/m³)	8400	
Resistance(m²K/W)	0.0057	
Thickness(m)	0.006	
	Surfaces	
	Outside	Inside
Emissivity	0.9	0.9
	Thermal Performance	
U-Value(W/m²K)	5.5617	
U-Value(W/m²K) Glass Only	5.6928	
Transmittance	0.78	
G-Value	0.8199	

Table 4-9 shows the glazing thermal and solar transmittance properties. The glazing has not been replaced since construction nor is there secondary glazing.

4.9 Building Climate Data

The impact of climate on building energy performance has been demonstrated for long-term climate predictions by (Rastogi, 2016) through his synthetic weather data generator. The generator creates a diverse set of probable climate models for EnergyPlus and ESP-r. His work establishes that given the uncertainty of future climates the standard approach to single climate scenario building design and retrofit decision-making is not enough for design confidence. He proposes that design decisions should be made through observation of strategy sensitivity from simulation with many climate scenarios. This thesis does not integrate stochastic climate modelling as developed by Rastogi. However, it does present two climate scenarios to demonstrate sensitivity beyond the significance of presence. This is achieved by producing results for simulations using the same building energy model with the 2016 and 2017 CIBSE climate data for Glasgow Airport.

4.10 Conclusion

This chapter outlines the case study building and how it was converted to its building energy model. It described the building in the real world and its history in terms of construction and retrofitting. It described the data that was that formed the constituent parts of the building energy model, including the services which are in the building but not the case study floor. The discussion proceeded with an explanation of how the building energy model was created from the data retrieved from the university's Estates department. It also explained why where there were gaps in the data from both the Estates department and resulting from the translation from the DesignBuilder interface to IDF. It explains the normalisation techniques to make retrofitting consistent with legislative methods, namely in binding the NCM lighting design illuminance levels. Finally, it described the scope of the climate conditions considered why multiple climates were considered.

5 Chapter 5 – Results and Analysis

5.1 Introduction

This research in this thesis set out to demonstrate the ineffectiveness of building energy modelling in low-utilisation buildings where scheduling does not match real utilisation. It used a virtual case study based on using University of Strathclyde's Graham Hills building, floor seven as virtual case study. The primary practical hypotheses were that retrofit return on investment predictions have no relevance in the real world and conflicts between simulation and operation cause a functional simulation gap. It aimed to achieve this by running 245 EnergyPlus simulations combining three simulation methods and cost models with ten Schedule-Climate scenarios. This chapter presents the results from these simulations.

In this chapter, the reader will find data on overall building performance under different Schedule-Climate demonstrating the calibrating effect of proper scheduling and the effect of heating management on business-as-usual running cost estimation. The chapter proceeds with an exploration of the presence and gains assumed and recorded for classrooms. These data are used to demonstrate heterogeneity of schedules at zone level and how far NCM schedules deviate from reality.

The results proceed with presentation of the retrofit results. Boiler replacement and BMS installation are discussed in terms of cost, how they related and how they perform using discounted cashflow analysis. The chapter's results conclude with discussion on 80 constant-efficacy retrofits under the ten Schedule-Climate scenarios.

5.2 Building energy performance

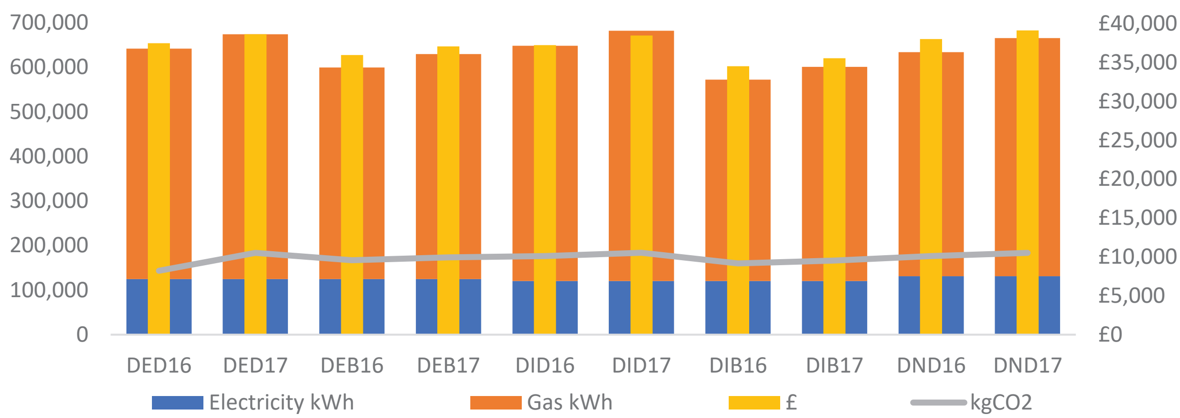


Figure 5-1Schedule-Climate base model simulated performance

Labelled bars show kWh/annum per fuel type and the grey line showing kgCO2/annum with both sharing the left y-axis. Yellow bar and right y-axis show annual running costs.

Table 5-1 Schedule-Climate end use and emissions

	Schedule-Climate scenario end use and emissions							
	kWh				£			
	2016		2017		2016		2017	
	Electricity	Gas	Electricity	Gas	Electricity	Gas	Electricity	Gas
NCM	131,303	502,438	131,303	534,033	20,024	17,987	20,024	19,118
Explicit	124,495	516,901	124,495	549,270	18,985	18,505	18,985	19,664
Implicit	120,435	527,555	120,435	561,346	18,366	18,886	18,366	20,096
	kWh/m²				£/m²			
NCM	45.75	175.08	45.75	186.09	6.98	6.27	6.98	6.66
Explicit	43.38	180.12	43.38	191.4	6.62	6.45	6.62	6.85
Implicit	41.97	183.84	41.97	195.61	6.4	6.58	6.4	7
	kWh % difference NCM				£-NCM difference			
Explicit	94.82%	102.88%	94.82%	102.85%	520.45		492.72	
Implicit	91.72%	105.00%	91.72%	105.11%	750.09		679.48	
	Total kWh				Total £			
NCM	633,741		665,336		38,011		39,142	
Explicit	641,395		673,765		37,490		38,649	
Implicit	647,990		681,781		37,253		38,463	
	$kgCO_2/m^2$				$kgCO_2$/£			
NCM	61.56		63.94		4.65		4.69	
Explicit	61.42		63.86		4.70		4.74	
Implicit	61.49		64.03		4.74		4.78	
	Schedule-managed heating adjustment							
	Electricity	Gas	Electricity	Gas	Electricity	Gas	Electricity	Gas
Explicit	124,495	474,843	124,495	505,024	18,985	16,999	18,985	18,080
Implicit	120,435	451,545	120,435	480,164	18,366	16,165	18,366	17,190
	Total kWh				Total £			
Explicit	599,338		629,519		35,985		37,065	
Implicit	571,981		600,600		34,531		35,556	
	$kgCO_2/m^2$				$kgCO_2$/£			
Explicit	58.26		60.53		4.65		4.69	
Implicit	55.77		57.92		4.63		4.67	

Figure 5-1 show the results from all Schedule-Climate scenarios using EnergyPlus in the virtual case study's a-built state. Heating demand grew slightly under 6% between 2016 and 2017 for NCM scheduled Schedule-Climate scenario. The Implicit-2017 Schedule-Climate scenario likewise near 6% though slightly compared to its 2016 counterpart though slightly over 6%. The premise of this thesis that unmanaged absence is a form of presence, the registration system-based Schedule-Climate scenarios increase base heating demand on NCM- Schedule-Climate scenarios. As would be expected, this is near proportional to the increase in zero-density presence hours or absence-as-presence. The resulting increase is 5% for Implicit-2016 compared to NCM-2016 and 10% compared to NCM-2017. In contrast, where heating is managed, or absence-as-absence Schedule-Climate scenario proportionally decreased heating energy demand, 12% compared to NCM-2016 and 18% against NCM-2017. The key observation from figure 1 is that absence-as-presence increases heating demand near proportional to the decrease in presence hours whereas absence-as-absence decreases heating demand near proportional to the decrease in presence hours. Slight deviation can be attributed to dynamic heat transfer between zones and deviations in occupant density.

The virtual case study is a simple discrete space which lends itself to exhibiting less volatility in the results than would be expected of the whole building includes some mechanical ventilation and cooling. Carbon emissions associated with interacting consumers are represented by a nonlinear system. Where net energy is the sum of the energy used across all systems to meet individual demand types, emissions are a function of the collective fuel consumption across all consumers whose operation affects any given demand type. For example, a simple lighting system contributes to an increase in lighting and cooling energy demand and decreases heating energy demand at constant rates. In contrast, lighting contributes heating and cooling, but the contribution is affected by the mix and operation of the systems which service the indirect consumer demands. This s particularly apparent with the results both Schedule-Climate scenario groups with results for 2016 Schedules sorted in ascending order Explicit, Implicit, NCM whereas 2017 Explicit, NCM, Implicit. In all cases, the change is insignificant with Explicit-2016 being only 0.12kgCO_2/m² less than NCM and Implicit-2017 being 0.07kgCO_2/m² greater

NCM-2017. However, it indicates a latent effect of internal gains from lighting or occupants on absence-as-presence inherently bound to the heating demand and fuel of the direct and surrounding discrete spaces. Furthermore, the results exemplify expected Climate sensitivity will not necessarily only diminish seemingly intuitive reduction form lower utilization but may also reach the turning point where further reducing utilisation causes deterioration of a buildings energy performance.

The heating system is fuelled by natural gas which has the lowest emissions conversion factor of all non-renewable fuels at 0.216kgCO2/kWh, where electricity has the highest at 0.519kgCO2/kWh. Were electric used to serve the teaching spaces the increase would be far more significant? Swapping the LTHW boiler with a direct electric system, increasing the SCoP from 0.738 to 0.8 (as per CoP of 1 handling in NCM models) changes the increase in emissions associated with the heating system to 4.56kgCO2/m^2.

includes an uncommon metric that would be useful for equiproportionate abatement policy kgCO2/£. This form of abatement enables exploitation of the equimarginal principle that if the opportunity is present, an agent will choose a combination of goods that maximise utility. Opportunity is dependent on availability of goods with quantifiable utility. That is, maximisation potential is related to the number of goods which can be described in cardinal.

The principle is self-explanatory when describing all building stock, but it also has the potential to mitigate the problems with defining a building as a set of discrete spaces. Consider a shopping centre in England which for the purpose of private rented sector minimum energy efficiency standards legislation is a collection of lettable spaces, otherwise referred to as discrete spaces in this thesis. Each leasable space is must be demonstrated to meet minimum energy efficiency before a new or a renewed lease may be granted. This raises a few issues, but the primary concern is the heterogeneity of fit-outs and leases preventing use of a shared energy performance certificate. A stationary store, for example, is unlikely to have a light power density similar to a high-end clothing retailer. Therefore, there is no guarantee any lettable space's next tenant will have a comparable fit-out to the current. However, they are still discrete spaces of the same building which share envelopes and may share HVAC services. This is where an equiproportionate system has significant potential. Retrofitting whole-building systems results in changes which are impervious to changing tenants and their contributions to subsequent EPC ratings persist in every model. This is particularly beneficial where leasing includes a strip-out clause. They also provide new tenants with more flexibility in fit-out design since the standing performance of the space is better than it would be without the upgrades. Additionally,

Central air handling units where present tend to contribute significantly to poor EPC ratings due to the rampant use of the default 3W/l/s specific fan power which contrasts with the L2B minimum 2.2W/l/s or L2A 1.6W/l/s. Therefore, mechanical ventilation retrofitting is desirable

5.3 Classroom scheduling

The registration system schedules used to produce the Compact:Schedule(s) which dictate utilisation to Energy Plus was translated from University of Strathclyde's Estates department registration system. Though the case study discrete space has only 13 registered spaces, 7 of which being completely vacant for the registration period, there were 2024 registered nonzero-density presence periods and 282 zero-density presence periods. As described in the methodology chapter, these registrations formed the basis of occupant and lighting schedules in the unmanaged Schedule-Climate scenarios and the heating availability schedule for HMS scenarios. While there were initial expectations about how the schedule would differ from design it became clear early on that differences are well beyond even the most reasonable assumption that may guide stochastic occupancy analysis. In fact, the registered periods are so contrasting with design schedules that the previous sections on the SMG utilisation function necessitated expansion. The register opened a Pandora's Box of utilisation avenues for economic, social, behavioural, operational and design-related questions. To that end, the disparity between real-world and design schedules is likely one of the more profound observations of this thesis. This section explores the deviation from design within the scope of teaching spaces.

Note: *Unless the context is explicitly stated as all teaching spaces, it should be assumed that discussion in this section is scoped to only the 6 teaching spaces with registered nonzero-density presence.*

5.3.1 Understanding the schedule overlap plot

In order to aid comprehension of overlap between design and registered utilisation periods, a bespoke graph format was created for representing individual zones. The graph is not designed for seeing subtle differences between design and registered periods but is useful for visualising the major disparities such as out-of-design days and significant periods of inoccupancy. Its secondary function is to show the divergence of cumulative presence which should be noted is not directly correlated with utilisation as defined by the SMG utilisation function.

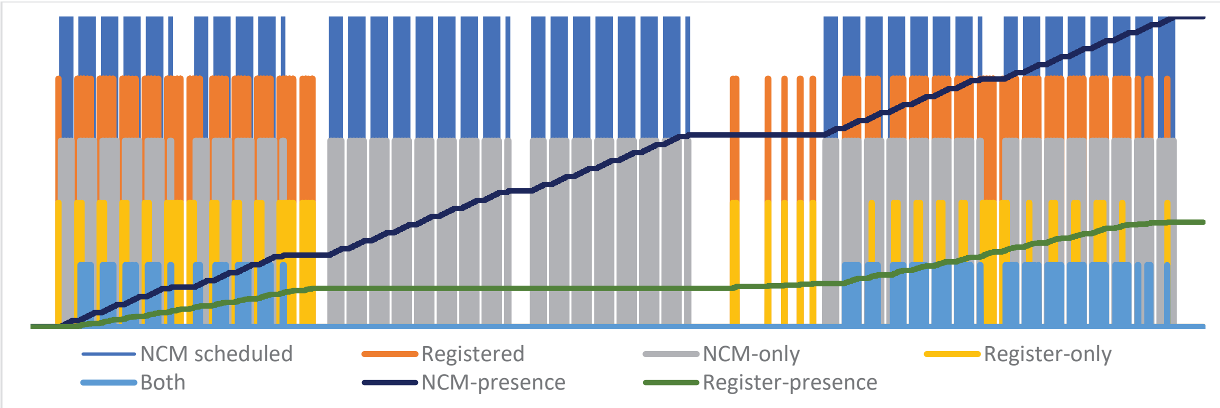


Figure 5-2 Example Schedule set membership and cumulative presence plot

The plots formatted as shown in Figure 5-2 Example Schedule set membership and cumulative presence plotFigure 5-2 represent a full year of their scheduled entry overlap between design and registered presence. It consists of two data groups, one for schedule overlap and one cumulative presence. The first group which consists of “NCM scheduled”, “Register”, “NCM-only”, “Register-only” and “Both” from the top demonstrates design and register presence periods and then overlap set membership. Each line is sorted such that hierarchical set representation is not impeded by varying membership. The lines have no numerical or categorical values, either they are present which indicates presence for the top two and membership for the remaining three or they are absent demonstrating inoccupancy or membership status. The three ownership sets are self-explanatory, those with “-only” in the name indicates exclusivity while “Both” indicates overlapping scheduled periods. However, the plot is ignorant of individual classes which were deemed meaningless in the context of simulation since the activity does not dictate special processing considerations beyond the necessity of high-end services such as high-efficiency particulate air filtering. Instead, the graph represents each individual period recorded in the results at whatever level of detail is requested during EnergyPlus output configuration. The x-axis denotes progression from January 1st to December 31st.

5.3.2 Utilisation overview

Classrooms account for 13 of the 79 zones, and 25% of a gross internal area which contributes to the calculated net energy demand. 6 of the zones have no registered utilisation while 1 has zero-density presence which has been treated as strictly no occupants or lighting for both Explicit and Implicit schedule strategies., 10% of the building is never utilised during the academic year with 2.5% which is reserved but never subject to nonzero-density presence. The two horizontal bars indicate the Schedule strategy to NCM design hours when considering all teaching spaces under as configured be their respective schedule. It can be seen that across all teaching spaces the percentage design presence is conservatively 60% with Explicit scheduling and 14% with strict Implicit scheduling which means over the simulation up to 86% of all simulated presence hours are wasteful.

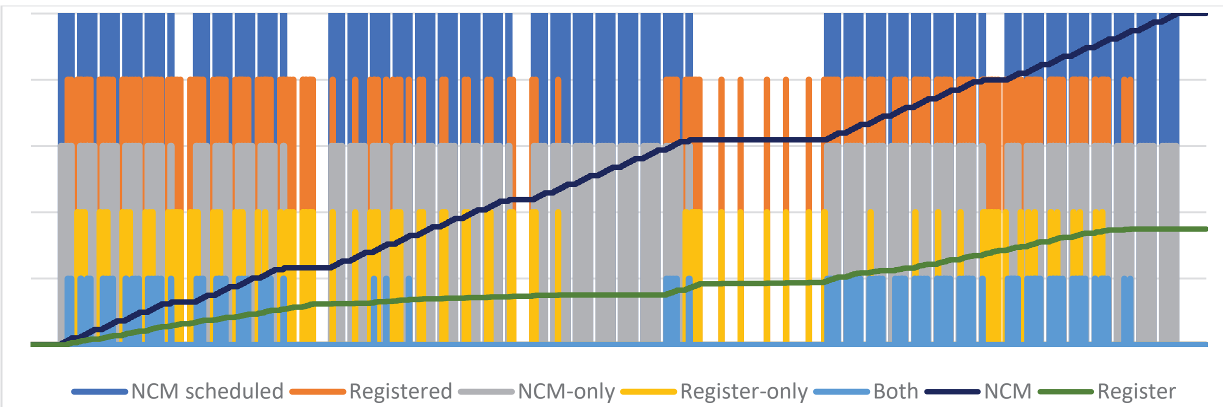


Figure 5-3 GH813 Schedule set membership and cumulative presence plot

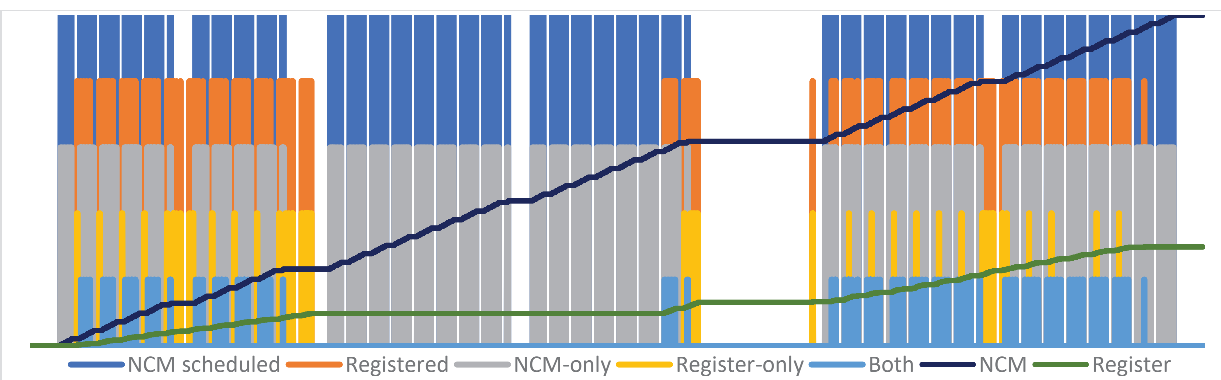


Figure 5-4 GH816 Schedule set membership and cumulative presence plot

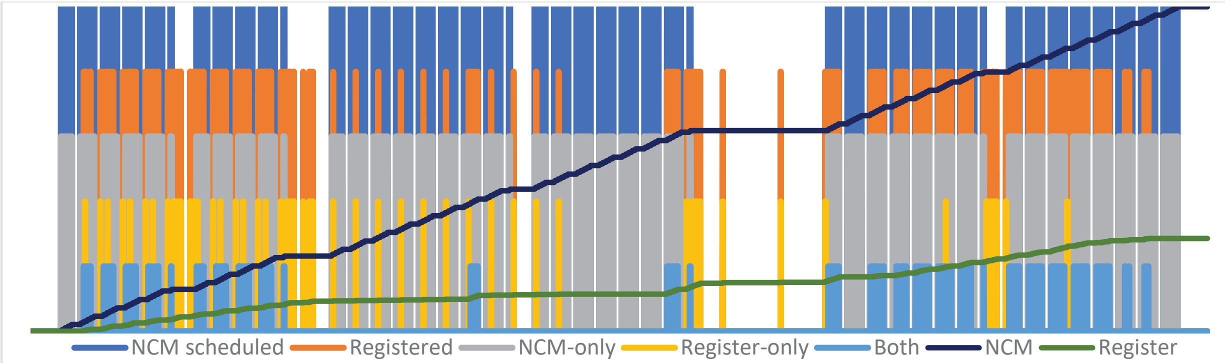


Figure 5-5 GH817 Schedule set membership and cumulative presence plot

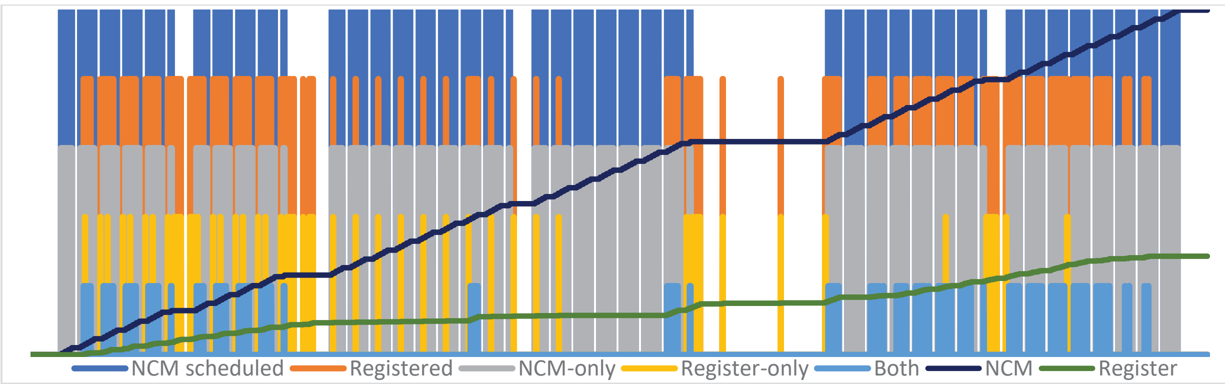


Figure 5-6 GH818 Schedule set membership and cumulative presence plot

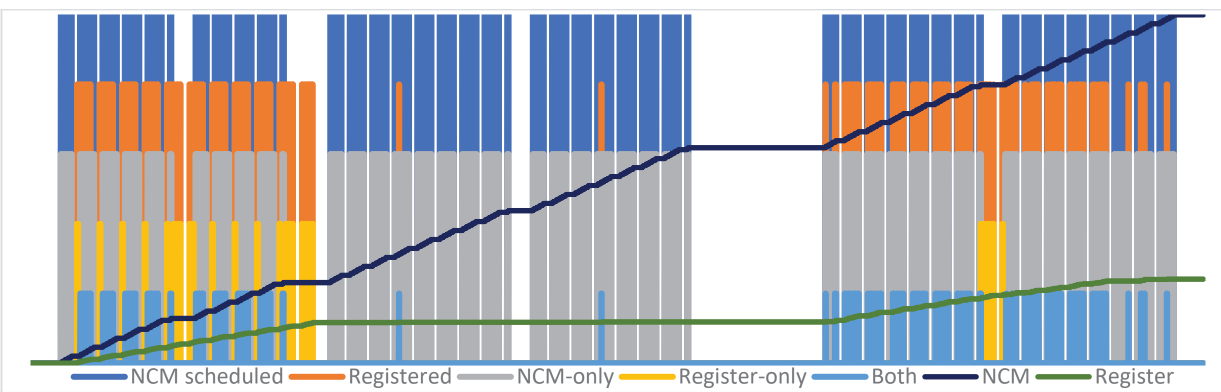


Figure 5-7 GH863 Schedule set membership and cumulative presence plot

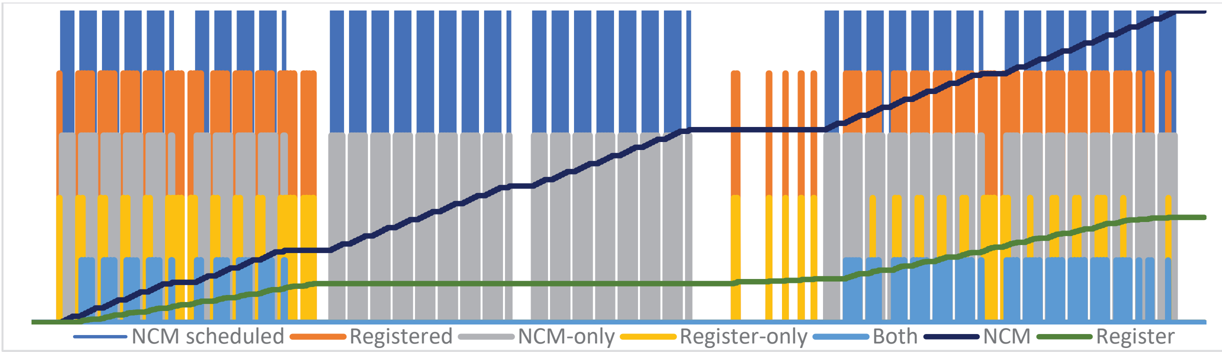


Figure 5-8 GH898 Schedule set membership and cumulative presence plot

As shown in Figure 5-3, Figure 5-4, Figure 5-5, Figure 5-6, Figure 5-7, Figure 5-8, the presence schedules for each teaching space. There is three significant observations from these figure. First, GH813, Gh863 and GH898 have almost zero presence between April and August. Second, GH863 is the only space which has no registered presence during the summer holiday in the NCM Schedule. Third, it is not uncommon for registered periods of presence over the weekend, typically a Sunday.

The 6 teaching spaces have 30% of design presence hours and 27% utilisation as defined by the Space Management Group (SMG) for months with greater than zero design presence hours. Utilisation is both in line with what the university estimates of 27% for occupied teaching space and slightly above the SMG's surveyed average utilisation rate for teaching spaces of 26%. Discussed in the needs discussion is the problem with the SMG utilisation calculation, which requires at least one nonzero-density design presence hour in the given assessment period. Only August has zero presence design presence hours during which there are only 26.5 nonzero-density presence hours which is 0.7% of the total registered hours. However, this demonstrates why the SMG method is not appropriate for all teaching spaces in a higher education facility. The SMG utilisation method is further impeded by the disparity in design and operational presence hours. 1173 operational hours occur outwith design presence. This means there is no comparable design density for these periods which would be another trigger for sub-annual SMG utilisation calculations. Without nonzero-density design presence for a given period, the function will necessarily return zero. This is not the same type of issue as previously noted. However, it shows that design presence domains do not include all potentially utilisable periods. On the surface, this suggests that design presence is 27%

of operational presence and that what is considered total presence hours, design presence, is at least 8% lower than necessary. While other criticisms of the SMG utilisation method are proportionally significant to the disparity in operational and design presence, this is an unobjectionable universal flaw. Though beyond the scope of this thesis, this should have a significant impact on building owners' marginal utility calculations involving floor space, energy and/or staff investment return.

Annual day utilisation is less disparate since teaching spaces are occupied on average of 135.5 nonzero-density presence day and 151 presence days compared to 194 design presence days. Figure 5-9, FIG shows the breakdown in days for each registered teaching space. However, as shown in the presence days diagram, there is an obvious disparity in the weekday distribution of presence days, notably an average of 17% presence schedules on weekends which have zero design presence. This observation of weekends was obviously suspicious which merited manual interrogation of the registration system data which confirmed the simulated schedule and registered align correctly. The process also provided a secondary confirmation of correct zero-density presence handling. The collective registered teaching days have 167 instances of mornings where a teaching space is occupied before the design period begins. The concern this present is further exacerbated with only 71 taking place on design days.

Bringing it back to the SMG definition of utilisation, there is an inherent flaw in its building-level application. Removing weekend days from the design presence hours percentage of 30%, only 27% of operational presence hours occur on days with design presence. As noted with other discussion on the SMG utilisation method, would not cause an error in the calculated results at annual or monthly with the exception of August which has zero design presence. However, it demonstrates a couple of issues with the calculation clearer than is implied by the 1173 hours not represented in the design presence schedule. Not only does the SMG utilisation function breaks down at the hourly and monthly levels, it can also produce erroneous results at the individual day level. Furthermore, a significant case for redefining what it means to be utilisable during out-of-design periods occurs.

Previously in this section utilisation was adjusted to accommodate the extra hours not included in design presence; however, if classes are scheduled during the weekend

Saturdays and Sundays should surely be included in the practical utilisable period? Conservatively, this would make design presence 5% less than as defined and operational presence 2% less. This is under the assumption that only the out-of-design weekend hours are added to the design presence. However, if each day is considered fully utilisable with 11 hours as per the typical NCM day the total presence hours increases from 12,804 to 19,404 reducing current SMG utilisation function presence hours to only 65% of the potential. The design to operational presence rate would be reduced from 30% to 20%. Though it would not be the recommendation of this thesis if this were to incorporate the average day length for days with greater than design presence hours, design presence hours would be 39% under and operational presence rate would be only 18%. Finally, the most extreme case based on the longest run period for any given day of 15 hours operational presence rate is reduced to 17% and design presence is under by 41%. As noted, the SMG does not work with zero presence spaces; however, the extreme estimate across all teaching spaces using an operationally adjusted SMG utilisation function would closer to 10% - 12%.

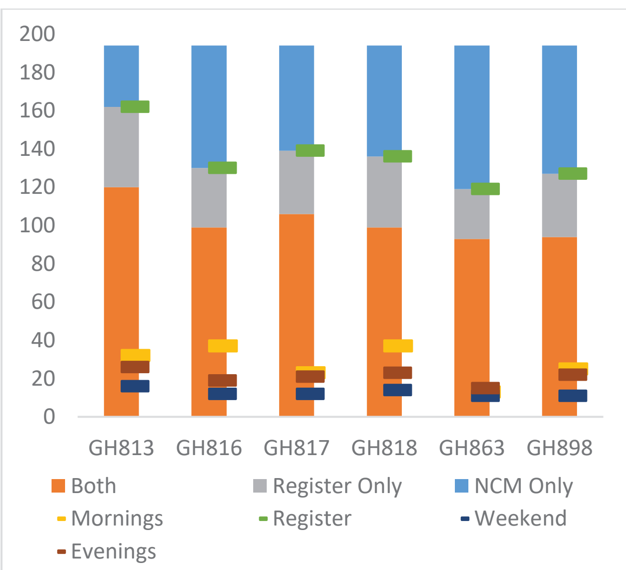


Figure 5-9 Schedule source day set membership

Classroom annual schedule overlap and distribution of out-of-design presence days. The three bars ticked with a green mark denote the schedule scenarios set membership between both NCM and exclusively registered, and exclusively NCM scaled to 100%

NCM. The three additional checkmarks show the total number of out-of-design periods which fall under the three comparable states. Morning and evening occur out-of-design on design days and weekend both out-of-design and on non-design days.

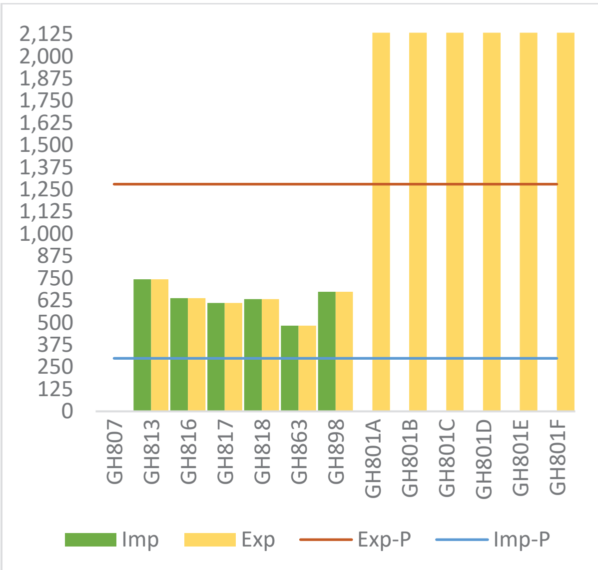


Figure 5-10 Schedule scenario presence summary

Classroom annual presence used for each Schedule-Climate scenario Explicit and Implicit scenarios with bar scale 100% at NCM level. Lines represent total percentage NCM presence for Explicit and Implicit schedules.

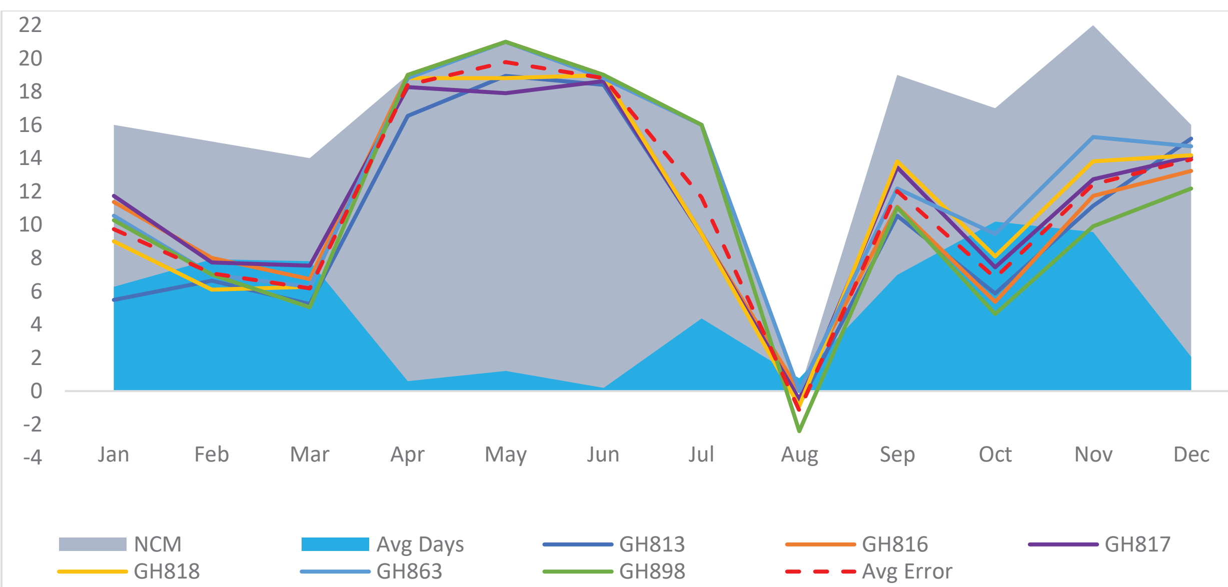


Figure 5-11 Register and NCM schedule comparison: Days per month

Monthly breakdown of the difference in days between the NCM and register Schedule scenarios for each registered teaching space.Grey and cyan areas represent the total number of days for each month in the NCM and the average number of registered days across the classes. Solid lines representing individual classes show the difference in the number of days between the register and NCM. The red dotted line shows the average difference or divergence from the NCM schedule.

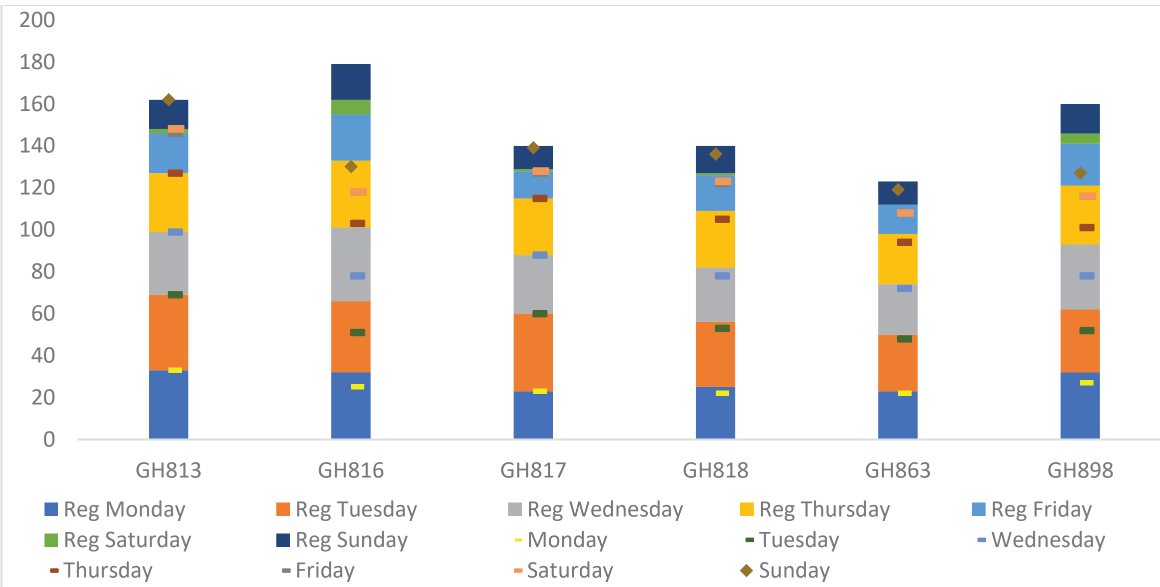


Figure 5-12 Weekday presence hours distribution overview

Weekday breakdown of registration system registered periods of occupancy. The stacked bar represents the total presence periods per weekday for each class with "Reg" prefixed labels. Stacked tick marks represent filtered register periods removing those with zero-density presence. Tick value represented by the base of the tick.

5.3.3 Utilisation and dependent consumer demands

Deviation between design and operational presence is not exclusive to the number of hours utilised. Only 69% of the registered presence hours occur during periods where there is both design and registered presence. This means that roughly one-third of registered periods are not treated as occupied periods during design. Since the NCM design day has uninterrupted presence, these unaccounted-for periods occur either at the end of the day, at the start of the day or on days which are considered to have no presence in design. The first scenario is less of a concern than the others in terms since they occur during the decreasing external temperature and fall at the end unmanaged heating cycle. That is, as discussed in the previous section, the periods occur within close proximity to the last design period. Therefore, if they were added to the design the internal gains from the previous periods would soften the increase in net energy demand. Operationally the worst-case scenario is related to thermal comfort rather than building performance. However, the latter two are of bigger concern. The HVAC whether statically time-constrained or controlled by optimum start-stop starts reheating the building each occupied day at a certain time which is necessarily bound to the initial presence period. This has two profound effects. First, the earlier start period increases the degree-days that must be offset increasing demand exponentially. Second, if the first is not remedied then the thermal comfort of the first occupants is not considered during operation or design and all else equal, the opposite of the first would be offset indirectly through internal gains.

Figure 5-9 provides an indication of how many heating periods are antagonistic to design in the form of days where the registered classes occur before the first NCM scheduled period. In the registered classes, these range from 10% to 28% of their respective total registered days. All-in, there are 167 collective registered teaching days whereupon the heating system is not modelled considerate of occupant comfort or the real-world latent and lighting gains during the warmup period. The case study does not have optimum-start/stop or weather compensation controls which under normal circumstances would improve heating system utilisation. However, with varying start periods, these would not be useful measures. Similarly, time controls without BMS, as discussed later in this chapter would not be suitable.

The dilemmas surrounding earlier registered morning periods is more concerning when considering the building as a whole. It can be assumed that for a nonconstant operation building, ancillary staff must enter the building prior to the first registered primary activity. This obviously raises the question of when the true first occupant arrives but more pressingly, it is important to know the role of the ancillary occupants. For example, a maintenance staff member is unlikely to require frequent access to primary activity zones or at least this access should not be a frequent event. Additionally, their presence for nonemergency visits can be logged in advance which is ideal for heating management. In contrast, cleaners will require access to all primary and secondary spaces with varying entry times, frequency and durations. In the case of the maintenance occupant, their actions could be integrated with a BMS to mitigate with significant value assuming that role is the only occupant present during their initial periods. However, the same cannot be said for cleaners. The problem is further complicated by the presence of passively conditioned spaces. Circulation areas often do not have their own outlets on the heating network, instead reliant on heat gains from adjacent spaces. Additionally, some conditions spaces rely on negative pressure pulling tempered air into them upon an occupant's entry.

Figure 5-9 also provides an indication of how many periods there are whereupon classes begin after the end of the teaching space contribution to total design presence. Unlike morning periods these are at earlier points in the evening are synergistically needy especially if the surrounding spaces are either scheduled to be or operationally vacant during evening registered spaces. That is, any tempered air or thermal mass in the building is dissipated wastefully at the end of an operating day since. However, this becomes less of a benefit and potentially a burden at later points in the evening. The latest registered class appearing the register, for example, is at 10 pm on the 30th of November with an average external dry bulb temperature of 2.93°C during the design period with the last design period temperature 2.7°C and 1°C at the last registered period. The offset between last design and registered periods during the winter period suggests that mitigated demands from passive heat recovery would not meaningfully persist throughout the entire post-design heating period.

Operational heating period degree difference was estimated to be 28% greater than design from design start to registered close by using external dry-bulb temperature and activity set point as a proxy for degree day variables, 34% if the earliest registered period is considered and 42% if a one hour preheat is added. The problem extends to functionality as well as expressed previously regarding passively tempered spaces. Passively tempered spaces are dependent on neighbouring spaces' conditioning which means that in order for these spaces to serve their function with acceptable thermal comfort tolerances, they must be artificially tempered, or their neighbours tempered. This suggests that in addition to this thesis' predictions on out-of-design contributions to the building performance gap, it has the potential to prevent buildings from functioning to minimum standard as designed. It is impossible to predict depreciation of passive heat recovery or indeed out-of-design heating demands from evening classes, but it clearly affects performance, occupant needs and design function. Therefore, it unquestionably should be considered during design.

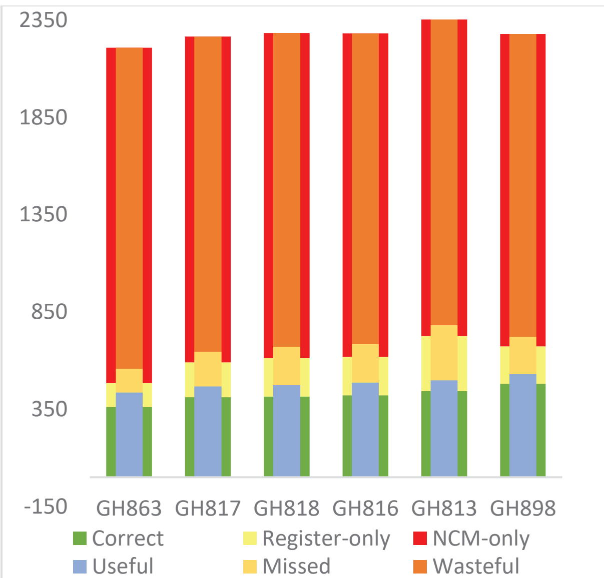


Figure 5-13 Heating mismanagement overview: Hours per classroom

Composite stack of all hour presence periods from both NCM and registration system entries for each class. Thick stack bars represent literal entries where nonzero-density presence occurs in their respective set with "correct" representing membership of both NCM and registration system, and "Register-only" and "NCM only" representing exclusivity to one schedule source. "Register-only" may best be considered out-of-design periods. Skinny stack bars represent register-appropriate heating periods in the NCM schedule, out-of-design periods which were entirely missed by the NCM heating schedule and NCM heating periods which have no overlap with the heating requirements of the registered classes. The latter is defined as periods which exist I the NCM which have no related register period either at the NCM presence time or within one hour prior to the time. In lieu of a full heating period calculation, the external dry bulb temperature was used to filter any entries which met or exceeded the activity set point temperature which removed 70 hours.*

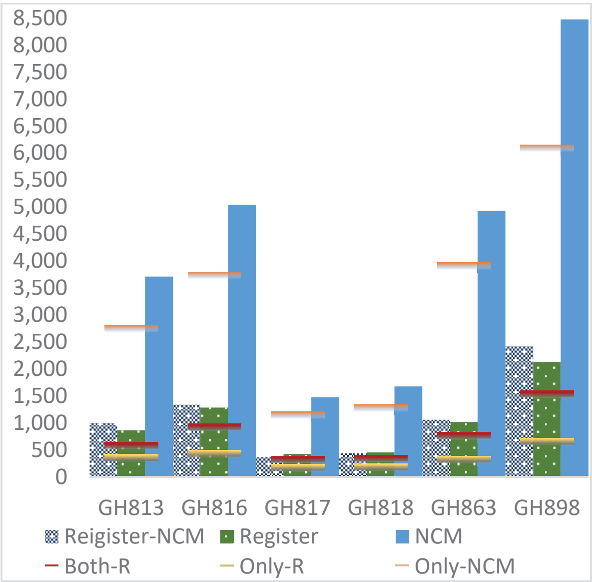


Figure 5-14 Classroom latent gains by Schedule set membership

Mixed plot of anticipated and realised latent gains in Wh when a given period falls within the respective schedule membership set plus the NCM equivalent for periods which have membership in of both NCM and register schedules. Bars for "NCM" and "Register" represent the latent gains from related name's related Schedule scenario where "R-NCM" shows the related latent gains accounted for in the NCM during registered periods. Lines show the exclusivity and dual-membership sets. Labels denote whether they which are delimited by "-"represent schedule exclusivity state followed by source schedule for its aggregated latent gains, "R" for register and "NCM" for NCM.

The gas-fired LTHW boiler described in Table 4-2 is sized to meet the design load of the building as calculated without consideration for internal gains. However, given the disparity between the NCM and registered periods for teaching spaces – which aligned with SMG utilisation estimates – its divergence from simulation, operational and optimal have less to do with its efficiency than utilisation. Using the teaching space heat setpoint and external dry bulb temperature as filtering criteria with the assumption that there is a 1 hour preheat requirement, the heating system is unnecessarily active for 75% of design hours across the teaching spaces with registered presence and 82% across all teaching spaces.

This means that if the building operation were at least consistent with design at 11 hours operational weekday and zero weekends, the 82% of heating hours would be served by the heating system with the additional demand resulting from missing latent and lighting gains. Though total absent gains alone are not a good metric for calibrating real-world and predicted heating demands, absent gains in registered spaces alone are equivalent to 92% of the increase in heating fuel demand between the NCM-2016 and Implicit-2016 Schedule-Climate scenarios. If zero-density presence spaces are included absent gains are equivalent to 1.58 times the 2016 increase. Again, it is important to note there is no expected correlation between absent gains and demand which is as much design, function, run period, occupant needs, climate and behaviourally sensitive. However, it clearly has profound effect on net energy demand. The lighting and net energy demand section discusses net energy demand in relation to mixed fuel and interdependent services further.

Figure 5-14 shows there is little correlation between the gains expected or realised between Schedules in relation to itself and other spaces. The gains expected under NCM and Implicit Schedules are not proportional or necessarily having one gains Schedule's contribution greater or equal to another. The estimated gains when considering each Schedule and the ratio of each to one another are inconsistent. These are annual estimates which if considered with results in Figure 5-3 to Figure 5-8 where scheduling is also inconsistent by time period, presence-gains Schedule combinations, suggest NCM schedules differ in more than utilisation.

A brief aside worth mentioning based on the previous two talking points. There is a lot of needlessly tempered air that could potentially be recovered through mechanical or possibly passive ventilation heat recovery (PVHR). Normal heat recovery rescues heat from air exchanges, as air is extracted from a space it is exposed to a thermal wheel or similar that draws its heat into an element such that the heat can be redirected back to a space with tempering needs. These recover from polluted air assumed to be polluted by ultimately exhausts the air. However, the tempered air itself has potential value in spaces which need tempering especially outwith design periods. In its simplest form, the suggestion here could be described as transferring the tempered air directly between one zone to another. In broader terms, it may be better represented by the concept of district heating (DH). DH systems are effectively centralised heat generators connected to multiple tempered environments at worst fuelled directly. At best, they can be supported by waste heat from industrial sites such as refineries.

This principle may be applied at building level which would be ideal for heterogeneous scheduled buildings such as higher education facilities. Say for example there was a registered class in GH801A from 7 pm until 8:30 pm then another in GH801B from 9 pm until 10 pm. Where a form of PVHR controlled by a BMS present the tempered air from GH801A could be partially transferred to GH801B. However, this has its greatest potential at the site or neighbourhood level. The Graham Hills building itself is 19,000m ^{2}~ and it is surrounded by easily 100,000m^2 of tempered university spaces. Figure 5-13 notes 82% of design heating periods are wasteful if design and registered presence states are compared with consideration for preheat. While this is picked apart in the proceeding section, a significant portion of this is functionally waste heat. Combined with waste from the site this will be a substantial well of heat which may be routed by an intelligent PVHR BMS whether inter-site or with surrounding buildings, perhaps with a tariff agreement.

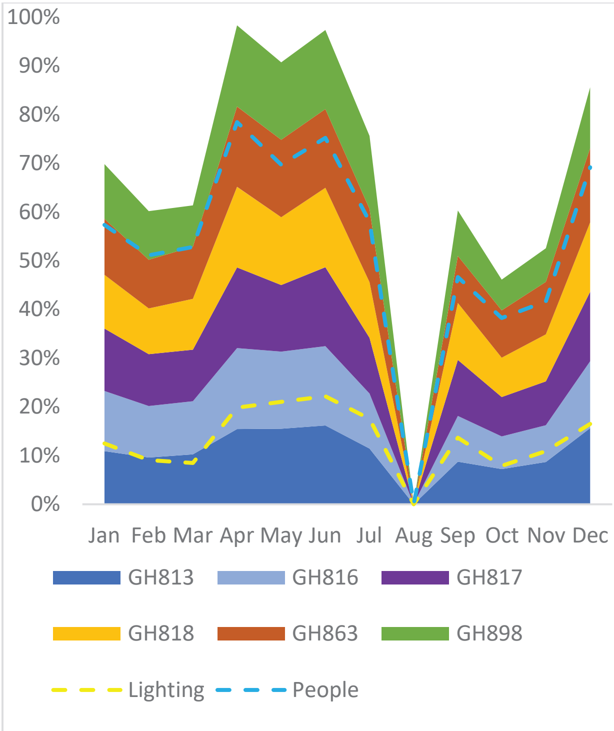


Figure 5-15 NCM and registration system expected gains error: Monthly

Monthly breakdown of the percentage difference between the NCM expected and registered latent and lighting waste heat gains. Stacked areas represent the aggregate of latent and waste heat gains for each zone per as their percentage contribution to the disparity between the two Schedule scenarios. Dotted lines represent absolute classroom aggregated gains disparity per gains type, cyan for latent and yellow for lighting waste heat. NOTE: Months are not scaled uniformly and cannot be compared on a one-to-one basis

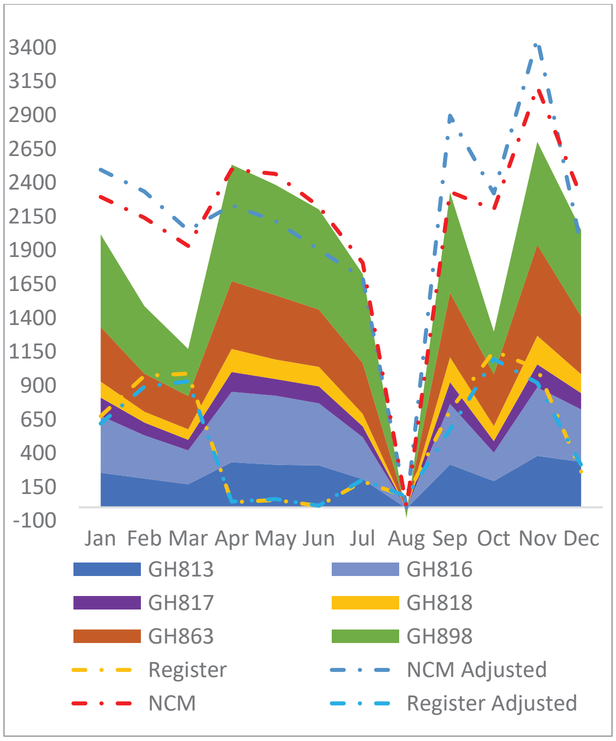


Figure 5-16 NCM and registration system, degree-day adjusted expected gains error: Monthly

Total kWh disparity from aggregated design internal gains expectations weighted by the ratio of design and register period degree-days proxy of activity heating setpoint minus external dry bulb temperature. Dotted lines represent the NCM expected internal gains per month with red representing the aggregated gains expectations of all listed classrooms as defined by the Schedule and lighting power densities. The cyan dotted line shows how the monthly adjustment factor affects the NCM expectations were they the aggregate being adjusted. Higher points on the cyan line represent a greater than 1 ratio indicating that NCM expectations occur during warmer periods than the realised gains from registered periods. Yellow and blue dotted lines represent the same information as the red and cyan but for the registered gains periods. Stacked areas represent the adjusted kWh absent gains for each classroom. Area segments do not represent one-to-one missing kWh. However, those are reasonably inferable through reference to the (dotted cyan) adjusted NCM expectations.

Figure 5-15 shows the error or divergence from the NCM expected internal gains and those realised from periods in the registration system. Despite the data used for the plot being ignorant of Schedule exclusivity, the inequality averaged 73% and only dropped below 50% for a month with design presence during October to 46%. The range across the set of error rates for classes is proportionally within roughly plus or minus 7% suggesting near uniformity in error for amongst classes for each respectively. Figure 5-16 shows the absolute kWh absent gains with an adjustment for degree-day difference between design and registered presence periods. The graph aims to demonstrate absences with consideration for increased work and decreased responsiveness of the heat source. The “Register adjusted” plot makes it clear that schedule overlap-ignorant met gains are less important to the simulated heating demand. However, this means that the registered gains occur during cooler out-of-design periods meaning they are more important to the heating system, but their absence should be represented inversely in the simulation. That is, if a calibration of the existing model were to be attempted, the inclusion of the registered gains should be diminished due to their introduction at cooler periods. It is also indicative that were needs used as an efficiency measure, meeting the equivalent presence hours during initial design day operation suggest higher marginal return than realised. Excluding consideration for retained internal gains from previous utilisation, registered presence would be closer to design were the adjustment closer to 1 or less demanding if less than.

This data inherently shows deviation from design heat unit value and registration unit value aggravated by out-of-design schedule periods. By this it is simply meant the steady-state loss at 6:30am registered is greater than at 7:30am initial design periods which is very significant given the 1.7W/m²K opaque and 5.68W/m² transparent, envelope U-Values. There are registered periods whereupon the temperature delta is 1K. As discussed in the lighting and net energy discussion, this increases the synergistic value of lighting energy on net energy demand. Though, lighting retrofits in most cases spare Tungsten with direct electric heating (NCM 9lm/CW, SCoP 0.8), reduce operational emissions underutilisation results in savings being less than 1-Watt net energy per Watt electricity. However, this separation has a peculiar property of accessibility to the occupant. One Watt-hour of heat from lighting may reduce a space’s demand without necessarily being accessible to the occupant. In some cases, this might be relevant to efficiency but not wellbeing. One salient observation not directly visible from the plots but implied and in the results is that peak demand on the heating system increases by 27kW from NCM-2016 to Implicit-2017. This indicates the system's responsiveness will be diminished which affects its capacity to fulfil its employment. The increase is also likely conservative considering the unmapped utilisation of other primary spaces.

The takeaway from these plots is that even exclusivity set membership-ignorant contexts the expected gains are not being met and those which are being met dissipate quicker than expected gains. There is conflict in the gains value and meeting the needs of a given registered tempered space. On one hand, the latent gains have inherently greater value in an unmanaged, tempered space from mitigating what would otherwise be exclusive steady-stated losses of the heating system's contribution to temperament. And, the net energy contribution from lighting would likewise be more important than in periods with higher external temperatures. However, the realised gains occur during out-of-design periods which makes building-level unrealised gains more likely in the real-world. Therefore, a needs-as-a-performance metric assessment of the space may indicate slightly better needs management than in reality. Not all gains are equal which is a significant difference between quasi-steady-state and dynamic heat transfer models; however, the statement expands beyond heat transfer. Their presence or absence affects the responsiveness of tempering system outlets which can affect comfort and it may also skew needs-as-a-performance metric indicators. The latter of which is a slight challenge for interdependent service needs management. In short, gains realised, and gains expected are not necessarily comparable nor do they have the same value in any form or granularity of calculation. This is an obvious but nonetheless significant failing of realising design operation occupancy assumptions.

5.3.4 Lighting and net energy demand

Table 5-2 Classroom Schedule scenario lighting demand: kWh per annum

	807	813	816	817	818	863	898	801A	801B	801C	801D	801E	801F
NCM	2134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134	2,134
Explicit	---	745	639	611	633	483	675	2,134	2,134	2,134	2,134	2,134	2,134
Implicit	---	745	639	611	633	483	675	---	---	---	---	---	---
%-Imp	0.00 %	34.91 %	29.92 %	28.61 %	29.66 %	22.63 %	31.61 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %	0.00 %

Lighting systems are independent of the environmental contributions from other buildings services making them distinction from tempering or conditioning systems. However, they do not have a one-to-one relationship with net energy demand. A fraction of lighting power consumption is released into its associated space as heat possibly better thought of as visually imperceptible heat. Lighting systems more familiar from 10 years ago, such as incandescent lamps waste up to 95% of the energy they consume, producing infrared radiation. LEDs despite common misconception also produce heat though from the semiconductor and drive at around 35% consumption, but not as infrared radiation. When considered in conjunction with latent gains, this waste heat can have a profound impact on net energy demand. In some cases, namely SBEM calculations where the heat source is direct electric (SCoP 0.8) and the lamps Tungsten (9lm/cW) lighting is a synergistic contributor to net energy. The lighting system's heat production at 95% is greater than the heating source's 85%. Since lighting is a nonthermal need, the lighting system is effectively producing compensating the heating system by 10% of its power consumption. That is not an endorsement for terrible lighting systems in certain conditions, but it is a noteworthy observation that infects both retrofit decision-making and NCM conventions. Strictly following the NCM conventions for strip-out clauses or regulation conflicts (no heating for activities now requiring heating) can inject this issue into the decision-making process. This is a major failing of Part L2B and is a supplementary example of conflicts between design, policy and the real world. However, in the context of this thesis, it is the extreme example of lighting's relationship with space tempering and net energy demand.

Table 5-2 shows the annual lighting energy consumption of the lighting systems serving each teaching spaces. These systems contribute 20%~ to the buildings lighting energy and 10%~ of its grid-supplied electricity demands. The lighting systems in the building waste heat fraction is 0.84 meaning for every 1W the consume they subsidise 0.84W heating demand. However, introducing the register Schedules to the model results in a significant reduction of consumption and therefore subsidy. Their energy consumption decreases to 10% and 3.6% for Explicit and Implicit Schedule scenarios, respectively. In terms of electricity consumption, this reduces the teaching spaces' demand by 6.8MWh and 10.8MWh. However, these reductions result in an increase in natural gas demand of 14.5MWh and 25.1MWh for Explicit- and Implicit- 2016 Schedule-Climate scenarios, and 15.2MWh and 27.3MWh for 2017 scenarios. The relationship between lighting and simulated natural gas demand is not easily expressed. There are temporal, seasonal, utilisation [presence, density, humidity, adaptive comfort measure adoption], external gains latent value of realised gains from previous time steps. Even when internal adjacencies are ignored as per quasi-steady-state models like SBEM, 1W, when considered as a unit of net energy, is incomparable with 1W in any other space or time. Although more detail than is meaningful or practical to model, this statement can be extended to include the individual luminaires' consumption. Given net energy cost is a function of the sum of each fuel and their respective unit cost at time of consumption, lighting energy costs cannot truly be thought of as units of electricity. This becomes clear when also considering a cooled environment whereupon the inverse effect on net energy demand may occur. Combined with peak/off-peak temporal changes to unit costs, it is unlikely lighting can ever be attributed an absolute unit cost in buildings which are not in free-running operation.

The natural gas demand increase can be used to estimate the relative unit cost of lighting energy at a given time interval size under the different Schedule-Climate scenarios. Heat gains from lighting contributed 23.8% and 23.3% of the internal gains' to heating system demand for Explicit and Implicit scenarios for full-year though reduced to roughly 21.3% for both for academic year-only simulation. When this is factored into the increased natural gas demand observed in the EnergyPlus simulations, it can be seen that each Watt-hour of lighting energy consumption was worth 1.5Wh and 1.55Wh net energy demand for Explicit- and Implicit- 2016 Schedule-Climate scenarios, respectively. Considering the Implicit-2016 Schedule-Climate, full-year run period scenario in isolation the unit cost of lighting energy is £0.1525/kWh or £0.1253/kWh depending on whether it is considered in the context of gross or net energy consumption. In terms of natural gas for the same Schedule-Climate scenario, the difference is between $0.0358/kWh and £0.44/kWh. Alternatively, in carbon emissions which is the underlying unit for most energy efficiency metrics, properly scheduled lighting only reduces by 0.181kgCO_2/kWh, nullifying 0.3tCO_2 expected emissions reductions. It is impossible to

5.3.5 Heating management

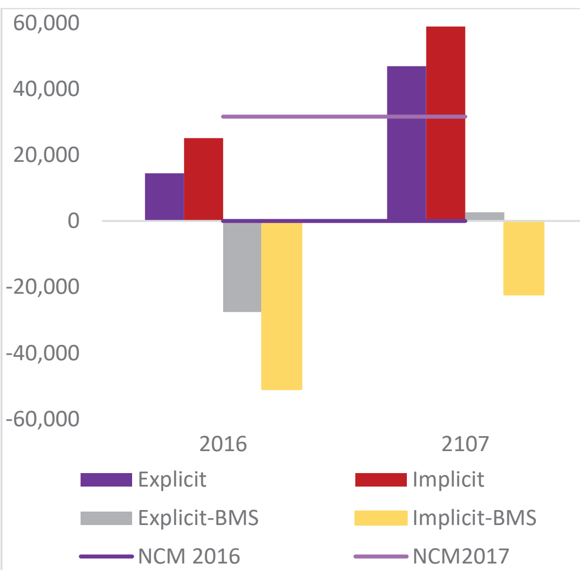


Figure 5-17 Schedule-Climate scenario net energy comparison with NCM-2016

Net building energy difference compared to NCM-2016 Schedule-Climate scenario for managed (BMS) and unmanaged heating systems.

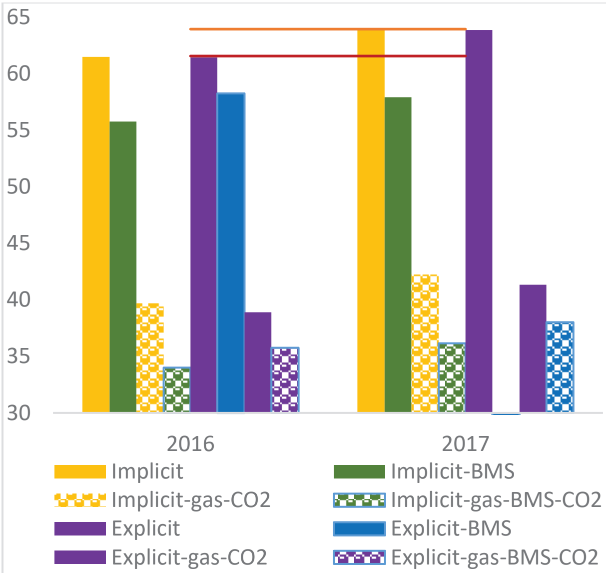


Figure 5-18 Annual carbon emissions by Schedule-Climate scenario

Annual emissions in kilograms carbon per metre squared for each Schedule-Climate scenario with and without heating management. Patterned and solid bars are paired by colour with solid and patterned for unmanaged and managed, respectively. Lines represent annual emissions for NCM scenarios

Figure 5-18 shows how net energy under each Schedule-Climate scenario compares with the NCM-2016 scenario. The increase in net energy is not surprising but given the net energy relationship with internal gains when heating is unmanaged as discussed in lighting and net energy demand section . However, it is a demonstration of the performance gap. The increase is not accommodated by NCM scheduling, and more importantly, the NCM presence model treats absence as managed. The increasing divergence from NCM to Explicit to Implicit schedules shows how the gap can only be greater when full building utilisation is considered since offices are likewise underutilised. If electricity is considered then the problem is exacerbated, particularly with Implicit- where a 10,000kWh~ reduction occurs from reduced lighting.

shows a greater issue, however. Not only are carbon emissions increasing as utilisation decreases, but Implicit scenarios are expected to produce more emissions than the NCM scenarios. This means that where heating is unmanaged the performance gap increases in both net energy reducing utilisation by up to 86% in teaching spaces is antagonistic for both net energy and emissions. The building is served by a natural gas heating system, the fossil fuel with the most lenient emissions conversion factor. If it were direct electric, the increase would change from a marginal increase of 0.07kgCO_2/m² to 17.02kgCO_2/m² for Implicit-2017. An increase which would be greater than a full A to D EPC rating band increase or nearly a full band change for E to G. In contrast, introducing heating management would result in a 6.11kgCO_2/m² and were the heating system direct electric, only a 4.54kgCO_2/m² increase on NCM-2017 levels.

The behaviour of the results in both net energy and emissions becomes consistent with NCM modelling and intuition with managed heating with Implicit- scenarios having the best performance for both metrics whereas the opposite is true of unmanaged heating. Herein lies one of the main problems, retrofit analysis is based on the behaviours expected of in the simulation process, reduced presence causes reduced service demands. This is clearly in conflict with the real world. The problem extends beyond performance potentially to wellbeing. As discussed with the proposed “Pseudo-ancillary (enabler)”, occupants and lighting services work with the heating system to temper the environment. With small utilisation drops, it may not be significant, but as the utilisation diverges, the responsiveness of the heat and outlets will inherently decrease. This may be particularly bad for out-of-design utilisation whether morning, late evening or weekend.

This thesis proposed using needs as an efficiency metric, weighing up energy used, or emissions attributed to, the servicing system used to meet the needs of occupant(s). The increase is compounding with both occupant density decreasing and consumer energy increasing. That said, lighting is inherently a Boolean-state consumer, so the decreased in lighting should be weighted greater than the increased heating consumption. Using emissions as the secondary unit for needs as a metric though flips the weighting. Lighting emissions being tied to discrete space presence constrains its needs efficacy to luminaries/m².lx or similar whereas heating is multidimensional encompassing time, class allocation, occupant density, space envelope orientation, and surrounding space utilisation.

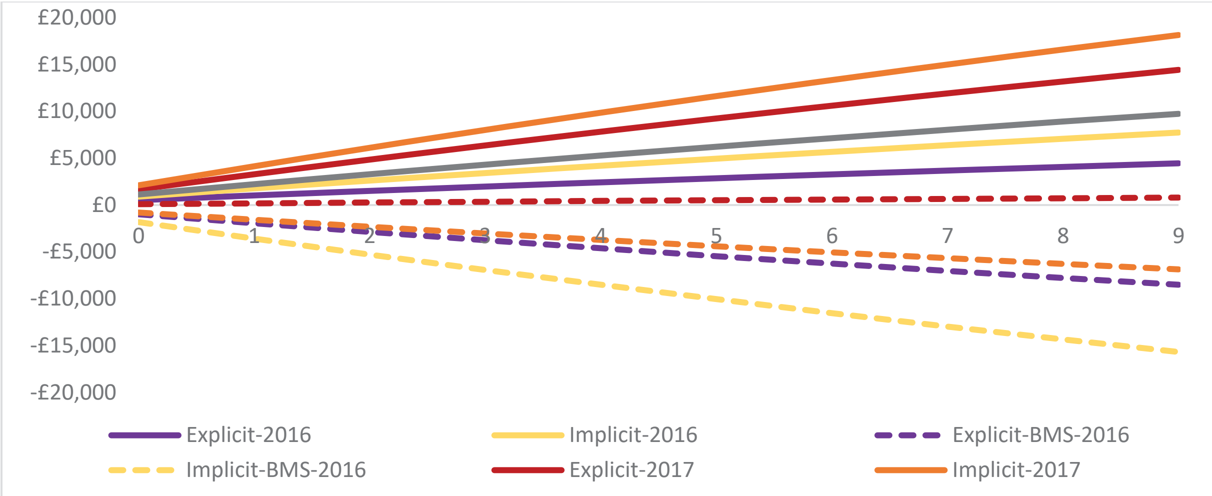


Figure 5-19 Schedule-Climate running costs estimates compared to NCM-2016: Ten-year projection

The ten-year simulated operational cost difference between each Schedule-Climate scenario and the NCM-2016 estimate. Dotted lines represent BMS-managed heating system scenarios and solid lines sharing the dotted line colour represent unmanaged heating. Annual monetary value discounted at 3.5%.

Figure 5-19 shows how each Schedule-Climate scenario compares to NCM-2016 which highlights results which are worse than initially expected. Given electricity averages 4.35 times greater in cost per unit than natural gas, it appears the increase in heating demand is greater. As with emissions, it would be expected that electricity would mitigate increasing gas consumption and the problem would be near three-fold if it were a direct electric heating system. Though only slight, the problem seems to occur even for the Explicit- scenario. Assuming average climate conditions were representative of the 2016 scenarios a BMS would nearly pay for itself within ten years compared to NCM-2016 alone and would pay back just under ten years accounting for adjusted business as usual. The difference between NCM-2016 and Implicit-2017 is concerning. If retrofit decision-making is based upon 2016 climate but 2017 is more prevalent, the do-nothing strategy is significantly poorer than it appears.

On all conventional metrics and needs-as-a-performance metric, it can be seen that the assumptions NCM scheduling would lead the users to have are incompatible with the real-world. While expecting density to affect conditioning requirements, presence is not considered in the same light. The heating system is a specialist in the role of tempering space, but occupants and equipment are support staff for its role. Therefore, needs efficacy is not just diminished by the reduced presence but like every other metric, the labour of the heating system increases, affecting all metrics and the heating network's responsiveness. Heating management is a unique retrofit option which while requiring an installation and careful scheduling, it can be optimised through strategic class planning. Above all, it seems it is a necessary retrofit if models are to be calibrated with the real-world and the performance gap is to be relatable to simulations.

5.4 Retrofit results

It will be clear from previous sections that the results of retrofits are very sensitive to the Schedule-Climate scenario and the state of heating management with the case study building. In the declaration of R-BMS, it is also noted that heating management systems (HMS) did not have an implementation for EnergyPlus. Nor is the Nondomestic Building Services Compliance Guide heating efficiency credits method meaningful in demonstrating the effects of heating managing in a building. This section provides an overview of the results of the 245 EnergyPlus simulations that define decision-making solution space for the selected retrofits in three parts. First, it discusses R-BMS compared to the heating efficiency credits method for modelling BMS systems in building energy models. Second, an overview of the results when using the R-LIG, R-BMS and R-HVC retrofit options. Finally, it discusses how constant-efficacy lighting retrofits behave under each Schedule-Climate scenario to emphasis why R-BMS is considered a necessary precursor to multi-option decision-making for low utilisation buildings.

5.4.1 Non-domestic building service compliance guide VS R-BMS heating management retrofit analysis

The Non-domestic Building Service Compliance Guide (NDBSCG) permits up to 4% CoP increase for BMS installation to existing heating systems in lieu of knowing their real impact on buildings (Government, 2013). This is applied to the total building heating consumption Using the Climate-Schedule scenarios this thesis proposed tool methodology for modelling a realistic BMS schedule for known presence. It was hypothesised this would calibrated building energy models through augmenting Schedules using the method described in the Scheduling strategies section of the research methodology. The building performance results show the difference between unmanaged and managed heating on simulated performance and metric behaviours. The key observation is the roughly +/- 6% margin of error on NCM-2016 from Implicit-2016-BMS and Implicit-2017 and a 14.4% difference between Implicit-2016 and Implicit-2016-BMS heating energy consumption.

The National Calculation method requires the cost includes all spaces associated with the heating system though, for comparability, secondary spaces have been omitted here. Office spaces contribute £24,500 to installation costs whereas teaching spaces only £6,500 resulting in 4.77 times greater cost for the intelligent unitary controllers (IUCs). If the NCM were truly followed the cost would span all 74 heated space at £37,000 or 5.79 times great cost for IUCs. The building the case study is from is roughly 6.65 times larger than the case study and as such the following adjusts head equipment cost to £2.250 resulting in £8,750, £33,250 and £39,250 for R-BMS, NCM(primary spaces) and NCM(global) respectively.

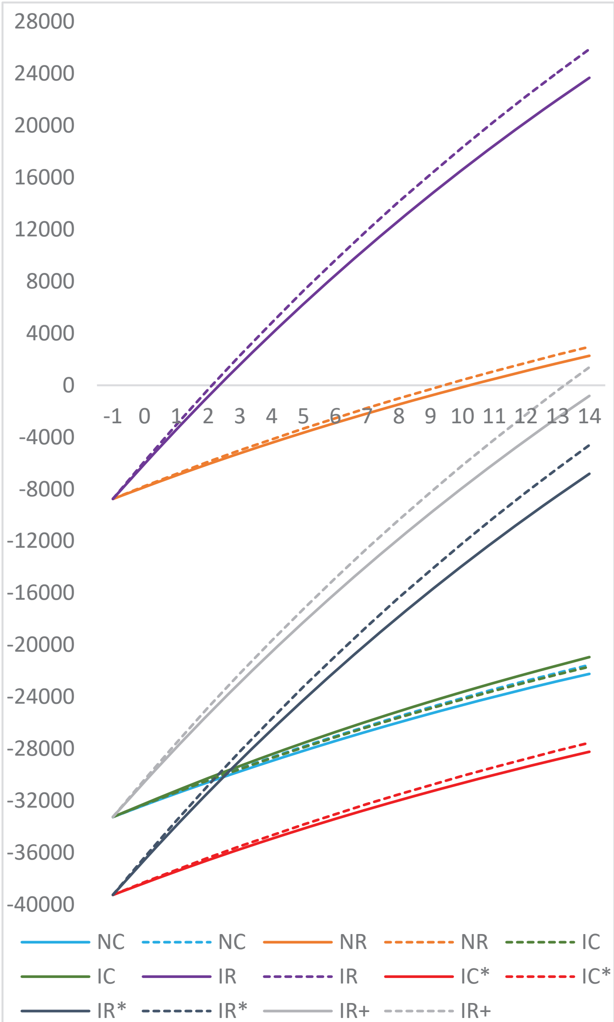


Figure 5-20 Schedule-Climate scenario running cost estimates: Pre-installed and retrofit groupings

BMS installation cost-benefit NPV at year 0 through year 14 and installation cost -1 on the x-axis. Solid lines represent 2016 and dotted lines 2017. Labels coded with (I)mplicit and (N)CM Schedule-Climate scenarios. NPV at year based on NDB(C)SG and (R)-BMS retrofit methods. Costs based on the global NCM method, including secondary spaces are labelled (*) and R-BMS installation costs shifted to primary spaces only NCM as (+). Seven-year-savings MEES cut off for cash flow discount rate of 3.5% labelled as 6 on the a-axis. Since BMS is not a standard MEES recommendation, the green book recommended rate is used rather than MEES bank base rate. 15-year limit based on rule of thumb for heating systems based on Part L2B heating plant replacement interval

Figure 5-20 shows how the virtual case study behaves under the standard NCM and Implicit Schedule-Climate scenarios with the NDBSCG efficiency credits method and R-BMS method for Implicit scenarios. There are several important distinctions between the NCM and Implicit which affect the importance of heating management beyond the simulation calibration discussed throughout the results and discussion. First, the arbnConsult retrofit analysis platform’s nonbinding “All MEES-compliant”, and its longer payback period, maximised rating strategies filter out individual retrofit options with payback period greater than 7 years and 15 years, respectively. Therefore, only Implicit scenarios would be considered for the former and only those based on R-BMS costs or the Implicit-2017 would be suggested in isolation for the latter. Secondly, as demonstrated by (Rastogi, 2016), retrofit analysis is sensitive to climate to the extent that he recommends retrofits must be tested for robustness under multiple probable climates. The cash flow results in BMS_NPV_FIG both support his observation and the hypothesis that occupancy requires similar consideration, albeit this thesis suggests focus on out of design presence and during design absence. The asserted unexpected behaviour of metrics from unmanaged heating can be seen with the Implicit with compliance guide method. In contrast with all other result pairs, IC performs better under 2016 climate.

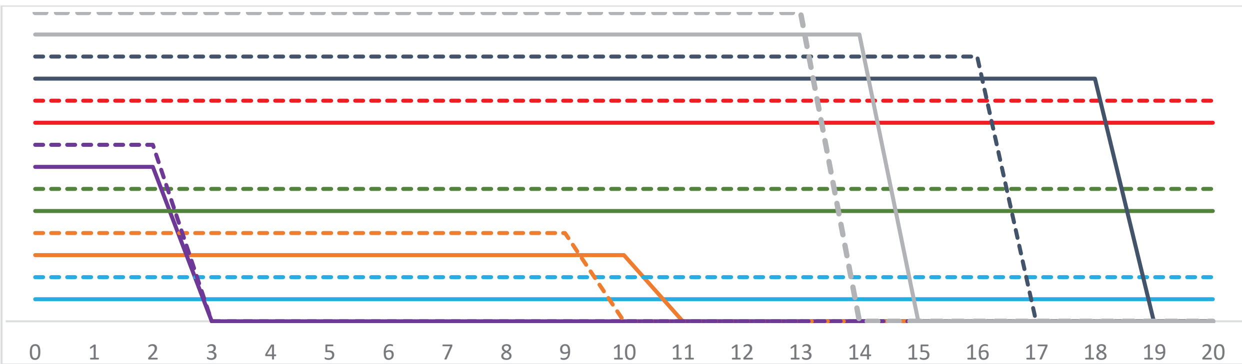


Figure 5-21 R-BMS discounted payback rates: Discounted at 3.5%

*Discounted payback period using data and labels from **Figure 21**.*

Figure 5-21 shows the year in which each Schedule-Climate-BMS scenario achieved a net present value of at least 0. The green, red and cyan lines representing NCM scenarios never reach an NPV of zero or greater, leaving only the R-BMS cost, NDBSCG efficiency credits method as the only NCM strategy which pays back which cannot exist in the real world. The opening of this section discussed adjusting the head equipment cost for the whole building, and therefore, these are lower than would be the case if the case study where a full building. However, as shown in Figure 5-22, even if the head equipment is included all R-BMS Schedule-Climate scenarios payback including those with IUCs for all heated spaces. This thesis recommends R-BMS as a calibration tool, and these results demonstrate that it is not only necessary as this chapter attempts to demonstrate, it can be very cost-effective regardless of the cost model when head equipment cost is adjusted. It is debatable; however, if the investment would realise a positive return in the real world with the raw head equipment cost and therefore if this were a full building, the only safe argument is model calibration.

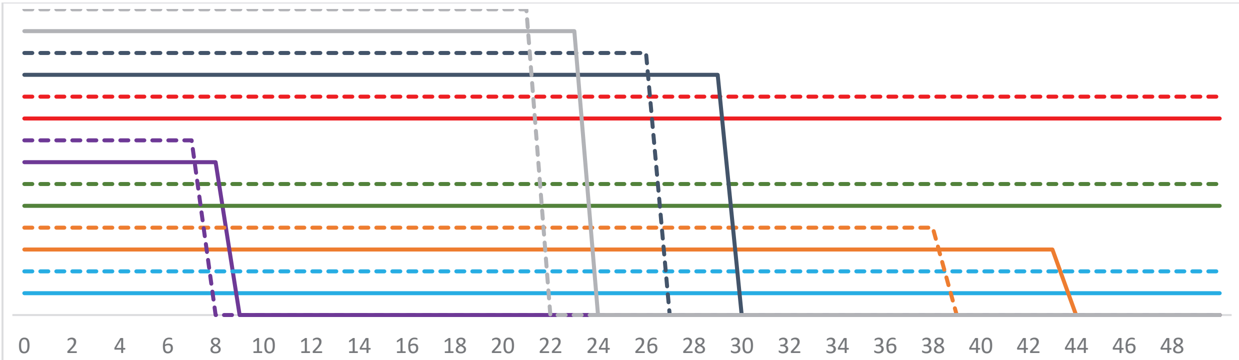


Figure 5-22 R-BMS discounted payback rates: Unadjusted head equipment costs

Discounted payback period using data and labels from Figure 5-21*, including full head equipment costs.*

5.4.2 HVAC heat source and BMS retrofits

Compared to the heating efficiency credits method for BMS installation, boiler replacement is a better solution in simulation. Instead of a detailed heating calculation, both methods are applied to the SCoP rather than the CoP which would be the case in SBEM. This is a 4% increase for BMS and a 10% increase for boiler replacement. Where the boiler replacement was estimated by creating the SBEM model for the case study and entering the replacement boiler CoP. The cost based on the R-HVC method was £15,600. The cost is 2.95 times cheaper than NDBSCG BMS cost for 2.5 times SCoP improvement.

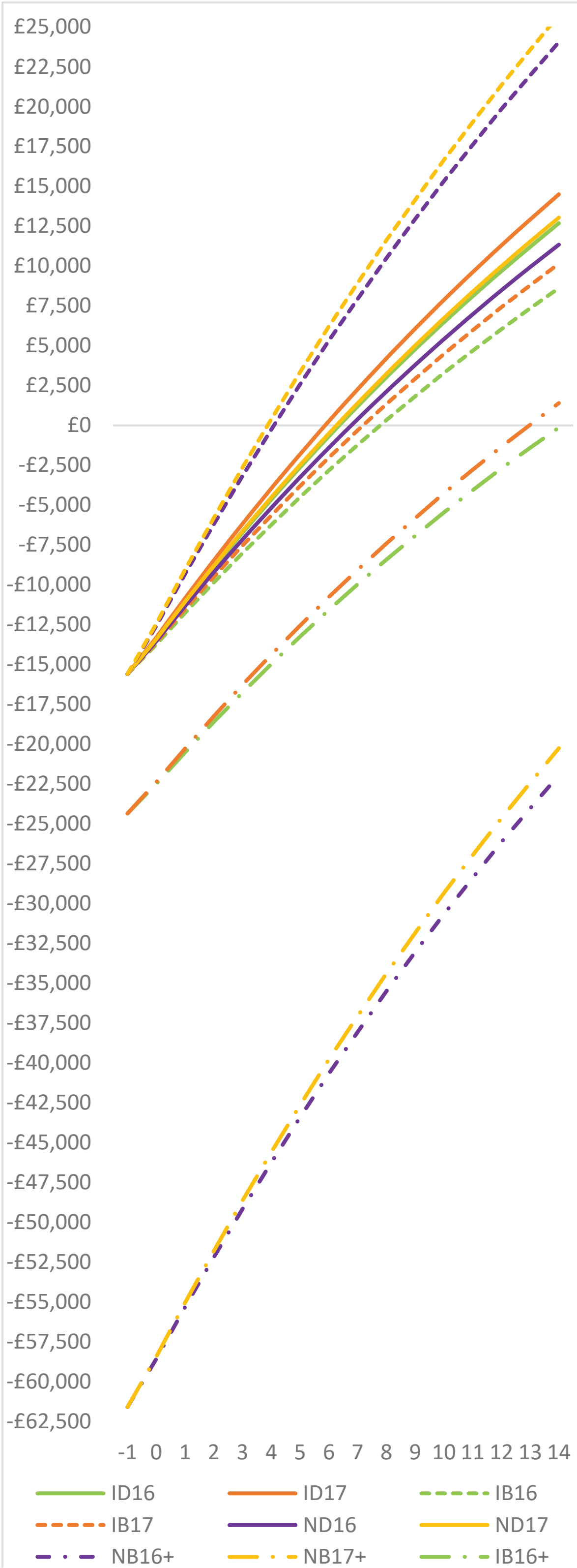


Figure 5-23 R-HVC Discounted cash flow projections for Schedule-Climate scenarios

: *Discounted cash flow for R-HVC boiler retrofit strategy applied to NCM and Implicit Schedule-Climate strategies. Line labels have four identifying components. First letter is for Schedule (N)CM or (I)mplicit. Second represents indicates presence or absence of a BMS (D)efault or (B)MS. Remaining numbers represent Climate year 20(16) or 20(17). The final character (+) if present, indicates that the BMS was included in the cost. BMS costs and implementations are based on the method appropriate for the Schedule scenario. Implicit scenarios priced and applied using the R-BMS method, NCM priced and applied using the NDBSCG rules. Line colours denote related Schedule-Climate scenarios with line types representing retrofit rules. Dotted lines represent when a BMS is assumed to be present at the time of retrofit. Solid lines when no BMS is implemented. Dash-dot when a BMS is assumed to be installed with the boiler replacement. X-axis represents years with cut-off defined as the L2B consequential improvements criteria for LTHW boilers. Discounted at 3.5%*

As with results in the NDBSCG and R-BMS comparison in the previous section, Figure 5-23 and Figure 5-24 show an inversion of return investment behaviours. NCM Schedule-Climate scenarios with NDBSCG

BMS and R-HVC suggest a payback rate greater than R-HVC on its own whereas Implicit with R-HVC and R-BMS scenarios indicate the opposite. This is because attributed to the difference in application between the heating efficiency credits method and R-BMS.

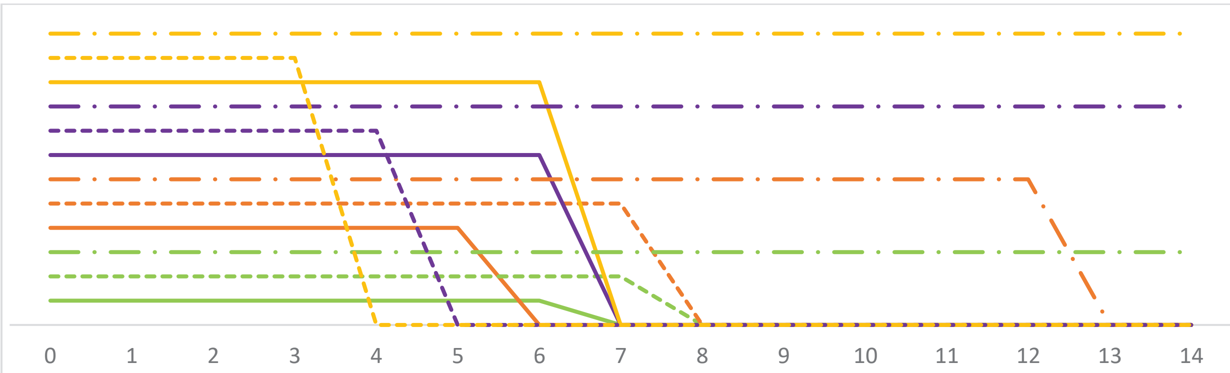


Figure 5-24 R-HVC Discounted payback grate

*Boiler replacement discounted payback period tracks for each Schedule-Climate. Lines represent their counterparts in **Figure 23**. X-axis represents years. Discounted at 3.5%*

In the case of the former, the heating demand is calculated and then adjusted for losses with the improved SCoP. In contrast, R-BMS reduces the heating demand before then adjusting for losses with the SCoP. Neither method is comparable either since R-BMS effectively contracts time where the NDBSCG method losable contributions.

5.4.3 Constant-efficacy lighting retrofits

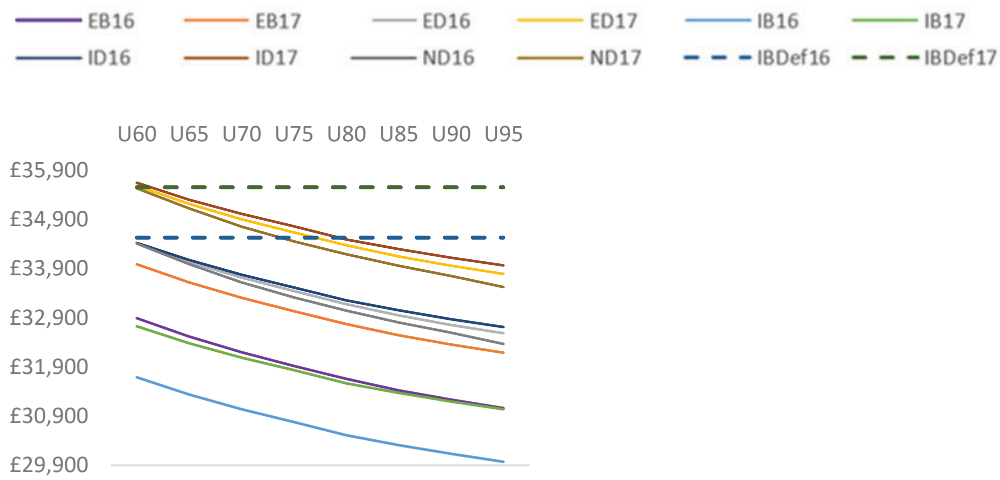


Figure 5-25 Constant efficacy retrofit Schedule-Climate simulated running costs

Building estimated annual running cost under each Schedule-Climate scenario based on a constant efficacy, whole-building lighting retrofitting. Solid lines represent Schedule-Climate scenarios with the naming convention <Schedule>-<has BMS>-<Climate-year> where "E" and "I" represent Explicit- and Implicit and "B" and "D" managed and unmanaged heating. Dotted lines represent Implicit-BMS- scenario running costs. X-axis labels prepended with "U" denoted the luminous efficacy of the constant retrofit at that intersect in Lumens per circuit Watt (lm/cW).

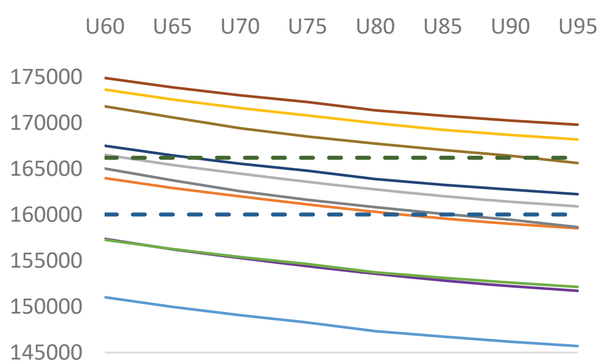


Figure 5-26 Constant efficacy retrofits simulated carbon emissions

Building estimated annual associated carbon emissions under each Schedule-Climate scenario based on constant efficacy, whole-building retrofitting. Labelling as neighbouring plot. Y-axis in kilograms carbon (kgCO2).

*Lighting retrofit costs in this section are based on the SPON's per luminaire cost rather than the R-LIG method, which is incompatible. The proxy cost is £65,750. Teaching space-only R-BMS costs of £21,500 is primarily used when discussing BMS. BMS cost is inherently skewed by the head equipment which would support the other 5/6 of the gross internal area.

Simulated running costs improve on Implicit-BMS operating costs for all bar Implicit-2017 at 60lm/cW which is marginally worse which means retrofitting while at least have a marginally higher return than the uncostly R-BMS. However, it is clear previous discussions on heating management are not diminished by high-efficacy lighting replacements. As with net energy demand under normal Schedule-Climate scenarios, Implicit scenarios perform worse than their NCM counterpart, as shown in Figure 5-25 and Figure 5-26. In fact, until the 80lm/cW retrofit the unmanaged heating system Implicit-2017 scenario fails to meet business as usual NCM-2016. A more pressing observation though is that despite the initial 86% reduction in teaching space lighting consumption in the Implicit- scenarios, the results from retrofitting suggest full design utilisation would result in better performance than is achievable under real utilisation. In contrast, every HMS retrofit scenario from 60lm/cW has lower resulting operating costs than NCM-2016, and as would be expected, registration system scenarios now outperform their NCM-counterparts. Results from managed heating scenarios also being to converge with their respective NCM- scenarios which indicates an expectable diminishing return as efficacy increases. Conversely, unmanaged scenarios diverge from their NCM- counterpart suggesting reality diminishes faster than expected compared to NCM. Although this may seem intuitive, this understanding is based on having the entire problem solution space presented which will is not possible for more complex decision-making. Additionally, this building is very simple by comparison to others having natural ventilation and convection wet radiators. The complexity is, however, slightly noticeable at U75, where the gradient from the previous U70 notably diminishes for unmanaged scenarios compared to other steps yet closer to consistent for managed scenarios.

In terms of building performance, carbon emissions results are far more profound. As with operating costs, the NCM scenarios outperform their registration system counterparts.

However, unlike operating cost, this means spending three times as much as the cost of BMS on lighting would never result in emissions lower than the installation of the BMS alone. In line with discussion throughout the chapter, IB16 and IB17 highlight the extremity in which BMS synergistically affects operation. Where unmanaged results are worse than their NCM counterparts though deviating only 5tOC2, unmanaged is closes in on 14tCO2 better than BMS-only, nearly 20tCO2 extra without the BMS for Implicit-scenarios.

The retrofit costs for these scenarios are generous for lighting while conservative for BMS with lighting being over £20,000 less costly than R-LIG. However, the R-BMS costs consider the head equipment to be exclusive to the cases study floor. Were it adjusted for gross internal area; it would be closer to £8,800. Furthermore, a pseudo-BMS solution for heating-only using smart radiator valve controllers could arguably be installed for less than £1,000. Though not a practical long-term recommendation, the opportunity to start managing heating immediately for next to no cost exists. Considering both the lighting installation cost to achieve the same operating cost at 60lm/cW for unmanaged scenarios compared to managed with no lighting retrofit, would eight times or sixty-six times heating management, respectively.

Constant-efficacy retrofitting, which affects an ecosystem-insensitive consumer which has a variable relationship with its energy consumption and net energy demand, is a simple but effective way to demonstrate the discussions in this thesis. The results clearly support the case made throughout regarding heating management with varying yet consistent profundity across differing metrics. The most surprising, though convenient observation is NCM scenarios outperforming their registration system counterparts for emissions. While this was also the case for standard operation simulations, the lighting retrofits are at lowest are nearly doubling the average base lamp efficacy. Even though costs for the lighting retrofit remain constant regardless of efficacy, there is little if any case for lighting-only even ignorant of all other discussions.

5.5 Conclusion

This chapter explored the results of simulating Graham Hills building floor seven energy performance using EnergyPlus and considered the findings of the literature review in relation to occupancy modelling. During the process, it was discovered that building service management for low utilisation buildings has a significant role to play in design and retrofit decision-making. It was demonstrated that the virtual case study under multiple Schedule-Climate scenarios that overexertion of tempering systems made the building perform erratically. Additionally, it was shown mismanagement led to poor returns from retrofits. And presence is a significant factor in determining the net energy unit value of energy consumption compared to gross fuel consumption. The conclusion that can be drawn from these was BMS and presence management should take precedence over direct service replacement. Furthermore, inefficiencies in the real-world do not necessarily present themselves in the simulated world.

Through discussion of utilisation and presence, it was suggested that simulated energy performance is not a suitable metric on its own either as a benchmark of performance or as valuation. A case for needs as and occupant function has been made which suggests supplementing building service management strategies with occupant planning is a more reliable method of improving operational performance. At its least controversial, having the Grahams Hill building, which is 19,000m² for a few maintenance staff is a form of poor performance no matter the efficiency of the services.

This thesis aimed to demonstrate how reducing utilisation diminished the relevance of energy performance simulation, which was evident from all building states under comparing Schedule-Climate scenarios. However, the research's most profound observations lie in identifying gaps in the extant literature and occupant classifications. The results present in this chapter should prove valuable to anyone looking to contribute to occupancy research. Finally, the findings also support other industry research which suggests decision-making should be considered a challenge of minimising critical decision failures rather than identifying optimal solutions.

6 Chapter 6 - Discussion

6.1 Introduction

This thesis reviews the extant literature on what it means to be an occupant, how occupants interact, and how they understand their needs and the malleability of those needs. The literature review served two purposes. First, facilitated analysis of standard occupants to understand the constraints and freedoms of occupant-building interactions and system-occupant interdependence. Secondly, combined with the results chapter, it enabled the identification of gaps in the current definitions of occupants including what constitutes as an agent and the absence of focus on indirect roles. It also aimed to prove in the results the hypothesis that at least in low-utilisation buildings. The belief that needs exist is as much a building performance gap concern as efficiencies in meeting the needs of confirmed occupants.

This chapter first discusses the experimentation results in terms of their relationship with the extant literature and how they should affect current practices. Throughout the related literature review, it was discovered there is little existing literature on considering the belief that needs exist. Therefore, the discussion is focused on conflicts with models reliant on these beliefs. The following section discusses gaps in existing building energy models and occupant ontology. This section aims to highlight conflicts between the real and virtual occupant and propose new classifications for guiding future research. The chapter proceeds with discussion on occupants' needs considering how needs differ from depending on occupants' roles and suggests needs may be a useful metric for assessing real-world energy performance.

6.2 Occupancy's role in observed performance

The literature divides occupancy roles into two categories, behavioural and utilisation. CHEN discusses behavioural contributions to the performance gap of up to 30% which is very significant. However, as discussed in Occupancy profiling's Overview, the utilisation of the spaces during operation is less than half that of the NCM. Furthermore, the zero density presence periods account for 86% of Implicit schedule scenarios' design schedule counterpart. Tabak (2009) suggests actions have four main attributes, frequency, duration, the priority and the location. Excluding duration, which is bound to the action not the occupant and relevant only when discussing cumulative duration, the lower utilisation affects each. Most occupant activities' frequencies are a function of occupant density. Certainly, all are during periods of inoccupancy or zero-density presence beyond latent intentionality as discussed in Computers as pseudo agents. Priority and location are inherently linked to the presence of the occupant. As a result, the potential for and probability of an action being carried out. Whether behaviour would be more significant for this research than presence is, however, is still complicated by the outcome of an action's duration being decoupled from the occupant. Opening a window at the start of the year and leaving it until the end will have significant impact on the space and building's performance even though it is a single action. However, the case study building does not have operable windows and control of its services is limited.

Utilisation overview of the results and Schedule calibration and energy efficiency discuss periods of nonzero-density presence in the Implicit schedule outwith the NCM schedule. A notable number of these occurred during weekends which are not included in the model and contribute nearly all cumulative presence for their respective days. Parker *et al.* (2017) discuss NCM schedules underestimating heating by 10% in their dataset. Their results align with expectations and those presented in Experimentation results and importantly, support the discussion in Lighting and net energy demand on utilisation and presence's relationship with net energy. Though their test buildings have greater utilisation than this case study, the simulation models are susceptible to the presence-bound tempering, functional simulation gap discussed throughout this thesis. It must be kept in mind however, that only zero-density presence contributes to the functional gap, expected nonzero-density is related to the epistemological gap due to the presence-bound tempering assumption.

6.3 Experimentation results

6.3.1 Heating system retrofitting and Schedule-Climate scenarios

The HVAC retrofit results section show the extremity of the problem with using NCM Implicit and BMS calibrated scenarios. As predicted, the real-world presence and BMS implementation contradict the NCM scenario's prediction of retrofit results. By inverting the managed and unmanaged results it makes it clear that were heating managed, boiler replacement would be less effective. This is attributed to the time contraction approach to BMS modelling compared to the NDBSCG loss reduction method. The most concerning observation resulting from the results of R-HVC across Schedule-Climate scenarios, however, is where NCM-BMS scenarios are compared to Implicit-BMS, Implicit and NCM scenarios. Not only is its relationship with not having BMS inverted compared to Implicit scenarios, boiler replacement when a BMS is in place for NCM scenarios. The significantly higher return on investment rate and achievement of NPV >= 0 suggests it would meet Rastogi (2016)'s climate robustness constraint. Not necessarily because it is roughly three times more volatile than Implicit Schedule-Climate scenarios with R-BMS. That is an important conflict because its return on investment rate is extremely high. In contrast, hypothesised presence sensitivity Implicit scenarios reaffirmed Rastog's work and supported this thesis' claim that there are parallels between climate and occupant sensitivity.

6.3.2 Effect of scheduling on simulated performance and legislated commitments

Corgnati *et al.* (2017) suggests that the building performance gap can be as high as 30% in mixed-use buildings. The building energy performance results suggest that the gap in the case study is between 2.5% and 5.1% between NCM and Implicit 2016 Schedule-Climate scenarios. This is on account of an 8% decrease in lighting and a 5.1% increase in heating. It does not necessarily translate over to the real-world since idealised lighting was included as per the NCM. However, this more likely a simulation gap as demonstrated when heating management is introduced which calibrates heating to match both the real-world and EnergyPlus scheduling. Calibration increases heating disparity in Implicit and NCM scenarios to 14.5%. Contradictory emission from Implicit and NCM schedules were presented as a feature of the simulation gap from introducing heating management. Beforehand, unmanaged heating increased emissions whereas managed decreased. It can be attributed to the way NCM schedules define heating using nonzero-density presence and preheat to define heating availability schedules. EnergyPlus is considered an accurate model. Therefore these behaviours should translate to the real world. The divergence is very apparent when considering the constant-efficacy lighting retrofit emissions results. Retrofitting lighting produced better results against the NCM than Implicit scenarios. That is, with the 84% reduction in lighting demand already accounted for then retrofitting, the emissions for Implicit were 3% higher at the lowest efficacy and the gap increasing with efficacy. In contrast, with heating management, the performance was in the order expected, and Implcit went from worst to best result.

Kordjamshidi (2013) suggests that scheduling occupancy in simulation is the most important factor in producing results relevant to the real building. The lighting and net energy demand seem to support the claim and the use of ranges in the previous paragraph. The lighting in the virtual case study has an 84% waste heat output factor meaning that percentage of its consumption has an ideal net energy value of 184%. Despite this, roughly 76% of net energy increase in the Implicit scenarios is attributable to the absence of occupants. Therefore, latent gains made significantly higher contributions to meeting heating requirements and thus reducing net energy demand. Heating management, as would as expected, changed the relationship. Though not entirely, it can be inferred from the adjusted net energy monetary value of lighting energy consumption that lighting gains became more relevant to net energy demand.

6.3.3 Effect of climate

Rastogi (2016) demonstrated building sensitivity, similarly suggesting retrofitting should focus on robustness rather than optimal simulated performance. This thesis integrated this concept by using two climate datasets for each simulation. Results building energy performance can be seen to reaffirm his findings and exacerbate occupancy's effect on simulated performance. The 5.1% disparity between 2016 NCM and Implicit scenarios increased to 8.9% when NCM was changed to its 2017 counterpart. Furthermore, the heating management gap increased to 19.5%. Even in the context of retrofitting the observations were confirmed. Introducing heating management to 2016 and 2017 using the unadjusted BMS cost seen the payback period for installation differ by nearly 2 years between the two climates. As with the previous section of this chapter, constant-efficacy lighting retrofit results were more pronounced with the 2017 climate. The Implicit results were the worst of the entire Schedule-Climate scenario set with unmanaged, yet just short of second-best with managed heating.

82% of heating demand in the UK is attributed by gas-fired with heating said to contribute 46% of the UK's final energy demand (Chaudry *et al.*, 2015). The case study building being gas-fired has significant relevance to these observations, especially given scheduled area was only 25% of the building. Firstly, depending on whether the standard or real schedules were used was the difference of 25MWh in 2016 and 27MWh in 2017, creating a range of 59MWh. The difference shows that despite being only a quarter of the conditioned area, this is a difference of nearly 12% which would only inflate as accuracy of scheduling increased.

6.3.4 Nondomestic building service compliance guide BMS, operation/simulation calibration and BMS retrofit analysis

The Nondomestic Building Service Compliance Guide (NDBSCG) heating efficiency credits method of modelling a BMS permits up to 4% CoP for linked HVAC systems. (Government, 2013). This thesis proposed a methodology for realistic BMS modelling for EnergyPlus, demonstrating its effect on Schedule-Climate scenarios described in R-BMS. The results in building energy performance and the comparison between NDBSCG and R-BMS on simulated performance. The key observation is the roughly +/- 6% margin of error on NCM-2016 from Implicit-2016-BMS and Implicit-2017 and a 14.4% difference between Implicit-2016 and Implicit-2016-BMS heating energy consumption. The difference in methodologies has a profound effect on real-world implementation, retrofit cost and real-world relevance. The calibration benefits from the R-BMS method are profound, but in terms of real-world performance and legislative compliance, the method dictates the economic and compliance value of installation. Considering the 2017 climate, calibrated schedules and the R-BMS reduce predicted emissions by 6.08/kgCO2/m² whereas the NDBSCG method only 2.26kgCO2/m². A section 63 action plan has not been proposed for the building, so the prescriptive target is unknown. However, the arbnConsult platform area-weighted average for target reductions is 19.7%. Based on this estimate, the difference in working towards meeting an S63 target for NDBSCG and R-BMS is 17.8% and 47.8%, respectively. Furthermore, the NDBSCG cost is roughly 4.5 times greater for adjusted head equipment costs or 2.47 time greater when unadjusted.

6.4 Behaviours, devices and wasteful consumption

Many articles in the literature suggest behaviours are one of if not the most significant contributor to the building performance gap (T. Hong *et al.*, 2016; Kneifel *et al.*, 2016; Ridley *et al.*, 2014). The results do not invalidate that claim for the case study. However, the building energy performance and lighting and net energy demand results suggest that for net energy, the simulation gap is closer related to absence if lighting behaviours are not entirely irresponsible. That said, up to 50% of energy consumption has been observed to occur outside occupancy (Gandhi & Brager, 2016; Gunay *et al.*, 2016). The classroom scheduling results identify utilisation that is outwith design and with long gaps between occupied periods. Therefore, it would not be possible to attribute this consumption to irresponsible behaviour or comparable to design without zealous occupancy monitoring.

The proceeding occupant taxonomy section identifies a nomadic occupant class which is not considered in building energy modelling. These occupants spend little time in any one zone and can be sole occupants, such as janitors, cleaners or security. However, these interactions with the building and each other can change what it means to be wasteful or necessary, with interactions loosely relatable to the proposed collective classification. On one hand, building-specific education can lead to energy-conscious behaviours (Berg *et al.*, 2017). In the case of University of Strathclyde's may see nomadic or other staff mitigate wasteful behaviours form others. On the other, the proposed Collective classification attempts to reconcile social and situationally-aware behaviours. Haidarian *et al.* (2010) discuss these features of agents which imply energy consumption can be meaningful to occupants aware of one another. Therefore, it may be the case that what is considered wasteful general may be somewhat considerate of the presence of others at a later time. In contrast, efficient and wasteful could be attributed to the proposed Delegate class which describes an occupant who controls the services in spaces they do not reside. Their contribution to wasteful consumption is an occupant-controlled version of the beliefs consume energy principle presented in this thesis. However, they may drive efficiency through ignorance or decisions led by their second-order interests.

The discussion in the computers as pseudo agents section of the literature review further obscures the definition of behavioural and absent wasteful contributions The proceeding occupant taxonomy discussion further skew the definition of outwith occupancy. The pseudo agent classification it proposes discussed described in the occupant taxonomy section notes Pseudo (referred to as surrogates in computer ethics) can have latent intentionality when not in use as described by Deborah G Johnson (2006). Additionally, according to (Jones *et al.*, 2013), computers have some form of socio physiological personalities and the social personalities can affect engagement between occupant and device Oliver and Pour Rahimian (2018). Therefore, the definition of waste and inoccupancy is not reliable. Device usage may be desired during inoccupancy. Identical tasks on identical machines do not have identical physiological profiles, and occupant actions and presence can be altered through device interactions.

The point of this discussion is that the results in this thesis cannot account for wasteful consumption to infer to properly rank behaviour, wasteful consumption and absence but there is a much more pressing concern. The built environment literature discusses presence related consumption in terms of primary occupant behaviours, social cohesion and even metacognitive adaption. However, it does not consider ancillary occupant behaviours, nor does it define. Additionally, its definition of wasteful breaks down when computer science and ethics are considered, relationships between noncurrent presence for multiple occupant classes or when consumption changes from a second-order interest to wasteful. That is, what is considered wasteful may be related to the purpose of presence despite occupant absence or maybe considerate of other occupants. Even efficient energy use is not necessarily from present occupants or driven by energy consciousness. As shown in the classroom scheduling results, utilisation in the real world does not match its theoretical definition from the Space Management Group (Space Management Group, 2008). Given spaces are required to be preheated before presence, it is debatable whether the recorded four-hour period between end of design day and last period of occupancy the Implicit schedule November 31st can be considered utilisation. Finally, the question arises of how many occupants need to be in a building before utilisation is registered and do occupants need to be present in zones for presence in the building to be considered utilisation of individual spaces?

6.5 Occupants

The computers as pseudo agents literature review section discusses the idea that nonancillary equipment should be considered occupants. There are many reasons covered, but primarily three stand out as salient features. First, in contrast to existing design methods equipment such as computers are considered Boolean-state power densities which are at most suitable to the archaic “occupants are thermal disturbances” definition of occupants. However, as demonstrated in the precedence section in the literature review section, computers have physical psychophysiological personalities. That is, they have some form of intentionality and control over their actions which result in varying levels of immaterial gains. For example, a machine training a neural network will inherently exert more physical activity than say one which is idling. Secondly, they have social personas, whether through the mediums of media richness and social presence or as intermediaries between standard agents. Finally, they breach the building closed system. They can transmit information and commands between systems.

The discussion in the computers as pseudo agents section which concluded that equipment should be considered a form of pseudo occupant. Combined with the literature review, this led to the question of whether there are other meaningful occupant classes which are currently absent in the literature. The concept of agent types is not new; however, the types are synthetic behaviours, not entity classifications.

Another theme that arose from considering the heating management system discussed in proceeding results discussions is how agents relate to the building’s operation. It did not appear true to claim that all occupants interact needs are should be treated as equal or if different ancillary roles’ traversals through the building can be treated equally. Can thermal comfort needs be met via a standard method and are all needs equal? Ultimately, if needs are considered as a measure of efficiency with incentive to reduce necessary power, can all ancillary roles’ needs be met with the same amount of energy.

This section attempts to answer these questions to set the tone for future research into their application.

6.5.1 Occupant ontology

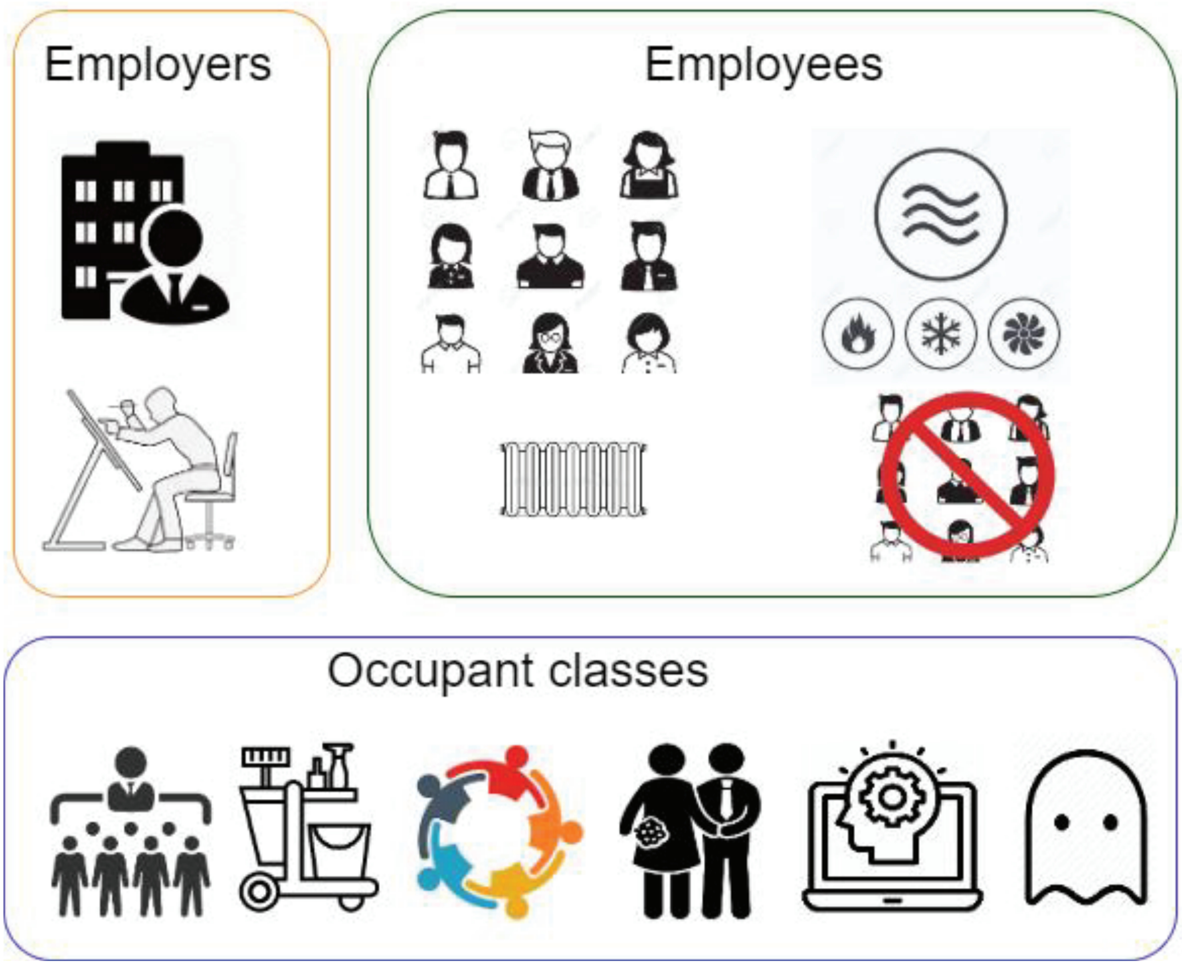


Figure 6-1 Identified real-world occupant ontologies

Janda (2011)'s famous h "buildings don't consume energy: people do" formalised the underlying premise of the relationship between building energy demand and occupants as discussed in the literature. Janda's framing may alternatively be written such that people are replaced by the needs of people since their actions are either to meet their subjective perception of their needs rather than to mindlessly consume energy. The statement is salient, but it may be too constrictive on the definition of occupant and does not accommodate the separation of real-world utilisation and simulated, occupancy patterns. An objective in this thesis was to show various forms of occupant which are not covered by standard definitions. The identified classes which are discussed in this section are not necessarily in conflict with the sentiment of this statement. However, the observation from the experimental stage of this thesis demonstrates a gap in Janda's statement arising from the disparity between real- and virtual-world presence: either the statement implicitly includes "ghosts" or must be included to encompass the superstitions of designers and misbeliefs of occupants and building managers. This is due to the DNAS principle of sub-hourly occupancy models where utilisation of equipment and services is driven by the functions carried out in a given zone. Occupants fulfilling their second-order objectives have needs such as tolerable lighting levels. Their needs are met by direct or indirect actions whether interacting with a lighting control or a Delegate occupant controlling the heating system. However, when zero-density presence in the form of unmanaged services occurs, issues arise in both space utilisation calculation and needs as an efficiency metric. A logical adaption to the occupancy model is to introduce immaterial occupants (ghosts) with negative needs such that equations are not at risk and a reversal of the needs models; the building services must be justified in their use during presence disparity which may only be true when some form of occupant is present.

This thesis initially proposed the need for a new class of occupant encompassing certain forms of nonancillary equipment explored in computer are pseudo agents and discussed in greater detail in (Oliver & Pour Rahimian, 2018). An additional Delegate class defined in the proceeding subsection was identified as an extension to Janda's framing to accommodate remote occupants managing zone conditions. Combined with the literature review, particularly in terms of social and dyadic relationships arose; are there other forms of occupant which implied in the literature and design which are not yet formalised? After all, not all needs are equal, needs are not exclusive or genetic, and occupants do not necessarily have control of the all adaptive measures which may optimise environmental conditions for an individual. Figure 6-1 shows the ontological groups which appear to be absent from the literature but appear to have significant effect on the definition of an occupant in relation to the simulated occupant.

The answer is to an extent. Some agent-based models, as discussed in the literature review's agent-based modelling section, accommodate basic forms of metacognitive learning regarding the actions of the cohabitants. (T. Zhang *et al.*, 2011) prove reactive metacognition can be modelled. However, this was the only socially sensitive research found in the literature. That is, learning the preferences of other agents and weighing their preferred adaptive measures along with their own. It is an interesting characteristic to introduce because it effectively causes the agent to consider the individuality of other agents while accommodating social projection. However, even in its simplest form, this type of cognition modelling may better be considered exclusively as a mixture of individuality and altruism where in reality it there are socio-personal and/or intersocial characteristics. The social characteristics are where models proven to be uncategorisable. The intersocial principles of a group, agreeing to adapt to thermal discomfort by operating windows rather than using desk fans or internal blinds, whether as a means of energy conservation or minimising noise pollution or maintaining natural light levels. The socio-personal principle is a function of dyadic and Collective relationships: if occupant A's socio-personal image as viewed by occupant B is given greater importance than that with occupant C, then their agent personality will likely be closer to the image they create for B if B is present and the characteristics may not persist when B is absent. Even in nondomestic settings, these characteristics suggest two classes of agent which do not appear to be present in the agent-based modelling literature, a Collective and Dyad agent.

Finally, every year, the American media publish divisive articles on sexism in building design, namely the operation of HVAC systems and comfort temperature definitions. As would be expected, the articles conclude with observations in chapter 2 and the literature in general: gender is not a good indicator of thermal comfort preferences. However, the articles albeit provocatively identify a class of occupant which is referred to in this thesis as a "delegate". A common complaint relating to the understandable perception of missing agency in adaptive control is that a person (occupant – universally described as a man in the media – who is not present in a given zone control the conditioning services. This "delegate" is in direct conflict with all forms of occupant modelling and best aligns with the postulated superstition-led conditioning, post-design. The media tends to portray this “delegate” as akin to a club DJ, frequently interacting with the conditioning controls to produce the least objectionable environment state which at best may be seen as outsourcing adaptive agency to an expert or at worst outsourcing to an ignoramus or biased agent. Additionally, their second-order interests – managing the building environment – may not be driven by the social image, and if it is the image may have no relation to the occupants of any zone they manage. They may, for example, aim for the adoration of their supervisors through what they perceive to their second-order interests. Alternatively, they may be driven by professional constraints such as not exceeding a certain level of consumer consumption during a given period. Regardless of the responsiveness, second-order interests or bias of the “Delegate” agent, the key conflict they present is they do not experience the environments they control. It is likely in some buildings’ occupants have the opportunity to communicate with the Delegate but they can never express the Collective needs nor can the Delegate be emphatic.

The term “enabler” attributed to two suggested classifications which are intended to indicate they do are not conventional in any sense related to normal occupants. They have no perceptual needs, nor are they relatable to interaction models standard, and other proposed classes fit. Instead, they are suggestions which in isolation and perhaps in combination resolve issues with existing utilisation functions which are discussed throughout the chapter. They should not be considered agents but rather as entities which exist to hold place. Ostensibly like an internal partition which exist solely such that gross internal area may be considered and utilised as subspaces.

6.5.1.1 Delegate

An occupant which whose actions serve to meet the needs of others irrespective of their own needs. This type of occupant may exist as multiple forms of occupant within a given building or discrete space or as an external entity controlling systems remotely. Arguably, their actions may fall under the category of external interference, defined in this thesis as transmittance of information between the closed system and encapsulating system. However, the thesis considers them to only spatial reside outwith the building, and therefore, their actions need not be considered as breaching into the closed system.

6.5.1.2 Absent (ghost, enabler):

The class not yet accommodated by agent models described in the literature serves to bridge the gap between real- and virtual-world operation. An occupant with no mass does not affect the condition of the environment, has negative needs and no intentionality or adaptive control enables application of Janda's statement during unmanaged inoccupancy. Design modelling assumes zero presence to translate to inoccupancy in the real-world which relies on the assumption of ideal building service system management via BMS and/or occupant control usage. However, the disconnect between real and virtual world zone presence can result in two divide by zero situations. Firstly, a prerequisite of calculating space utilisation is a period of greater than zero density during the assessment period in at least one discrete space in the building or space being assessed. Secondly, as a metric has the same criteria as space utilisation. Without meeting these. It is proposed in the needs as a performance metric section that needs for absent agent be negative since the relationship between servicing and occupants is reversed; the absent occupants exist to meet the needs of the space.

Ghosts may be representations of the previous occupants rather than design as originally thought since the preferences of the zone those of the previous occupants unless a delegate is in control.

6.5.1.3 Pseudo

Entities in nondomestic buildings which share properties with standard occupants but are not living animals. Though "entities" is used a placeholder here, the term "equipment" may be less objectionable when considering the limitations of the computers as pseudo agents section. The level in which each device may be considered an occupant is uncertain; however, devices have traditional occupant characteristics. In their simplest form, nonancillary equipment has non-conditioning needs and produce variable rate latent gains based on their activity and second-order interests. In broader terms, they exhibit many of the social characteristics which are becoming prevalent in the occupancy literature. Computers particularly share many characteristics with standard occupants though their intentionality is inherently latent or absent once it is no longer interacting with a standard occupant. The class may itself benefit from subcategorisation for its role in social external interference. Some forms of equipment can transmit energy and social information between buildings which are typically considered closed systems. The former may best be considered akin to preparing and consuming food offsite and therefore not likely meaningful; however, the needs and adaptive actions of standard occupants. The latter may also cause unpredictable changes to occupant density or otherwise affect the Collective occupant. The extent to which agent models can currently facilitate pseudo occupants is uncertain, but the current Boolean-state power density definition does not reflect the social and moral entity characteristics of certain equipment.

6.5.1.4 Pseudo-ancillary (enabler)

The Absent classification serves a special purpose which does not relate to the literature. Its recommendation is to resolve issues with the SMG utilisation function when real-world utilisation occurs outside design days, or the granularity is increased from average annual. However, the special class has its weaknesses. While it resolves the SMG utilisation limitations and the negative needs principle has potential for needs as an efficiency metric, it is not immediately clear how it may be integrated universally. An alternative approach that requires a smaller leap of faith is treating some ancillary equipment as composites of the Delegate and Pseudo classifications. Heat sources, for example, have inherent needs or expectations of the occupants within a building. While they're sized for steady-state losses during early inoccupancy, their performance relies on teamwork from standard occupants. That is, its role is to temper the environment and both standard and Pseudo occupants alleviate its workload. As discussed elsewhere in this chapter, there is some value in considering occupants and equipment as employees of the building owner. Like the Nomad occupants, boilers can be considered employed as per the transitive verb 1(a) definition from Merriam-Webster. This is further supported if failure to fulfil requirements occurs. The boiler's existence and utilisation are conditional on performance metrics. If it cannot fulfil its role, it loses its position. As with Pseudo occupants, boilers have no perceptual needs, but unlike all other classes, their efficacy cannot be bound to standard occupants. That is, though their performance, not capacity is linked to contributions from standard occupants, standard occupants' employment cannot be measured in allowed absence. Nonetheless, they enable consistent application of utilisation functions when simulated, and real presence diverge and needs as efficiency metrics. Both of which are inherently significant to the primary experimental observation form this thesis; the retrofit process should fits assess utilisation and consider passive management measures before active replacements. Unless of course, the active measures are prescribed by Part L2.

6.5.1.5 Collective

Agent-based modelling adapts the premise that each occupant is an independent entity which is not entirely accurate in real-world shared environments. In reality, occupants in addition to being individual agents form a collective which should be represented either as an agent in its own right or in place of one or more agents. As an example, consider the opening discussion of the literature review's psychology section. The perception of self-efficacy affects comfort temperature ranges in individual occupants. The perceived ability to modify the environment through interaction with the thermostat regardless of whether it is functional contributes to perceived thermal comfort loosely proportional to the number of occupants in the zone. Similarly, add the closing observation in the same paragraph notes an occupant merely making a statement about the thermal comfort in an environment can affect the perception of others. The extent to which collectives change with respect to its constituent occupants becomes increasingly more complex when mood is considered as noted in closing of psychology. Positive mood negatively affects glare sensation making happy occupants more inclined to reduce natural light which may compete with the interests of other occupants. Additionally, mood can affect the clothing decisions made by occupants which may increase diversity in physical properties associated with thermal comfort. However, all these considered people have socio-personal images and groups have social identities which affect the way they perceive the environment and what constitutes as a comfort criteria. The perception of being "cool" as a teenager and collectively rejecting entities or concepts in align with peers declines with age. In summary, the needs, contributing factors to perceptions and the resulting perceptions themselves of individual occupants are shaped by the collective they are in many forms. Therefore, independent agents cannot truly represent a group of occupants in shared environments suggesting the need for a form of amalgamated occupant

6.5.1.6 Nomad

Several ancillary occupant roles might be considered between partially and completely nomadic in the sense that their roles require involve any number of zones in a building intermittently. Roles such as janitors or cleaners, for example. Additionally, their traversal routes are not consistent with observed patterns such as those identified through visual graph analysis. Traversal is also a significant component of their activities which cannot be said of standard occupants. Their activities and purpose in primary spaces have little relation to the activities these spaces are designed for. They are possibly closer to servicing systems in that respect; while they are necessary for standard occupants' activities, they maintain the space and equipment. Their distinction extends to metabolic output, clothing levels and opportunity for adaptive comfort management. To that end, there is a need for considering these occupants as irregular or otherwise not standard. Their second-order interests are to make sure the standard occupants can effectively and comfortably meet their own second-order interests. Discussed further in proceeding sections, transferring needs management from the building system to individual comforting technologies may have a significant effect on building performance, utility and their wellbeing.

6.5.1.7 Dyad

Couples in residential spaces and inclusive of professionals who have an intimate social relationship beyond colleagueship. Similar to the suggested collective occupant class, intimate dyadic relationships result in compromise and mitigation of the characteristics traditionally associated with an individual's comfort needs. However, in contrast with the proposed collective class, couples and families, in general, are invested in the interests of their spouses or children exclusive of socio-personal image. This class was loosely identified during the literature review but since the thesis is focused on nondomestic occupants, discussion in chapter 2 is absent. This class exists purely as a placeholder in the context of this thesis.

6.5.2 Occupants in the real and simulated worlds

Occupants in the real world differ greatly from those in simulated worlds regardless of the complexity of the model which describes the population and agents' interactions with the built environment. Even the most creatively designed causal network cannot be expected to predict the knock-on effects of agents' actions within a population. It only can strive to achieve a reasonable model for injecting actions into a simulation that on average, are better aligned with real-world consumption than if the network weren't present. Some literature considers occupants as "thermal disturbances" and other individual entities which require independent agent representations. This thesis considers the former in terms of absence-as-presence and supports the latter questioning where a nonancillary device should be considered an agent in its own right (Oliver & Pour Rahimian, 2018). Even the concept of external interference has merit which arguably is intrinsically linked to the Computers as Social Actors (CASA) described in (Oliver, 2019). They are also may be linked to the ethical agents discussion (Deborah G. Johnson & Powers, 2008). That is, for all intents and purposes an external interference in the context of occupancy or energy modelling is an event which conflicts with the notion that energy models are a closed system. For example, termination of a bus service or poor weather conditions may lead to one or more occupants being absent; however, the same can be said for an email from management inviting the occupants to remain absent. To an energy model, these are indistinguishable as external interference or otherwise eternal event affecting the closed system even if the latter email is sent from within the building. These considerations lead to three questions 1) What the extent is a real-world occupant can or should be represented realistically in an energy model. 2) What should be considered an occupant and how significant should unconventional occupants' actions be weighted? 3) Is it possible or necessary to include external interference, defined as any form of transmittance which at one or more stages exists outside the closed system, in the modelling process? This subsection considers these questions with the aim to extend the definition of an occupants' interactions beyond the limitations of the closed system definition. Discussion in this section related to nonancillary lends itself heavily to previous publications from the author noted in the other publications section which discusses computer media communication and social presence in AEC (Oliver, 2019).

6.5.3 Key differences between real and virtual occupants

Virtual world occupancy models range in complexity from standardised hourly densities bound to an activity type, typically templated for Monday to Friday, and Weekend for normal and holiday periods, to sub-hourly occupancy schedules (SCHOCC) generated using time inhomogeneous Markov models or multi-agent models. Both types have a place in building performance simulation depending on the purpose of the simulation. However, no matter how well their impact on the simulation results correlates with the real world, they can never truly be representative for several reasons:

- Simulated agents' actions and transitions are naturally time inhomogeneous meaning that the probability of any event or action is not static. However, the actions or transitions happen in discrete time. That is, there is no discrete interval between actions nor are agents acting synchronously.
- Simulation models though sensitive to climate are otherwise closed systems which cannot be affected by external events or actions. Buildings in the real world are not closed systems. Information communicated by a remote agent can change the behaviours of one or more internal agents, noise pollution from a neighbour may trigger an agent action, or on a grander scale, real-world consumption is susceptible to external interference. The computers as pseudo agents section of the literature review chapter and (Oliver, 2019) contains a discussion on the premise of interference from distal agents.
- Real-world actions or transitions happen in uncountable state space. As much a technological as it is epistemological, a model cannot learn every possible action or interference that may affect the environment, or its actors nor can it be expected to model every "agent". Though not every model requires all features from it, not even cutting-edge models accommodate more than a handful of superficial forms of the concepts discussed in the occupants and agent-based modelling sections of the literature review.
- T. Zhang *et al.* (2011), discusses how agents can be socially aware in the form of learning other agents' preferences for adaptive comfort measure. The occupants' section of the literature review identifies numerous social interactions which affect

comfort and therefore, energy performance. H. Wang *et al.* (2018) discusses how occupants declaring alleged perceptions of the environment affected other occupants' perceived comfort, for example. (Marcel Schweiker & Wagner, 2016; Yun, 2018) observed perceived self-efficacy improving perceived comfort, though diminishes as the population increases. Short-erm effects can affect sensitivity to environmental conditions and therefore the likelihood of taking adaptive action. The acclimatisation is not ethnicity section discusses what Tabak (2009) considers as adaptation theory's role in endurance or insensitivity as exposure conditions is prolonged. These observations are exclusive to the occupancy literature. (Oliver, 2019)'s discussion on trust and communication provides a discussion on how these social interactions can manifest from outwith the occupancy literature, covering social intimacy, trust and communication's roles.

These features are worth mentioning if not to remain consistent with the pessimism present throughout this thesis. They demonstrate that much like how occupant comfort within a tolerance is perceived and not an objective metric, how representative a probabilistic or agent-based model is moot. Models exist to create accurate representations of environmental conditions, not real people, and therefore it does not matter what the model does to achieve accuracy so long as it achieves it, even if its actions are out of the realms of possibility.

6.6 Needs

The psychology section discusses the SHOCC energy model occupancy scheduling model used to define the drivers for activity, the needs of the occupants carrying out the activity and the adaptive measures occupants may take. Drives, while relevant to the model, are arguably metaproperties or hyperparameters as they are static characteristics of their associated space(s). Needs, however, are a mixture of subjective, and service- and climate-sensitive environmental prerequisites which must be met to a reasonable extent for occupants to operate in nondomestic settings. It is evident from the literature and further explored in section occupant taxonomy that needs can and should be evaluated for both standard and Collective occupants. In isolation, both classes of occupant's needs are difficult to quantify and subject to time inhomogeneous, unpredictable changes. This is for several reasons including task-specific, intermittent adaptive measure actions, external climate, cloud density and time, external noise pollution, and arguably, service capacity and performance. The underlying model of needs is, needs can be described as interdependent and dynamic sets. However, as proposed in the occupant taxonomy section of this chapter, and expressed to an extent in agent models from (T. Zhang *et al.*, 2011) in section the literature review's agent-based modelling section, standard occupants' socio-personal, population social and Collective occupants' needs are overlapping subsets of independent supersets. Further complicating the problem is the sets at standard and Collective occupant levels are fuzzy. In short, needs evolve, and the adaptive measures required to meet them are defined in physically and socially sensitive fuzzy sets with overlapping subsets. Time inhomogeneity as discussed in the key differences between real and virtual occupants section of this chapter, and arguably the likelihood marginal utility theory – agents make rational decisions – does not apply means the solution space is likely uncountable. Nonetheless, understanding and formalising needs is the first step to learning what it means to an energy model for an occupant to have social relations or a population to be defined as a Collective. This subsection considers the aspects discussed here, needs as an efficiency metric and how "negative" needs in terms of the proposed Absent occupant class relate to an efficiency metric.

Task-specific such as task lighting requirements as discussed in the behaviour section of the literature review where needs are dependent on whether the occupant is engaging in an intricate activity. Intermittent adaptive measures both in isolation and considering Collective occupants can interfere or complement needs as inferable through the literature in the psychology section of the literature review, the occupant taxonomy section of this chapter, and specifically relatable to the hue heat hypothesis. Perceived lighting intensity was most accurately estimated by occupants where ambient temperature was in line with neutral temperature, and perceived shivering was greater at colour temperatures greater than 5800K. In the event the zone population is greater than one and less than the total population are using task lighting, the adaptive measure preferences of those utilising task lighting are less constrained activity technicality or microenvironments but may be constrained by social considerations for the occupants using task lighting.

Intermittent adaptive behaviours bound to antagonistic measures may lead to adaptive actions which mitigate the actions used to meet separate needs. For example, residential window operation behaviours can be reasonably predicted by internal CO2 concentration (Marcel Schweiker *et al.*, 2012). Jeong *et al.* (2016) observed window operation increasing “steeply” from 10°C upwards, which very low compared to comfort temperatures. Window operation in residential settings is a more extreme form of the adaptive behaviours discussed in the occupants' section of the literature review since it is a conflict between servicing and comfort rather than increasing demand for purpose. These create an efficiency conflict where the free filtering of air affects the capacity of the heating system to heat the zone, the ability for the heat to be distributed to the relevant areas of the zone and the form of the heat received by the occupant. Additionally, assuming a wet radiator system, depending on the position of the radiator whether under the window elsewhere the airflow direction will differ, up under the window, down elsewhere. In the event of reduced thermal comfort, the occupant is likely to adapt their clothing level. This pedantic example of intermittent adaptation and needs management encapsulates conflicts between needs, actions and systems, and would make a good starting point for discussion on Dyad occupants. The heating system’s capacity to temper the environment is challenged by increased heat removal. In residential settings likely exclusively at the outlet, though as discussed in the classroom section of the results, may overburden the heat source. The airflow not only affected by position and non-isothermal heat transfer from furnishings, mentioned briefly in the computers as pseudo agents section of the literature review, but also the location and type of the heating outlet. An outlet under the window is strategically placed to prevent a blanket of cold air at floor level which may result in longer periods of perceptually tolerable window open state climate effects.

6.6.1 Do needs have the same servicing demands for mixed occupant roles?

When occupant needs such as thermal comfort are discussed they tend to be discussed in terms of their relation to space activities and psychophysiological attributes or as space servicing demands. However, these discussions tend to focus on primary activity space users which precludes ancillary roles better considered as nomadic: cleaners, janitors, technicians or security, for example. In contrast to traditional occupants, those who perform one or more of these roles are present in serviced spaces for short periods of times with differing clothing levels and performing activities which are not the spaces' intended purpose. nomadism inherently changes the nature of occupants' interactions with spaces and the adaptive opportunities available to them. Additionally, any relative class from the taxonomies section namely Collective have no bearing with the boilerplate definition outlined above or at least; their collectives have entirely different social structures and hierarchies. Finally, a sordid question similar to how Delegate's second-order interests can affect their incentive to be more generous or attentive, to what extent should building managers even care about the needs of nomadic occupants? To be clear, that is not a question of whether these occupants have equal rights to be considered a traditional occupant. It is a question of whether there is a point where investing in their comfort exceeds the value of any occupants' needs. Additionally, is there a point where investment in meeting their needs is not met by their capacity to reap the benefits of investment. Though it is not a consideration of this thesis, an interesting characteristic of these nomadic occupants are their ascension beyond management's trust to their confidence. While many standard occupants are not permitted to traverse buildings freely, ancillary staff often have total or prescribed free roam.

Janitors, building service engineers and security share more commonalities than they do with a cleaner. While janitors and security do tend to have offices or spaces for static activities, their primary roles are to traverse their respective building. Building service engineers are a bit more complicated since they are not necessarily employed by the building owners directly and therefore not a permanent occupant. Given their roles require frequent traversal and varying durations of presence in primary spaces, their needs cannot be attributed to any individual space nor can their needs be effectively or justifiably met if they were the sole user of a building. That is, if only the janitorial staff are present on say the Graham Hills building, it would be incredibly inefficient to condition all 19,000m². In contrast, however, there is a limit to how far from comfort levels temperature, for example, can be before they are unable to complete their activities. However, the activities of janitors and service engineers are not also emergency and therefore may be schedulable to an extent. Future discussion in this chapter considers out-of-design utilisation and heating management systems; it seems there may exist a compromise between the untenable 19,000m²/agent and failure to reasonably meet their needs.

The same cannot be said for cleaners. While they are somewhat nomadic and do not perform the primary activities spaces are designed for, they can spend moderate periods of time in spaces. Additionally, they tend to visit numerous spaces during most cycles. These pose significant challenges for servicing management since even a well-designed recurring traversal conditioning strategy could not guarantee management of dynamic heat transfer and unpredictable climate. It is not necessarily an unsolvable version of the 19,000m² conditioning example discuss with regards to janitorial staff. However, it is not likely something that can be resolved through careful management of the centralised system. It is also unlikely suitable for local systems either.

Regardless of the roles of ancillary staff, they are equally distinct from the standard definition of any relevant classifications discussed in occupant taxonomy section of this chapter in significant ways. These differences should be particularly related to the behavioural and social characteristics discussed in the behaviour section of the literature review. While this thesis steer clear of discussing the social status of “standard-Collective” and “Nomad-Collective”, behavioural and adaptive measure opportunities are significant with mostly unobjectionable explanations. One cleaner in the Inovo Building in Glasgow across the street from the Grahams Hill building spends roughly 10 to 15 minutes per session cleaning and 80m²~ office. Typically, they arrive at this office around 6 am to 7 am. These sessions do not encompass every task involved in cleaning the office. Instead, tasks are staggered. The building is mechanically ventilated with tempering service by fan coil systems. Though these systems are responsive, they could not change the environment quick enough to be considered a practical adaptive measure. Their tempering also does not follow the occupant between zones. The windows are inoperable, and the circulation areas are passively served from primary space. Therefore, their only adaptive options is clothing adjustment. Similarly, cooling while present would not be responsive enough for use, therefore, leaving the occupant with clothing adaption as well. However, cooling is more complicated at different time and locations in the space. Around 70% of the office's envelope is transparent. Therefore, being near the glazing has significant radiant heat. In fact, the recorded temperature difference between the centre of an office and glazing provide a significant challenge for the tenant. The key problem with both heating and cooling examples is that adaptive measures accessible to "standard" occupants are not necessarily accessible to Nomad occupants.

6.6.2 Needs as a performance metric

In the opening of the occupants' section of this chapter is suggested that Janda's statement may alternatively be framed as the needs of people. Both statements do not fully support the underlying premise of the results in this thesis that consumption is a function of a utilisation belief system rather than real-world utilisation. The latter while a necessary framing tool for this section is also an optimistic take on the original in that the consumption described by both is not mindless. Regardless of optimism, both statements are implicit of a failing in current building design; buildings only behave as expected when real-world utilisation correlates with design utilisation. This thesis does not prove this in the real world, but the building performance and retrofit results demonstrate that the simulation gap is functional as epistemological. Therefore, either this translates over to the real world and is a demonstration of a functional building performance gap in addition to the normal gap, or EnergyPlus is not an effective tool. The latter is not likely true since it is one of the best representation of building physics available. The problem becomes significantly worse during zero-density presence where services may be exerting beyond design to condition zones with no discernible qualities from cavities. This indicates two things which appear to be overlooked in current building design. Firstly, buildings are designed for ideal use, not real-world use. It is impossible to guarantee real-world operation of buildings, even those with fairly stable patterns such as university teaching spaces. However, SMG reports combined with observations in the experimental results of this thesis clearly show divergence from simulated schedules to the point where it is debatable if simulated results are meaningfully relatable to the real world. In fact, the building performance in this thesis, for higher education facilities at least, suggest they are in conflict effective retrofit analysis.

Despite reliance on correlation being part of the Collective occupant needs calculation and seemingly an integral part of efficiency analysis, needs may potentially be decoupled from simulation or even energy performance. In the, do needs have the same servicing demand section of this chapter, an example is offered for efficiency measured against out-of-design ancillary staff utilisation of the Graham Hills building. The building, which is 19,000m² may be occupied by one or a few ancillary staff outside design periods or any form of standard occupancy. Each ancillary staff member has a quantifiable monetary value albeit likely better considered in indirectly as increase anticipated rate of return from standard occupants rather than absolute since their roles are insurance. An assessment of their marginal value may be the anticipated reduction in downtime per unit of money; however, that is ignorant of building operating cost.

6.7 Conclusion

This chapter discussed the results of the from the experimentation stage of the research. In doing so, it outlined how the observations affect retrofit analysis. It proposed that the simulation gap is not necessarily marginal but functional, and epistemological concerns present in the extant research. It suggested that its findings must translate to operation in some way through discussion of performance metrics behaviour under NCM and real Schedule-Climate scenarios unless the EnergyPlus model is wholly ineffective for low-utilisation buildings. It also offers discussion so support the proposal that needs may be a useful metric for evaluating operational efficiency and for leading class registration.

Through consideration of the literature and interactions with people in buildings over time, there are gaps in existing taxonomies of occupancy. These gaps, particularly the absence of the Nomad classification, change the nature of how occupants should be modelled in agent-based models and how designers should view them. In some cases, they may also raise challenges efficiency and planning challenges which cannot be resolved by conventional strategies. The literature does not encompass these occupants who can be those who have the highest marginal consumption at the time where the building is most inefficient. While discussing important and interesting features of occupant interactions with each other and buildings, it falls short of considering social first, and professional second-order interests. The former covered by the Collective and Dyad classifications and the latter the Delegate.

7 Chapter 7 - Conclusion

7.1 Introduction

This chapter concludes the thesis with commentary on the successes and failings of the research. In this chapter, the reader will find an overview of how and to what extent the aims and objectives outlined in chapter 1 were met. A set of recommendations are made for reducing the performance gaps and needs-centric efficiency evaluation. They will also find an extensive list of future research opportunities whose themes were beyond the scope of this thesis. The chapter proceeds with a summary of this thesis' limitations. The nature of this thesis is not controversial in terms of experimentation and discussion on occupant ontology and needs are talking points arising from experimentation and literature review. Therefore, the section shorter than is common. The chapter concludes with closing remarks on the research, its findings and its affirmation of previous works.

7.2 Were objectives met?

This thesis set out five objectives, including epistemological, ontological and experimental aims. The results chapter presents the discussions and experimentation results which support the claim that these objectives have were met.

Objective 1: Develop an understanding of the current occupancy literature surrounding occupant behaviours and the psychophysiological characteristics that drive their interactions with each other and buildings.

A critical analysis of the literature surrounding occupant-building interactions, the characteristics which ultimately may humans, human, and how they relate to building operation was carried out. The occupant and computers as pseudo agents sections of the literature review provide a primer on related interdisciplinary literature, primarily focused on publications in built environment journals. In contrast to other publications, this thesis contains greater focus more on agent epistemology, inclusive of psychology, computer science and computer ethics themes than is common. The observations and experiment led to aims and objectives being met to the extent describe in the list below:

Objective 2: Develop the tools necessary to integrate registration system data with EnergyPlus to accommodate blending simulated and operational environments such to draw comparison between the two. The tools should include a building management system (BMS) modelling tool which enables representing efficient conditioning system management.

An extension to the ePPy Python library for EnergyPlus was developed as described in the development section to enable the interactions with EnergyPlus necessary to fulfil the research goals. The library not only provided the necessary registration system translation functionality but also included numerous helper methods which enable instant scripting results interrogation. The success of the development stage can be seen from the disaggregation and present of results throughout the results.

Objective 3: Using the BMS modelling tool demonstrate the building simulation results performing closer to the expectations one may have going into the decision-making process for standard utilisation buildings.

The development stage of this research required the production of a tool to translate registration system data to Schedule:Compact EnergyPlus occupancy and lighting schedules. During the development process, an investigation into how EnergyPlus may be convinced there is a building management system installed in the building. The tool became the basis for the implementation of the R-BMS retrofit method described in the research methodology chapter. The new method was then used to demonstrate why it is an important utility for reducing the simulation and performance gaps and assessing the value of a BMS proposal. Discussion is prevalent throughout the results as a calibration method and in the context of retrofitting in the results chapter's section retrofit subsection comparing the heating efficiency credits method to R-BMS.

The results presented in the heating management section notably demonstrate that during some periods or always for some spaces, zones probably should not be considered a conditioned space. The results in this section were well beyond those hypothesised.

Objective 4: Discuss the characteristics of occupants which do not have prominent exploration in the literature to suggest ways in which future researchers may improve building simulation and utilisation planning. This shall include discussing how needs may be considered as a metric for performance in line with discussion on Janda (2011)'s philosophy.

The occupant taxonomy and needs sections of the discussion chapter provide extensive discussion on why an extension to Janda (2011)'s interpretation of occupants' contributions to energy consumption is significant. The amended expression is not intended to discount Janda's but rather expand on her seminal paper. The discussion makes a simple case for needs as a performance metric. No matter how efficient a building is, if its services are meeting needs that do not exist, it is an inefficient building.

Objective 5: Present the simulation results in terms of building service consumption and inter-occupant contributions to the perceived needs of utilised spaces – where occupant is extended to incorporate non-living agents. The results should be explained in a way that makes the underlying claims of divergence between real and simulated results unobjectionable.

The results were presented in many forms exploring commonly interrogated features surrounding consumer energy and conventional performance metrics. Greater focus, however, was made on the occupant and presence related features of the model and operations periods. The observations led to many discussions on expected latent and equipment heat gains and demonstration of how far the operation deviates from design presence. A new graph was created for showing schedule exclusivity set membership with added cumulative presence to demonstrate the extreme deviation between design and real schedules. By highlighting presence at different levels of granularity from annual to hourly and absent gains, there is no question that the building cannot be operating as designed.

7.3 Contributions to the existing body of research

This thesis contains a detailed virtual case study demonstrating building sensitivity to occupant presence and critically analysed the extant literature. In doing so, it produces several contributions to the existing body of research and paved the way for future research into modelling the operation and calibrating building energy models. It also demonstrated results which must translate over to the operation unless EnergyPlus is ineffective. The list below summaries the key contributions:

- A methodology for modelling registered utilisation in University education secondary, further and higher education facilities.
- A methodology for representing a building management system in EnergyPlus that represent well-managed HVAC based on operational utilisation.
- It demonstrates how heating management calibrates building energy models to reflect the scheduling methods used for legislation-led retrofit analysis.
- It demonstrates why standard schedules are not useful for retrofit analysis or building energy modelling in general.
- A detailed explanation as to why the simulation gap is marginal, functional and epistemological. Features which must hold to the building performance gap if EnergyPlus is not to be labelled ineffective.
- It described gaps in occupant ontologies which reflect the heterogeneity of occupant activities.
- It justifies the need for acknowledgement of building managers as delegates.
- It provides a case for using needs as an efficiency metric for operation stage evaluation.

7.4 Recommendations for reducing the performance gaps and optimising decision-making

The most notable observations from the philosophical and experimental research in this thesis is that building operational performance simulation and practice is fraught with management issues. Many of these such as deviation from expected behaviours arising from dissimilar virtual- and real-world utilisation schedules appear relatively easy to resolve while others are best resolved for unconventional measures. Other observations were arguably as significant in terms of the redefining utility assessment. The following sections offer recommendations for increasing utility of occupant-centric assessment.

7.4.1 In lieu of reliable utilisation data, simulate poor utilisation scenarios during design and decision-making

The Schedule-Climate scenarios simulation results underpinning the experimentation in this thesis have parallels with Rastogi (2016)'s – On building sensitivity to climate – with occupant presence instead of climate. In both theses, it is shown that design and reality are not necessarily comparable, which indicates a need for protection against operation counter to design. Both retrofit analysis and design should not be an optimisation challenge but rather a robustness to uncertainty analysis. To that end, it is the primary practical recommendation of this thesis that design incorporates Schedule-Climate scenarios which deviate from standard assumptions. Current design and retrofit analyses rely on assumptions of how the services will perform under design scenarios. The results in this thesis in reaffirm Rastogi's proposal and indicate parallels with occupancy. Services and fabric selection should be considerate of sensitivity to divergence between design and operational conditions.

7.4.2 Start measuring performance as a measure of needs

Janda (2011)'s discussion on what consumes energy alludes to the notion that needs to consume energy, not buildings and inherently, the presumption that needs exist. The results from this thesis show that operational presence is significantly under design assumptions, yet the buildings necessitate design heating system operation. No matter how efficient a building is and how close the operation is to simulated performance, Results from analyses with static design conditions may not be great metrics. Needs, on the other hand, may. That is not a dismissal of simulated performance but rather to highlight that the most efficient building perfectly aligning with simulated performance during operation is still inefficient if there is only one occupant. Shifting operations alone may be a more significant retrofit than any active system replacement with little to no cost beyond management opportunity cost. Designers and analysts should consider energy consumption with a measure such as kgCO2/kWh.person to ensure high-efficiency consumption is not defeated by a lack of occupants to perceive the conditioning.

7.4.3 Prioritise building management systems over active service replacements

Though this research only explored one building the observations surrounding conflicts in utilisation and the function used to assess utilisation make it clear a priori knowledge from simulation is not sufficient alone. At least in the case of higher education facilities, there is no real case for independent or interdependent consumers before creating an effective consumer management strategy. As the building performance overview and classroom scheduling, heating management results demonstrate, without management tied to occupancy buildings begin to behave unpredictably as simulated and operational utilisation divergence. Furthermore, the results chapter sections on lighting and net energy demand and constant-efficacy lighting retrofits demonstrate at best diminishing and at worst antagonistic results from consumer retrofitting without consumer management. To that end, consumer management system consideration should likely precede direct service retrofits.

7.4.4 Nomadic occupant planning strategy

Ancillary and other Nomad occupants' needs can occur at inopportune periods during the day, whether early in the morning or during low-utilisation periods such as the weekend. Not every Nomad's building traversal is schedulable or otherwise integrated with the servicing systems. However, some may, and others can be integrated into lower demand periods. Where Nomads can be scheduled, such as janitors, their actions may potentially be integrated with a BMS. Those who might be open to alternatives to conditioning the building to meet their needs. Needs can be assigned a monetary or energy efficiency value which should be used to guide a BMS. Where not possible, they should guide staff activity planning if neither are practical, they should guide the adoption of alternative measures.

7.5 Future research

Through a review of the literature and experimentation, this thesis identified several ontological gaps and epistemologically inconsistent a priori knowledge inherent to occupancy-led retrofit analysis. The classification of occupants not just as behavioural probabilities commonly in agent-based models but as entities which transcend the existing definition of occupants in energy simulation. These new classifications while mostly anodyne may potentially change future occupant modelling research and open up the definition of retrofit option beyond building services, control measures, thermal element upgrades or education. The proposed Nomad classification and the efficiency in meeting their needs, for example, does not appear to have any related existing literature and the resolutions to the inherent inefficiencies are not conventional building energy performance measures. Needs as an efficiency metric in its own right appears on the surface at least to have applications in energy efficiency-led space management. Space utilisation assessment has also been questioned, particularly with regards to the SMG utilisation function's general relevance and granular application. These suggestions, queries and concerns merit exploration in isolation hopefully paving the way toward a better-integrated model of occupant building interactions. However, while they are mostly common-sense observations, their application and construction are inherently complex and outwith the scope of this thesis. This section outlines some avenues for future research based on these observations and concerns which may improve occupancy modelling or quantify the concerns on a grander scale.

Note: The reader should consider these suggestions with an emphasis on algorithm development. While they have benefit for conventional analyses, they are primed for iterative processing which is inaccessible humans. The brunt of the research for these in many cases surrounds the development of confidence in their application rather than justifying their application.

7.5.1 Needs as an efficiency metric

The needs as a performance metric discussion proposes the concept of using the energy or lifecycle cost to meet the needs of occupants over a given period as a measure of a building's performance. On obvious application of this concept relates to the problem noted in the results chapter discussion: tempering a 19,000m² for a few "Nomad" occupants is extremely inefficient. However, understanding how this may be mitigated excluding personal adaptive comfort measures will require investigation into how these types of occupants' employment in the eyes of the building owner and the designer. Understanding these roles how these parties view them and how they operate in buildings will facilitate agent models which consider more than agents interact with services and control measures. Understanding may suggest changes to building design methodology along with the other findings from this thesis to consider giving greater attention to how performance outside design schedule.

A potential solution for ancillary Nomad occupants is personal adaptive comfort measures. Outdoor jackets with heating elements have existed for a while, and recently high visibility jackets for construction workers with cooling fans have reached market. These measures while not fitting of any traditional retrofit measure, would resolve the previous efficiency problem. Ergonomics and functionality of personal measures aside, evaluating the measure in terms of the occupants itself is a needs-as efficiency challenge. It may be valuable for 5 in a 19,000m² building with low utilisation and frequent out-of-design presence, but not likely for twenty replacing ten every year in a 500m² building.

A thesis with parallel themes to this referenced several time throughout this thesis is Rastogi (2016)'s “On the sensitivity of buildings to climate”. His work considers building energy performance sensitivity to uncertain climate conditions. In a similar vein to the arguments of this thesis, he notes it is not enough to analyse buildings under one climate scenario but rather multiple likely scenarios. Both theses indicate retrofit analysis should consider multiple scenarios with each demonstrating simulation and expected return disparity under differing scenarios. Needs as an efficiency metric has potential for constraining the observations from both theses. Some existing methods compare millions of scenarios alone under static conditions which suggests there is a necessity for intelligent targeting of representative conditions. To that end, needs as an efficiency metric may be a supplementary constraint mechanism for sensitivity analysis and genetic algorithm scoring weighting. Running a thousand likely scenarios analysing the results by time period to generate a model-specific scoring system has little computational processing time in the grand scheme of things. Less than a few hours if planned carefully. However, this hypothetical reduction methodology is an attempt to reduce trillions of possible scenarios to a demonstrably consistent model is a large research project on its own. This the most contentious recommendation of this thesis, however, developing such a model would seem to be the logical extension to the climate and occupancy uncertainty in retrofit optimisation for real-world operational performance assurance.

7.5.2 Occupant taxonomy

Agent-based modelling requires assumptions surrounding the nature of occupant interactions with buildings which are occasionally integrated as behavioural probabilities or what may be considered extraversion classes. That is behavioural probability classes with likelihood of adaptive measure interaction by agent class. While these classes serve the purpose well, they are ignorant of the features identified from the behaviour and psychology observations in the literature. Additionally, the least controversial suggested occupant classification in this thesis, the Delegate, changes the concept of needs management entirely. With focus shifting towards occupant wellbeing in addition to energy performance for building marginal utility rather than just performance, it is necessary to understand who controls what and how their collective or dyadic relationships affect their interaction models. It is unclear within the scope of this thesis, the extent to which these can be integrated. However, it has a significant effect on and how it integrates with other recommendations. Each of these items would make for interesting research directions which if not fruitful in producing new utilities, would certainly make a significant contribution to the literature.

The Delegate classification especially would benefit from further investigation due to their imperception of the environmental conditions they maintain and their second-order interests which are not necessarily exclusive to the comfort or wellbeing of the Standard or Nomad occupant.

7.5.3 Absent (ghost) agents

This thesis suggests a potential for resolving issues with the SMG utilisation function and accommodating more complex models of building energy and private benefit analyses. The discussion in this thesis is short, with an exploration of the concept beyond its scope. Nonetheless, its place in models extend from conventional analysis to algorithmic evaluation. As with the proposed Pseudo-ancillary (enabler), and Absent both patch existing models and simplify calculation methods. It may be over-the-top to consider both, but they can be used to decouple BEM and impact assessment which is inherently linked to algorithm design.

Research in this area will enable resolution of the SMG function problems identified in Utilisation overview which identifies several significant faults. Future work for this classification should focus on accommodating out-of-design schedule occupancy. It should whether all absent occupants are equal given some scheduling during inefficient times such as weekends in unavoidable; some classes must occur over weekends for example, where other classes cannot be scheduled at similar times for more efficient use. Ultimately, future research in this area should lead toward algorithm design which is currently inhibited by the SMG function definition.

7.5.4 Pseudo agents (computers and servicing equipment)

The Pseudo occupant classification proposed has some merit, albeit currently less than the thesis may suggest. However, at its simplest form, physical personalities, it bears consideration that not all devices exert themselves equally. There is a disconnect between the conventional agent and the device with latent intentionality contradicting current Boolean-state power density definition. SCLs demonstrate quasi-intimacy between standard agents and the devices; their efficacy is a function of their ability to understand the standard occupant. The extent computers as agents is covered in this thesis may be too liberal. However, these features would prove fruitful and as software develops, social presence will likely have a greater significance.

Classifying servicing equipment as Pseudo-ancillary (enabler) occupants is briefly touched upon in this thesis though not well explored. The concept itself does not necessarily fill a void in the extant literature or models. However, it simplifies some quantification method problems, namely the SMG utilisation function issues discussed. Additionally, it is an alternative solution from the Absent classification which introduces a negative needs principle. Though the latter may have benefits in some form, it is significantly more contentious and complex than this suggestion.

Best utility of this proposal would come from focusing on physical personalities of equipment in relation to their energy performance and constraints on user activities.

Current design scheduling assigns a nominal power density to equipment which is betrayed by the activities of occupant roles. While other personality features may be worth considering in the future, it is likely difficult to quantify. However, if it were considered it would be best focused on the Psychology section discussion on perceived efficacy and communication discussion in (Oliver, 2019). Social cohesion and perceived efficacy appear closely bound and their effects span beyond comfort and wellbeing.

7.5.5 External interference

This concept suggested in the thesis is debatably moot in many respects outside the Delegate classification's second-order interest definition. However, the concept in some way changes the definition of a building model from closed to somewhere between closed and open. Since the offset of building energy modelling circa 1957 with Fanger's nuclear bunker model, there may have been some form of benefit in understanding information transmission from external environments. With the advent of matured computer-mediated communication and social presence's role in communication as discussed by (Oliver, 2019), there is now a more than reasonable case for its consideration. The term external interference is used as a placeholder in this thesis. However, in the long term, it is a recommendation that future research considers how this may be quantified and introduced in less specious terms.

The key focus of future research related to external interference should align with the theme of this thesis and Rastogi (2016)'s observation on the need for mediocre but robust design over optimal simulated performance under uncertainty. It should focus on increasingly aggressive energy policy which will invariably expedite Delegate intervention with servicing. It cannot be verified via citation currently, however, discussion in MEES industry for operational efficiency is gradually gaining traction. Though it is unclear if it will come to fruition, a shift to operational efficiency would have profound effect on building operation given MEES prohibits leasing where performance is deemed unsatisfactory (DCLG, 2017b).

7.5.6 Dyadic vs social intimacy in relation to adaptive measure adoption

Although likely a less significant feature noted from the literature is the difference between dyadic and social intimacy's effect on adaptive comfort behaviours. Where social relations informing others, the environment is comfortable despite contrast with the occupant receiving the information can affect their comfort levels, dyadic relationships can have shared comfort. That is, understanding your partner and devoid of social image concerns, knowing your partner or family members are comfortable may is to some extent at least, a mitigating factor in the environmental comfort needs of the individual.

7.5.7 Artificial intelligence

It is likely the same can be said for needs as an efficiency metric. Combined with Rastogi (2016)'s work and the divergent schedule concerns it seems the typical limit from the government's current exemption model could exponentially inflate. Admittedly, NDEPC model is not necessarily about optimised design, instead taking the less mature "improve anything with an efficacy or efficiency" approach. However, retrofit-as-a-service models and non-UK building owners would benefit greatly from the recurrent solution space reduction problem.

(Oliver, 2019) suggests the next construction software innovations will be improvements to communication. A theme in the article is the necessity for tailored communication such as mediator's presentation of comments to maximise the recipient's perception of what was being conveyed. The learning aspect is not foreign to smart controllable loads; they can be systems that learn the behaviours and preferences of the individual. It is likely the same can be said for comfort models in relation to the proposed Dyad and Collective occupant classifications. Groups of occupants will never be comparable, but some qualities or probable traits of an expected population may be learnable or at least what it means to be a typical collective in a given space. (T. Zhang *et al.*, 2011)'s work on metacognitive social learning for agents discussed in the agent-based modelling section of the literature review, agents learn the preferences of others. This principle should transfer over to AI for learning to suggest adaptive measures that will be best received by or least objectionable to the collective. As AI advances it is desirable to understand to some extent the way in which AI interprets and accommodates the information it builds models upon. Moral bias is becoming an issue with some applications of AI and although moral is not likely the key concern for building systems, linking preferential treatment to known properties will aid future development As with psychiatric professionals, the standard definition of intimacy “the willingness to accept one cannot reside within the mind of another” is in direct conflict with the role of the professional.

Finally, wellbeing is an emergent concept finding its way into legislation and private sector decision-making. The relationships and differing occupant classification characteristics such as those between the suggested Dyad and Collective classifications are inherently complex. Google’s translator was speculated to have developed its own “universal” language which may be what is needed for unification of social, interpersonal, behavioural and psychophysiological characteristics of wellbeing and comfort.

Less interesting but of greater importance is focus on feature selection. As Janda notes, it is the people who consume energy, and systems do not care about their privacy. Therefore, knowing which features have the best utility to personal privacy intrusion rates will define how successful models are in both adoption and acceptance.

7.5.8 Heat recovery (Partial district heating networks)

The idea present in the thesis of heat recovery networks is not a new concept. However, it has failed to gain traction. This thesis has demonstrated the waste heating issues surrounding unmanaged and difficult to manage needs. Given the incredibly low utilisation observed, education sector buildings are primed for partial heat recovery district heating (HR-DH) networks. These need not be exclusive to building energy performance or comfort either. Tempering air in external air in surrounding environments will make passing agents more comfortable which while admittedly unproven in this thesis, may spur marginal economic growth. Comfort is a factor in exposing one’s self to environments which may have a knock-on effect on retail environment exposure duration.

Future research in this area should focus on how waste space tempering may be delivered to other spaces. As discussed in Behaviours, devices and wasteful consumption and observed in the Utilisation overview results, some significant wasteful consumption is unavoidable. Research should focus first on feasibility of retrofitting such networks proceeded by consideration for optimal scheduling to reduce waste inefficiencies. In the case of the latter in the case study building, for example, all out-of-hours scheduling may be constrained to the ground floor enabling disabling of the remaining 7 floors' conditioning. In the case of the former, see the proceeding section General (Strategic planning and marginal value estimation).

7.5.9 General (Strategic planning and marginal value estimation)

All discussion in this thesis and extant literature have a role to play in economic analyses, productivity and company valuation. The primary researcher of this thesis has a modest background in environmental economics and significant background in retrofit analysis. These backgrounds lead them to stress that integrated evaluation of economic, wellbeing, building performance and policy assessment would be a significant step towards the next major evolution of strategic environmental assessment. It cannot be stressed enough that this research direction is the most important subject for future research, whether as supported by this thesis or simply as the logical conclusion of interdisciplinary consideration of interdependent analysis models. Some suggested targets:

- Energy-led class allocation / seasonal class allocation: Allocating classes densely during winter around afternoon or sparsely around morning during summer especially if free cooling is utilised. Not all classes can be scheduled during design periods, but avoiding situations like 30/11/2017-22:00pm registration, 4 hours after the previous class could be better managed.
- Introducing needs as a performance metric to staff cost and utility analysis. Staff value is not exclusively their wage and management cost subtracted from their return; they are also consumers.

Future research should focus on spatial and temporal clustering to minimise the energy consumption to needs during winter and perhaps maximise wellbeing from energy during summer. The latter is applicable to heating-only buildings where the former may be more appropriate for comfort-cooled or conditioned spaces.

7.6 Limitations

The experimentation in this thesis is not controversial nor is it difficult to apply to other buildings with registration systems. However, experimentation based on the discussions on occupant ontology, efficiency metrics and utilisation functions were inherently outwith the scope of the thesis. Therefore, the data in this thesis does is not suitable for prioritising future research into the identified absent classifications. The efficiency metrics section in particular merits a doctoral research project on its own. While the occupant ontologies suggested may not all be as fruitful as each other, the Nomad does not appear in the literature yet is likely the occupant class with the highest consumption to meet their needs. Modelling this, however, will be very complex and require changes to existing dynamic simulation software which was not in the scope of the research.

Heating system sizing and associated efficiency-based calculations were idealised. Therefore, sizing remained static and the application of efficiency upgrades lower in resolution than advisable for real-world application. However, since changes to CoP were applied 1:1 with the SCoP, the results related to R-HVC and NDBSCG efficiency credits BMS method are more generous than they would be in the practice. Therefore, results with these skew the data toward the null hypothesis that Schedule-Climate scenarios have negligible impact.

During the initial stages of this research, an ethics application was written with the intent of obtaining basic demographic information for the individual occupants for calibration of the weighted metabolic rates from the People objects of EnergyPlus. However, it was later decided that the privacy concerns the accompanies demographic information was deemed to outweigh its value for this research at the academic level it is studied. This data would not significantly affect the results presented in this thesis since presence was a greater contributor to the observations than utilisation and the difference in latent gains, mostly negligible. Nonetheless, at site level or in buildings pursuing high-efficiency operational accreditation this data would not be meaningless.

Occupant presence and behaviours are discussed in this thesis but are not applied to the experimentation. Therefore, the results cannot be said to have relevance to the wellbeing of real-world occupants. This is true of compliance-driven retrofitting also, however, there is no value in a retrofit that results in wellbeing degradation to or greater than the performance benefits.

As is implied by the previous paragraph, this thesis does treat retrofits purely as closed system efficiency and management changes exclusive of their overlap with the architectural retrofit classification. Therefore, its analyses are purely in metrics quantifiable in relation to consumption and not external or nonmonetary benefits.

The data used for simulations are inherently limited by the availability of relevant design data and constraints on the detail of achievable service integration with EnergyPlus. While registration data was readily available, the level of service system detail and design was limited to that which would be identified by a Part L2B survey unless present in the IES model. However, it should be noted that this data would only be critical in practice where the simulation results are for real-world application. The granularity of the data used in no way invalidates the results.

7.7 Closing remarks

“Buildings don’t consume energy: the belief that needs exist to be met does”

This thesis is a tribute to Janda (2011)’s framing of building energy consumption “buildings don’t consume energy: people do”. The opening quoted phrase is a proposed amendment to include the belief systems that lead to inefficient operation and lead to building energy models becoming ineffective for retrofit analyses of low-utilisation buildings. The results in this thesis demonstrate that without properly calibrated occupancy schedules building energy models will not reflect the operational consumption of the building. Furthermore, they show the results of simulation cannot be relied upon as representative of how a low utilisation building will react to retrofit in the real world by any metric. It also demonstrated that system and envelope inefficiencies might be mistaken for operational inefficiency.

The initial research goal was to demonstrate occupancy’s role in the building performance gap and divergence from simulated and realisable return on investment from retrofits. However, the results appear to be more profound than anticipated especially the 86% overestimation of utilisation from standard scheduling of classrooms. The results in this thesis demonstrate that the building performance gap in low-utilisation spaces is inherently closer related to presence rather than behaviour and the simulation gap for low utilisation buildings can largely be attributed to difference in utilisation levels and the difference between presence-bound simulated consumption and presence-ignorant consumption. This thesis does not claim the performance gaps can be closed entirely, but it clearly demonstrates significant contributors from the operation, scheduling and heating load assumptions. It is not clear the extent to which the findings can be applied to the real world in the short term. However, one thing is clear: the industry must stop designing under the assumptions that operation can be generalised or that occupants are homogenous or even exist.

In closing, building energy modelling for nondomestic buildings is essentially needs-based. However, the needs do not necessarily exist in the real world and if they do, meeting them is not necessarily an interest of the operator. It is time for a paradigm shift as proposed by Rastogi (2016) towards robust designs with good performance rather than those which are optimal in the simulated world.

Bibliography

Ahmadi-Karvigh, S., Ghahramani, A., Becerik-Gerber, B., & Soibelman, L. (2018). Real-time activity recognition for energy efficiency in buildings. *Applied Energy, 211*, 146-160. doi:https://doi.org/10.1016/j.apenergy.2017.11.055

Ahn, K.-U., & Park, C.-S. (2016). Correlation between occupants and energy consumption. *Energy and Buildings, 116*, 420-433. doi:10.1016/j.enbuild.2016.01.010

Akhondzada, A. (2017). Modelling the Occupancy Profile Deterministically, Probabalistically and Stochastically: Thesis for degree of Bachelor of Engineering. *Metropolia University of Applied Sciences*.

Al horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A., & Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. *International Journal of Sustainable Built Environment, 5*(1), 1-11. doi:https://doi.org/10.1016/j.ijsbe.2016.03.006

Albadry, S., Tarabieh, K., & Sewilam, H. (2017). Achieving Net Zero-Energy Buildings through Retrofitting Existing Residential Buildings Using PV Panels. *Energy Procedia, 115*(Supplement C), 195-204. doi:https://doi.org/10.1016/j.egypro.2017.05.018

Altomonte, S., Kent, M. G., Tregenza, P. R., & Wilson, R. (2016). Visual task difficulty and temporal influences in glare response. *Building and Environment, 95*, 209-226. doi:https://doi.org/10.1016/j.buildenv.2015.09.021

Andersen, R. V., Toftum, J., Andersen, K. K., & Olesen, B. W. (2009). Survey of occupant behaviour and control of indoor environment in Danish dwellings. *Energy and Buildings, 41*(1), 11-16. doi:https://doi.org/10.1016/j.enbuild.2008.07.004

Andersen, V. R., Olesen, B. W., & Toftum, J. (2009). Occupant Behaviour with regard to Control of the Indoor Environment. *Kgs. Lyngby, Denmark: Technical University of Denmark (DTU).*

Antoniadou, P., & Papadopoulos, A. M. (2017). Occupants' thermal comfort: State of the art and the prospects of personalized assessment in office buildings. *Energy and Buildings, 153*(Supplement C), 136-149. doi:https://doi.org/10.1016/j.enbuild.2017.08.001

Arskey, H., & O'Malley, L. (2005). Scoping studies: Torwards a methodological framework. *International Journal of Scoial Research Methodlogy: Theory & Practice, 8*(1), 19-31.

ASHRAE. (2013). ASHRAE 55.

Azar, E., & Menassa, C. C. (2012). A comprehensive analysis of the impact of occupancy parameters in energy simulation of office buildings. *Energy and Buildings, 55*, 841-853. doi:10.1016/j.enbuild.2012.10.002

Beltrame, T., Rodrigo Villar, a. R., & Hughsonad, L. (2017). Sex differences in the oxygen delivery, extraction, and uptake during moderate-walking exercise transition. *Applied Physiology, Nutrition, and Metabolism, 42*(9), 994-1000.

Beltrame, T., Villar, R., & Hughson, R. L. (2017). Sex differences in the oxygen delivery, extraction, and uptake during moderate-walking exercise transition. *Applied Physiology, Nutrition, and Metabolism, 42*(9), 994-1000

Berg, F., Flyen, A.-C., Godbolt, Å. L., & Broström, T. (2017). User-driven energy efficiency in historic buildings: A review. *Journal of Cultural Heritage, 28*(Supplement C), 188-195. doi:https://doi.org/10.1016/j.culher.2017.05.009

Brady, L., & Abdellatif, M. (2017). Assessment of energy consumption in existing buildings. *Energy and Buildings, 149*(Supplement C), 142-150. doi:https://doi.org/10.1016/j.enbuild.2017.05.051

BRE. (2013). NCM modelling guide.

Brøgger, M., & Wittchen, K. B. (2018). Estimating the energy-saving potential in national building stocks – A methodology review. *Renewable and Sustainable Energy Reviews, 82*(Part 1), 1489-1496. doi:https://doi.org/10.1016/j.rser.2017.05.239

Bukauskas, A., Mayencourt, P., Shepherd, P., Sharma, B., Mueller, C., Walker, P., & Bregulla, J. (2019). Whole timber construction: A state of the art review. *Construction and Building Materials, 213*, 748-769. doi:https://doi.org/10.1016/j.conbuildmat.2019.03.043

Carbon+Sustainability. (2017).

Carlsson-Kanyama, A., & Lindén, A.-L. (2007). Energy efficiency in residences—Challenges for women and men in the North. *Energy Policy, 35*(4), 2163-2172. doi:https://doi.org/10.1016/j.enpol.2006.06.018

Cecconi, F. R., Manfren, M., Tagliabue, L. C., Ciribini, A. L. C., & De Angelis, E. (2017). Probabilistic behavioral modeling in building performance simulation: A Monte Carlo approach. *Energy and Buildings, 148*, 128-141. doi:10.1016/j.enbuild.2017.05.013

Chaudry, M., Abeysekera, M., Hosseini, S. H. R., Jenkins, N., & Wu, J. (2015). Uncertainties in decarbonising heat in the UK. *Energy Policy, 87*(Supplement C), 623-640. doi:https://doi.org/10.1016/j.enpol.2015.07.019

Chen, Y.-C., & Hsiao, T.-C. (2014). *Physiological Responses to Different CO2 Levels in Poor Ventilation Room* (Vol. 45).

Chen, Y., & Thomas Ng, S. (2016). Factoring in embodied GHG emissions when assessing the environmental performance of building. *Sustainable Cities and Society, 27*(Supplement C), 244-252. doi:https://doi.org/10.1016/j.scs.2016.03.015

Chen, Z., Xu, J., & Soh, Y. C. (2015). Modeling regular occupancy in commercial buildings using stochastic models. *Energy and Buildings, 103*, 216-223. doi:10.1016/j.enbuild.2015.06.009

CIBSE. (2015a). Building Performance Modelling. *AM11, 5.2*.

CIBSE. (2015b). Internal Heat Gains. *Guide A Environmental Design, 6-2*.

Ciriminna, R., Meneguzzo, F., Pecoraino, M., & Pagliaro, M. (2016). Reshaping the education of energy managers. *Energy Research & Social Science, 21*(Supplement C), 44-48. doi:https://doi.org/10.1016/j.erss.2016.06.022

Cliffard, N., Steuer, J., & Tauber, E. R. (1994). Computers are social actors. *CHI '94 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*(72-78).

Climate Change Committee. (2010). The Fourth Carbon Budget – reducing emissions through the 2020s.

CO2 Estates. (2013). Data analysis and technology risk management for MEES.

Committee for Climate Change. (2013). Reducing emissions from buildings. Chapter 3.

Committee for Climate Change. (2016). Next steps for UK heat polic.

Committee on Climate Change. (2016). Next steps for UK heat policy.

Corgnati, S. P., Cotana, F., D'Oca, S., Pisello, A. L., & Rosso, F. (2017). Chapter 8 - A Cost-Effective Human-Based Energy-Retrofitting Approach. In F. Pacheco-Torgal, C.-G. Granqvist, B. P. Jelle, G. P. Vanoli, N. Bianco, & J. Kurnitski (Eds.), *Cost-Effective Energy Efficient Building Retrofitting* (pp. 219-255): Woodhead Publishing.

D'Oca, S., & Hong, T. (2014). A data-mining approach to discover patterns of window opening and closing behavior in offices. *Building and Environment, 82*(Supplement C), 726-739. doi:https://doi.org/10.1016/j.buildenv.2014.10.021

D'Errico, G. E. (2009). Issues in significance testing. *Measurement, 42*(10), 1478-1481. doi:https://doi.org/10.1016/j.measurement.2009.08.004

Dagoumas, A. S., & Barker, T. S. (2010). Pathways to a low-carbon economy for the UK with the macro-econometric E3MG model. *Energy Policy, 38*(6), 3067-3077. doi:https://doi.org/10.1016/j.enpol.2010.01.047

Davis, J. A., & Nutter, D. W. (2010). Occupancy diversity factors for common university building types. *Energy and Buildings, 42*(9), 1543-1551. doi:https://doi.org/10.1016/j.enbuild.2010.03.025

DCLG. (2002). Approved Document L2: Conservation of fuel and power in buildings other than dwellings (2002 edition).

DCLG. (2013). Government emission conversion factors for greenhouse gas company reporting.

DCLG. (2015). Sbem Technical Manual.

DCLG. (2017a). Energy Performance of Buildngs Data.

DCLG. (2017b). THE NON-DOMESTIC PRIVATE RENTED PROPERTY MINIMUM STANDARD. 44.

de Boon, J., Bakker, I., Vink, P., & van der Voordt, T. J. M. (2013). Red or blue meeting rooms: does it matter?: The impact of colour on perceived productivity, social cohesion and wellbeing. *Facilities, 31*(1/2), 68-83. doi:10.1108/02632771311292527

Department for Business\, E. I. S. (2017). Final Uk greenhouse gas emissions national statistics 1990 -205.

Duanmu, L., Sun, X., Jin, Q., & Zhai, Z. (2017). Relationship between Human Thermal Comfort and Indoor Thermal Environment Parameters in Various Climatic Regions of China. *Procedia Engineering, 205*(Supplement C), 2871-2878. doi:https://doi.org/10.1016/j.proeng.2017.09.913

Dubois, C., Demers, C., & Potvin, a. (2007). *The Influence Of Daylighting On Occupants: Comfort And Diversity Of Luminous Ambiences In Architecture*.

Eliopoulou, E., & Mantziou, E. (2017). Architectural Energy Retrofit (AER): An alternative building's deep energy retrofit strategy. *Energy and Buildings, 150*, 239-252. doi:https://doi.org/10.1016/j.enbuild.2017.05.001

Elnakat, A., & Gomez, J. D. (2015). Energy engenderment: An industrialized perspective assessing the importance of engaging women in residential energy consumption management. *Energy Policy, 82*(Supplement C), 166-177. doi:https://doi.org/10.1016/j.enpol.2015.03.014

European Commission. (2011). Energy Efficiency Plan 2011.

Fang, Z., Liu, H., Li, B., Tan, M., & Olaide, O. M. (2018). Experimental investigation on thermal comfort model between local thermal sensation and overall thermal sensation. *Energy and Buildings, 158*(Supplement C), 1286-1295. doi:https://doi.org/10.1016/j.enbuild.2017.10.099

Fanger, P. O. (1973). Assessment of man's thermal comfort in practice. *British Journal of Industrial Medicine, 30*, 313-340.

Farjami, E., & Mohamedali, A. (2017a). Evaluating interior surfaces including finishing materials, ceiling, and their contribution to solar energy in residential buildings in Famagusta, North-Cyprus, Turkey. *Renewable and Sustainable Energy Reviews, 75*(Supplement C), 338-353. doi:https://doi.org/10.1016/j.rser.2016.10.074

Farjami, E., & Mohamedali, A. (2017b). Evaluating interior surfaces including finishing materials, ceiling, and their contribution to solar energy in residential buildings in Famagusta, North-Cyprus, Turkey. *Renewable and Sustainable Energy Reviews, 75*, 338-353. doi:https://doi.org/10.1016/j.rser.2016.10.074

Felgueiras, M. C., Martins, F. F., & Caetano, N. S. (2017). Sustainability in Buildings – A Teaching Approach. *Energy Procedia, 107*(Supplement C), 15-22. doi:https://doi.org/10.1016/j.egypro.2016.12.124

Feng, X., Yan, D., & Hong, T. (2015). Simulation of occupancy in buildings. *Energy and Buildings, 87*, 348-359. doi:https://doi.org/10.1016/j.enbuild.2014.11.067

Fountain, M., Brager, G., & de Dear, R. (1996). Expectations of indoor climate control. *Energy and Buildings, 24*(3), 179-182. doi:https://doi.org/10.1016/S0378-7788(96)00988-7

Gan, V. J. L., Chan, C. M., Tse, K. T., Lo, I. M. C., & Cheng, J. C. P. (2017). A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters. *Journal of Cleaner Production, 161*(Supplement C), 663-675. doi:https://doi.org/10.1016/j.jclepro.2017.05.156

Gandhi, P., & Brager, G. S. (2016). Commercial office plug load energy consumption trends and the role of occupant behavior. *Energy and Buildings, 125*, 1-8. doi:https://doi.org/10.1016/j.enbuild.2016.04.057

Geng, Y., Ji, W., Lin, B., & Zhu, Y. (2017). The impact of thermal environment on occupant IEQ perception and productivity. *Building and Environment, 121*(Supplement C), 158-167. doi:https://doi.org/10.1016/j.buildenv.2017.05.022

Giesekam, J., Barrett, J. R., & Taylor, P. (2016). Construction sector views on low carbon building materials. *Building Research & Information, 44*(4), 423-444. doi:10.1080/09613218.2016.1086872

Gilani, S. I.-u.-H., Khan, M. H., & Ali, M. (2016). Revisiting Fanger's thermal comfort model using mean blood pressure as a bio-marker: An experimental investigation. *Applied Thermal Engineering, 109*(Part A), 35-43. doi:https://doi.org/10.1016/j.applthermaleng.2016.08.050

Gobbi, S., Puglisi, V., & Ciaramella, A. (2016). A Rating System for Integrating Building Performance Tools in Developing Countries. *Energy Procedia, 96*(Supplement C), 333-344. doi:https://doi.org/10.1016/j.egypro.2016.09.156

Golasi, I., Salata, F., Vollaro, E. d. L., & Peña-García, A. (2019). Influence of lighting colour temperature on indoor thermal perception: A strategy to save energy from the HVAC installations. *Energy and Buildings, 185*, 112-122. doi:https://doi.org/10.1016/j.enbuild.2018.12.026

Government, H. (2013). Non-Domestic Building Services Compliance Guide. 21-22.

Government., S. (2018). Building Standards: Section 63.

Government., U. (2018). Private Rented Sector: Minimum Energy Efficiency Standards.

Guerra-Santin, O., Romero Herrera, N., Cuerda, E., & Keyson, D. (2016). Mixed methods approach to determine occupants' behaviour – Analysis of two case studies. *Energy and Buildings, 130*, 546-566. doi:10.1016/j.enbuild.2016.08.084

Gunay, H. B., O'Brien, W., Beausoleil-Morrison, I., & Gilani, S. (2016). Modeling plug-in equipment load patterns in private office spaces. *Energy and Buildings, 121*, 234-249. doi:10.1016/j.enbuild.2016.03.001

Gupta, R., & Gregg, M. (2016). Empirical evaluation of the energy and environmental performance of a sustainably-designed but under-utilised institutional building in the UK. *Energy and Buildings, 128*, 68-80. doi:https://doi.org/10.1016/j.enbuild.2016.06.081

Gustavsson, L., Joelsson, A., & Sathre, R. (2010). Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. *Energy and Buildings, 42*(2), 230-242. doi:https://doi.org/10.1016/j.enbuild.2009.08.018

Hahm, Y., Yoon, H., Jung, D., & Kwon, H. (2017). Do built environments affect pedestrians' choices of walking routes in retail districts? A study with GPS experiments in Hongdae retail district in Seoul, South Korea. *Habitat International, 70*, 50-60. doi:https://doi.org/10.1016/j.habitatint.2017.10.002

Haidarian, H., Dinalankara, W., Fults, S., Wilson, S., Perlis, D., Schmill, M., . . . Anderson, M. L. (2010). *The metacognitive loop: An architecture for building robust intelligent systems.* Paper presented at the AAAI Fall Symposium - Technical Report.

Haller, K. (2017). 14 - Colour in interior design A2 - Best, Janet. In *Colour Design (Second Edition)* (pp. 317-348): Woodhead Publishing.

Hamza, N., & Gilroy, R. (2011). The challenge to UK energy policy: An ageing population perspective on energy saving measures and consumption. *Energy Policy, 39*(2), 782-789. doi:https://doi.org/10.1016/j.enpol.2010.10.052

Hawkins, S. A., & Wiswell, R. A. (2003). Rate and Mechanism of Maximal Oxygen Consumption Decline with Aging

Sports Med, 33(12), 877-888.

Hirning, M. B., Isoardi, G. L., & Cowling, I. (2014). Discomfort glare in open plan green buildings. *Energy and Buildings, 70*(Supplement C), 427-440. doi:https://doi.org/10.1016/j.enbuild.2013.11.053

HM Government. (2011). The Carbon Plan: Delivering a low carbon future.

Hong, S. H., Gilbertson, J., Oreszczyn, T., Green, G., & Ridley, I. (2009). A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. *Building and Environment, 44*(6), 1228-1236. doi:https://doi.org/10.1016/j.buildenv.2008.09.003

Hong, T. Occupant Behaviour Research at LBNL BTUS - obXML documentation.

Hong, T., Sun, H., Chen, Y., Taylor-Lange, S. C., & Yan, D. (2016). An occupant behavior modeling tool for co-simulation. *Energy and Buildings, 117*, 272-281. doi:10.1016/j.enbuild.2015.10.033

Hong, T., Yan, D., D'Oca, S., & Chen, C.-f. (2017). Ten questions concerning occupant behavior in buildings: The big picture. *Building and Environment, 114*, 518-530. doi:10.1016/j.buildenv.2016.12.006

Horikiri, K., Yao, Y., & Yao, J. (2015). Numerical optimisation of thermal comfort improvement for indoor environment with occupants and furniture. *Energy and Buildings, 88*(Supplement C), 303-315. doi:https://doi.org/10.1016/j.enbuild.2014.12.015

Hosseini, B., Mirzaei, K., Maghbooli, Z., Keshavarz, S. A., & Hossein-Nezhad, A. (2016). Compare the resting metabolic rate status in the healthy metabolically obese with the unhealthy metabolically obese participants. *Journal of Nutrition & Intermediary Metabolism, 6*(Supplement C), 48-53. doi:https://doi.org/10.1016/j.jnim.2016.07.003

Huang, Y.-Y., & Menozzi, M. (2014). Effects of discomfort glare on performance in attending peripheral visual information in displays. *Displays, 35*(5), 240-246. doi:https://doi.org/10.1016/j.displa.2014.08.001

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2013). Operational vs. embodied emissions in buildings—A review of current trends. *Energy and Buildings, 66*(Supplement C), 232-245. doi:https://doi.org/10.1016/j.enbuild.2013.07.026

Ibn-Mohammed, T., Greenough, R., Taylor, S., Ozawa-Meida, L., & Acquaye, A. (2014). Integrating economic considerations with operational and embodied emissions into a decision support system for the optimal ranking of building retrofit options. *Building and Environment, 72*(Supplement C), 82-101. doi:https://doi.org/10.1016/j.buildenv.2013.10.018

Indraganti, M., & Boussaa, D. (2017). Comfort temperature and occupant adaptive behavior in offices in Qatar during summer. *Energy and Buildings, 150*(Supplement C), 23-36. doi:https://doi.org/10.1016/j.enbuild.2017.05.063

Indraganti, M., Ooka, R., & Rijal, H. B. (2015). Thermal comfort in offices in India: Behavioral adaptation and the effect of age and gender. *Energy and Buildings, 103*(Supplement C), 284-295. doi:https://doi.org/10.1016/j.enbuild.2015.05.042

Janda, K. B. (2011). Buildings don't use energy: people do. *Architectural Science Review, 54*(1), 15-22. doi:10.3763/asre.2009.0050

Jenkins, C., Young, R., Tsau, J., Razavi, H., Kaplan, J., & Ibeziako, M. O. (2019). Effective management of plug loads in commercial buildings with occupant engagement and centralized controls. *Energy and Buildings, 201*, 194-201. doi:https://doi.org/10.1016/j.enbuild.2019.06.030

Jeong, B., Jeong, J.-W., & Park, J. S. (2016). Occupant behavior regarding the manual control of windows in residential buildings. *Energy and Buildings, 127*, 206-216. doi:https://doi.org/10.1016/j.enbuild.2016.05.097

Jia, M., Srinivasan, R. S., & Raheem, A. A. (2017). From occupancy to occupant behavior: An analytical survey of data acquisition technologies, modeling methodologies and simulation coupling mechanisms for building energy efficiency. *Renewable and Sustainable Energy Reviews, 68*, 525-540. doi:https://doi.org/10.1016/j.rser.2016.10.011

Johnson, D. G. (2006). Computer systems: Moral entities but not moral agents`. *Ethics and Information Technology, 8*, 195-204.

Johnson, D. G., & Powers, T. M. (2008). Computers as surrogate agents. In M. J. van den Joven & J. Weckert (Eds.), *Information Technology and Moral Philosophy* (pp. 251): Cambridge University Press.

Johra, H., & Heiselberg, P. (2017). Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review. *Renewable and Sustainable Energy Reviews, 69*, 19-32. doi:https://doi.org/10.1016/j.rser.2016.11.145

Jones, M. E., Wei, B. W. Y., & Hung, D. L. (2013). Laptop energy-saving opportunities based on user behaviors. *Energy Efficiency, 6*(2), 425-431. doi:10.1007/s12053-012-9167-5

Joy E, P., Suart A, R., Ankita, R., & Alan C, D. (2014). A SURVEY OF COMPUTER POWER MODES USAGE IN A UNIVERSITY POPULATION. *California Energy Commission*, 29-39.

Juslén, H., & Tenner, A. (2005). Mechanisms involved in enhancing human performance by changing the lighting in the industrial workplace. *International Journal of Industrial Ergonomics, 35*(9), 843-855. doi:https://doi.org/10.1016/j.ergon.2005.03.002

Juslén, H., Wouters, M., & Tenner, A. (2007). The influence of controllable task-lighting on productivity: a field study in a factory. *Applied Ergonomics, 38*(1), 39-44. doi:https://doi.org/10.1016/j.apergo.2006.01.005

Karjalainen, S. (2007). Gender differences in thermal comfort and use of thermostats in everyday thermal environments. *Building and Environment, 42*(4), 1594-1603. doi:https://doi.org/10.1016/j.buildenv.2006.01.009

Kim, J., de Dear, R., Cândido, C., Zhang, H., & Arens, E. (2013). Gender differences in office occupant perception of indoor environmental quality (IEQ). *Building and Environment, 70*, 245-256. doi:https://doi.org/10.1016/j.buildenv.2013.08.022

Kim, J., Kong, M., Hong, T., Jeong, K., & Lee, M. (2018). Physiological response of building occupants based on their activity and the indoor environmental quality condition changes. *Building and Environment, 145*, 96-103. doi:https://doi.org/10.1016/j.buildenv.2018.09.018

Klimmt, C., Hartmann, T., & Schramm, H. (2006). *Parasocial interactions and relationships*.

Klöckner, C. A., & Nayum, A. (2017). Psychological and structural facilitators and barriers to energy upgrades of the privately owned building stock. *Energy, 140*(Part 1), 1005-1017. doi:https://doi.org/10.1016/j.energy.2017.09.016

Kneifel, J., Healy, W., Filliben, J., & Boyd, M. (2016). Energy performance sensitivity of a net-zero energy home to design and use specifications. *Journal of Building Performance Simulation, 9*(1), 70-83. doi:10.1080/19401493.2014.995708

Kordjamshidi, M. (2013). Application of fuzzy technique to integrate multiple occupancy scenarios into house rating schemes (HRS). *Energy and Buildings, 67*, 463-470. doi:10.1016/j.enbuild.2013.08.049

Korsgaard, V., & Madsen, a. (1971, 1973). New instruments for measuring thermal comfort. *Proceedings of the 13th International Congress of Refrigeration, Washington, 4*, 313-322.

Kucukvar, M., Haider, M. A., & Onat, N. C. (2017). Exploring the material footprints of national electricity production scenarios until 2050: The case for Turkey and UK. *Resources, Conservation and Recycling, 125*(Supplement C), 251-263. doi:https://doi.org/10.1016/j.resconrec.2017.06.024

Kundzewicz, Z. W., Krysanova, V., Benestad, R. E., Hov, Ø., Piniewski, M., & Otto, I. M. (2018). Uncertainty in climate change impacts on water resources. *Environmental Science & Policy, 79*(Supplement C), 1-8. doi:https://doi.org/10.1016/j.envsci.2017.10.008

Kwallek, N., & Lewis, C. M. (1990). Effects of environmental colour on males and females: A red or white or green office. *Applied Ergonomics, 21*(4), 275-278. doi:https://doi.org/10.1016/0003-6870(90)90197-6

Lai, A. C. K., Mui, K. W., Wong, L. T., & Law, L. Y. (2009). An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings. *Energy and Buildings, 41*(9), 930-936. doi:https://doi.org/10.1016/j.enbuild.2009.03.016

Lawrence, R., & Keime, C. (2016). Bridging the gap between energy and comfort: Post-occupancy evaluation of two higher-education buildings in Sheffield. *Energy and Buildings, 130*, 651-666. doi:10.1016/j.enbuild.2016.09.001

Lee, P., Lam, P. T. I., & Lee, W. L. (2018). Performance risks of lighting retrofit in Energy Performance Contracting projects. *Energy for Sustainable Development, 45*, 219-229. doi:https://doi.org/10.1016/j.esd.2018.07.004

Lee, Y. S., & Malkawi, A. M. (2014). Simulating multiple occupant behaviors in buildings: An agent-based modeling approach. *Energy and Buildings, 69*, 407-416. doi:https://doi.org/10.1016/j.enbuild.2013.11.020

Li, W., Xu, P., Wang, H., & Lu, X. (2016). A new method for calculating the thermal effects of irregular internal mass in buildings under demand response. *Energy and Buildings, 130*, 761-772. doi:https://doi.org/10.1016/j.enbuild.2016.08.057

Liew, K. M., Sojobi, A. O., & Zhang, L. W. (2017). Green concrete: Prospects and challenges. *Construction and Building Materials, 156*, 1063-1095. doi:https://doi.org/10.1016/j.conbuildmat.2017.09.008

Liisberg, J., Møller, J. K., Bloem, H., Cipriano, J., Mor, G., & Madsen, H. (2016). Hidden Markov Models for indirect classification of occupant behaviour. *Sustainable Cities and Society, 27*, 83-98. doi:10.1016/j.scs.2016.07.001

Lim, G.-H., Keumala, N., & Ghafar, N. A. (2017). Energy saving potential and visual comfort of task light usage for offices in Malaysia. *Energy and Buildings, 147*(Supplement C), 166-175. doi:https://doi.org/10.1016/j.enbuild.2017.05.004

Lim, Y.-W., Kandar, M. Z., Ahmad, M. H., Ossen, D. R., & Abdullah, A. M. (2012). Building façade design for daylighting quality in typical government office building. *Building and Environment, 57*(Supplement C), 194-204. doi:https://doi.org/10.1016/j.buildenv.2012.04.015

Lo, L. J., & Novoselac, A. (2010). Localized air-conditioning with occupancy control in an open office. *Energy and Buildings, 42*(7), 1120-1128. doi:https://doi.org/10.1016/j.enbuild.2010.02.003

Lu, S., Pang, B., Qi, Y., & Fang, K. (2018). Field study of thermal comfort in non-air-conditioned buildings in a tropical island climate. *Applied Ergonomics, 66*(Supplement C), 89-97. doi:https://doi.org/10.1016/j.apergo.2017.08.008

Maiti, R. (2014). PMV model is insufficient to capture subjective thermal response from Indians. *International Journal of Industrial Ergonomics, 44*(3), 349-361. doi:https://doi.org/10.1016/j.ergon.2014.01.005

Makaremi, N., Schiavoni, S., Pisello, A. L., Asdrubali, F., & Cotana, F. (2017). Quantifying the effects of interior surface reflectance on indoor lighting. *Energy Procedia, 134*(Supplement C), 306-316. doi:https://doi.org/10.1016/j.egypro.2017.09.531

Maley, M., Eglin, C., House, J., & Tipton, M. (2014). *The effect of ethnicity on the vascular responses to cold exposure of the extremities*.

Marshall, A., Fitton, R., Swan, W., Farmer, D., Johnston, D., Benjaber, M., & Ji, Y. (2017). Domestic building fabric performance: Closing the gap between the in situ measured and modelled performance. *Energy and Buildings, 150*, 307-317. doi:https://doi.org/10.1016/j.enbuild.2017.06.028

Marshall, E., Steinberger, J. K., Dupont, V., & Foxon, T. J. (2016). Combining energy efficiency measure approaches and occupancy patterns in building modelling in the UK residential context. *Energy and Buildings, 111*, 98-108. doi:10.1016/j.enbuild.2015.11.039

Martani, C., Lee, D., Robinson, P., Britter, R., & Ratti, C. (2012). ENERNET: Studying the dynamic relationship between building occupancy and energy consumption. *Energy and Buildings, 47*, 584-591. doi:10.1016/j.enbuild.2011.12.037

Martinez-Pabon, M., Eveleigh, T., & Tanju, B. (2018). Optimizing residential energy management using an autonomous scheduler system. *Expert Systems with Applications, 96*, 373-387. doi:https://doi.org/10.1016/j.eswa.2017.12.017

McInnes, B. T., & Stevenson, M. (2014). Determining the difficulty of Word Sense Disambiguation. *Journal of Biomedical Informatics, 47*(Supplement C), 83-90. doi:https://doi.org/10.1016/j.jbi.2013.09.009

McKimm, R. (2017). 9 - Colour, health and wellbeing through the lens of colour analytical psychology A2 - Best, Janet. In *Colour Design (Second Edition)* (pp. 215-239): Woodhead Publishing.

McMichael, M., & Shipworth, D. (2013). The value of social networks in the diffusion of energy-efficiency innovations in UK households. *Energy Policy, 53*, 159-168. doi:https://doi.org/10.1016/j.enpol.2012.10.039

Mikellides, B. (2017). 8 - Colour psychology: The emotional effects of colour perception A2 - Best, Janet. In *Colour Design (Second Edition)* (pp. 193-214): Woodhead Publishing.

Mirakhorli, A., & Dong, B. (2016). Occupancy behavior based model predictive control for building indoor climate—A critical review. *Energy and Buildings, 129*, 499-513. doi:10.1016/j.enbuild.2016.07.036

Mishra, A. K., & Ramgopal, M. (2015). An adaptive thermal comfort model for the tropical climatic regions of India (Köppen climate type A). *Building and Environment, 85*(Supplement C), 134-143. doi:https://doi.org/10.1016/j.buildenv.2014.12.006

Mustakallio, P., Bolashikov, Z., Rezgals, L., Lipczynska, A., Melikov, A., & Kosonen, R. (2017). Thermal environment in a simulated double office room with convective and radiant cooling systems. *Building and Environment, 123*(Supplement C), 88-100. doi:https://doi.org/10.1016/j.buildenv.2017.06.029

National Energy Foundation. (2019). Ways to Save Heat & Fuel at Home.

Neves, J. (2016). Energy Efficient Lighting in Buildings: Copenhagen Case Study on a Sustainable Transition to Energy Efficient Lighting in Buildings.

Nguyen, A. T., Singh, M. K., & Reiter, S. (2012). AN ADAPTIVE THERMAL COMFORT MODEL FOR HOT HUMID SOUTHEAST

ASIA *Building and Environment, 50*, 291-300.

Nico, M. A., Liuzzi, S., & Stefanizzi, P. (2015). Evaluation of thermal comfort in university classrooms through objective approach and subjective preference analysis. *Applied Ergonomics, 48*(Supplement C), 111-120. doi:https://doi.org/10.1016/j.apergo.2014.11.013

Niemelä, T., Levy, K., Kosonen, R., & Jokisalo, J. (2017). Cost-optimal renovation solutions to maximize environmental performance, indoor thermal conditions and productivity of office buildings in cold climate. *Sustainable Cities and Society, 32*(Supplement C), 417-434. doi:https://doi.org/10.1016/j.scs.2017.04.009

Oldewurtel, F., Parisio, A., Jones, C. N., Gyalistras, D., Gwerder, M., Stauch, V., . . . a, M. M. (2012). Use of model predictive control and weather forecasts for energy efficient building climate control. *Energy and Buildings, 45*, 15-27.

Oliveira-Lima, J. A., Morais, R., Martins, J. F., Florea, A., & Lima, C. (2016). Load forecast on intelligent buildings based on temporary occupancy monitoring. *Energy and Buildings, 116*, 512-521. doi:10.1016/j.enbuild.2016.01.028

Oliver, S. (2019). *Communication and trust: rethinking the way construction industry professionals and software vendors utilise computer communication mediums* (Vol. 7).

Oliver, S., & Pour Rahimian, F. (2018). *Are computers agents? Considering the implication of classifying computers as occupants on energy consumption and proximity-asutility equipment scheduling*.

Ormandy, D., & Ezratty, V. (2012). Health and thermal comfort: From WHO guidance to housing strategies. *Energy Policy, 49*(Supplement C), 116-121. doi:https://doi.org/10.1016/j.enpol.2011.09.003

Pacheco-Torgal, F. (2017). Chapter 1 - Introduction to Cost-Effective Energy-Efficient Building Retrofitting. In F. Pacheco-Torgal, C.-G. Granqvist, B. P. Jelle, G. P. Vanoli, N. Bianco, & J. Kurnitski (Eds.), *Cost-Effective Energy Efficient Building Retrofitting* (pp. 1-20): Woodhead Publishing.

Parker, J., Hardy, A., Glew, D., & Gorse, C. (2017). A methodology for creating building energy model occupancy schedules using personal location metadata. *Energy and Buildings, 150*, 211-223. doi:https://doi.org/10.1016/j.enbuild.2017.06.014

Pelenur, M. J., & Cruickshank, H. J. (2012). Closing the Energy Efficiency Gap: A study linking demographics with barriers to adopting energy efficiency measures in the home. *Energy, 47*(1), 348-357. doi:https://doi.org/10.1016/j.energy.2012.09.058

Permana, A. S., Aziz, N. A., & Siong, H. C. (2015). Is mom energy efficient? A study of gender, household energy consumption and family decision making in Indonesia. *Energy Research & Social Science, 6*(Supplement C), 78-86. doi:https://doi.org/10.1016/j.erss.2014.12.007

Pierson, C., Wienold, J., & Bodart, M. (2017). Discomfort glare perception in daylighting: influencing factors. *Energy Procedia, 122*(Supplement C), 331-336. doi:https://doi.org/10.1016/j.egypro.2017.07.332

Pisello, A. L., & Asdrubali, F. (2014). Human-based energy retrofits in residential buildings: A cost-effective alternative to traditional physical strategies. *Applied Energy, 133*, 224-235. doi:https://doi.org/10.1016/j.apenergy.2014.07.049

Pisello, A. L., Rosso, F., Castaldo, V. L., Piselli, C., Fabiani, C., & Cotana, F. (2017). The role of building occupants' education in their resilience to climate-change related events. *Energy*

and Buildings, 154(Supplement C), 217-231. doi:https://doi.org/10.1016/j.enbuild.2017.08.024
Pomponi, F., & Moncaster, A. (2017). Scrutinising embodied carbon in buildings: The next performance gap made manifest. *Renewable and Sustainable Energy Reviews*. doi:https://doi.org/10.1016/j.rser.2017.06.049
Raftery, P., Lee, E., Webster, T., Hoyt, T., & Bauman, F. (2014a). Effects of furniture and contents on peak cooling load. *Energy and Buildings, 85*, 445-457. doi:https://doi.org/10.1016/j.enbuild.2014.09.081
Raftery, P., Lee, E., Webster, T., Hoyt, T., & Bauman, F. (2014b). Effects of furniture and contents on peak cooling load. *Energy and Buildings, 85*(Supplement C), 445-457. doi:https://doi.org/10.1016/j.enbuild.2014.09.081
Rastogi, P. (2016). *On the sensitivity of buildings to climatethe interaction of weather and building envelopes in determining future building energy consumption.* EPFL, Retrieved from http://infoscience.epfl.ch/record/220971/files/EPFL_TH6881.pdf
Ridley, I., Bere, J., Clarke, A., Schwartz, Y., & Farr, A. (2014). The side by side in use monitored performance of two passive and low carbon Welsh houses. *Energy and Buildings, 82*(Supplement C), 13-26. doi:https://doi.org/10.1016/j.enbuild.2014.06.038
Robillart, M., Schalbart, P., Chaplais, F., & Peuportier, B. (2018). Model reduction and model predictive control of energy-efficient buildings for electrical heating load shifting. *Journal of Process Control*. doi:https://doi.org/10.1016/j.jprocont.2018.03.007
Rocchetta, R., Broggi, M., & Patelli, E. (2018). Do we have enough data? Robust reliability via uncertainty quantification. *Applied Mathematical Modelling, 54*(Supplement C), 710-721. doi:https://doi.org/10.1016/j.apm.2017.10.020
Schaudienst, F., & Vogdt, F. U. (2017). Fanger's model of thermal comfort: a model suitable just for men? *Energy Procedia, 132*(Supplement C), 129-134. doi:https://doi.org/10.1016/j.egypro.2017.09.658
Schweiker, M., Haldi, F., Shukuya, M., & Robinson, D. (2012). Verification of stochastic models of window opening behaviour for residential buildings. *Journal of Building Performance Simulation, 5*(1), 55-74. doi:10.1080/19401493.2011.567422
Schweiker, M., Hawighorst, M., & Wagner, A. (2016). The influence of personality traits on occupant behavioural patterns. *Energy and Buildings, 131*, 63-75. doi:https://doi.org/10.1016/j.enbuild.2016.09.019
Schweiker, M., & Wagner, A. (2016). The effect of occupancy on perceived control, neutral temperature, and behavioral patterns. *Energy and Buildings, 117*, 246-259. doi:10.1016/j.enbuild.2015.10.051
Seo, S., Foliente, G., & Ren, Z. (2017). Energy and GHG reductions considering embodied impacts of retrofitting existing dwelling stock in Greater Melbourne. *Journal of Cleaner Production*. doi:https://doi.org/10.1016/j.jclepro.2017.09.206
Shafaghat, A., Keyvanfar, A., Ferwati, M. S., & Alizadeh, T. (2015). Enhancing staff's satisfaction with comfort toward productivity by sustainable Open Plan Office Design. *Sustainable Cities and Society, 19*(Supplement C), 151-164. doi:https://doi.org/10.1016/j.scs.2015.08.001
Shaikh, P. H., Shaikh, F., Sahito, A. A., Uqaili, M. A., & Umrani, Z. (2017). Chapter 9 - An Overview of the Challenges for Cost-Effective and Energy-Efficient Retrofits of the Existing Building

Stock. In F. Pacheco-Torgal, C.-G. Granqvist, B. P. Jelle, G. P. Vanoli, N. Bianco, & J. Kurnitski (Eds.), *Cost-Effective Energy Efficient Building Retrofitting* (pp. 257-278): Woodhead Publishing.

Sinha, P., Kinderman, P., & Moody, W. (2010). An exploratory study: Relationships between trying on clothing, mood, emotion, personality and clothing preference. *Journal of Fashion Marketing and Management: An International Journal, 14*(1), 161-179. doi:10.1108/13612021011025483

Sivakrishna, A., Adesina, A., Awoyera, P. O., & Rajesh Kumar, K. (2019). Green concrete: A review of recent developments. *Materials Today: Proceedings*. doi:https://doi.org/10.1016/j.matpr.2019.08.202

Space Management Group. (2008). UK Higher Education Space Management Project - Evaulation.

SPON's. (2018). Mechanical and Electrical Services Price Book.

Stenberg, B., & Wall, S. (1995). Why do women report 'sick building symptoms' more often than men? *Social Science & Medicine, 40*(4), 491-502. doi:https://doi.org/10.1016/0277-9536(94)E0104-Z

Stoppel, C. M., & Leite, F. (2014). Integrating probabilistic methods for describing occupant presence with building energy simulation models. *Energy and Buildings, 68*, 99-107. doi:10.1016/j.enbuild.2013.08.042

Strachan, M. E. (2013). Energy-led, non-domestic building refurbishment : decision support for a whole-building approach to improvement of operational performance.

Su, S., Li, X., Zhu, Y., & Lin, B. (2017). Dynamic LCA framework for environmental impact assessment of buildings. *Energy and Buildings, 149*(Supplement C), 310-320. doi:https://doi.org/10.1016/j.enbuild.2017.05.042

Tabak, V. (2009). User simulation of space utilisation : system for office building usage simulation. doi:10.6100/IR640457

Tagliabue, L. C., Manfren, M., Ciribini, A. L. C., & De Angelis, E. (2016). Probabilistic behavioural modeling in building performance simulation—The Brescia eLUX lab. *Energy and Buildings, 128*, 119-131. doi:10.1016/j.enbuild.2016.06.083

Tokura, M., Iwata, T., & Shukuya, M. (1996). *Experimental study on discomfort glare caused by windows, part 3. Development of a method for evaluating discomfort glare from a large light source* (Vol. 489).

Treasury, H. (2013). The Green Book: appraisal and evaluation in central government. 101-106.

Tuaycharoen, N., & Tregenza, P. R. (2007). View and discomfort glare from windows. *Lighting Research & Technology, 39*(2), 185-200. doi:10.1177/1365782807077193

UK Government. (2008). Climate Change Act 2008.

United States Environmental Protection Agency. (2017). Greenhouse Gas Emissions.

Vassend, O., Røysamb, E., Nielsen, C. S., & Czajkowski, N. O. (2018). Fatigue symptoms in relation to neuroticism, anxiety-depression, and musculoskeletal pain. A longitudinal twin study. *PloS one, 13*(6), e0198594-e0198594. doi:10.1371/journal.pone.0198594

Veitch, J. A. (2001). Psychological processes influencing lighting quality. *Journal of the Illuminating Engineering Society, 30*(1), 124-140.

Veitch, J. A., & Newsham, G. R. (1998). Lighting Quality and Energy-Efficiency Effects on Task Performance, Mood, Health, Satisfaction, and Comfort. *Journal of the Illuminating Engineering Society, 27*(1), 107-129. doi:10.1080/00994480.1998.10748216

Vilches, A., Garcia-Martinez, A., & Sanchez-Montañes, B. (2017). Life cycle assessment (LCA) of building refurbishment: A literature review. *Energy and Buildings, 135*, 286-301. doi:https://doi.org/10.1016/j.enbuild.2016.11.042

Wang, H., Liu, G., Hu, S., & Liu, C. (2018). Experimental investigation about thermal effect of colour on thermal sensation and comfort. *Energy and Buildings, 173*, 710-718. doi:https://doi.org/10.1016/j.enbuild.2018.06.008

Wang, R. Y. (1996). Beyond accuracy: What data quality means to data consumers. *Journal of Management Information Systems, 12*(14), 5-34.

Wang, W. (2017). Smartphones as Social Actors? Social dispositional factors in assessing anthropomorphism. *Computers in Human Behavior, 68*, 334-344. doi:https://doi.org/10.1016/j.chb.2016.11.022

Wardono, P., & Soelami, F. X. N. (2016). Effects of Luminous Furniture on Mood. *Procedia - Social and Behavioral Sciences, 222*(Supplement C), 342-350. doi:https://doi.org/10.1016/j.sbspro.2016.05.178

Wolisz, H., Kull, T. M., Streblow, R., & Müller, D. (2015). The Effect of Furniture and Floor Covering Upon Dynamic Thermal Building Simulations. *Energy Procedia, 78*(Supplement C), 2154-2159. doi:https://doi.org/10.1016/j.egypro.2015.11.304

Wu, Y., Shen, J., Zhang, X., Skitmore, M., & Lu, W. (2017). Reprint of: The impact of urbanization on carbon emissions in developing countries: a Chinese study based on the U-Kaya method. *Journal of Cleaner Production, 163*(Supplement), S284-S298. doi:https://doi.org/10.1016/j.jclepro.2017.05.144

Yamaguchi, Y., & Shimoda1, Y. (2014). Behavior model of occupants in home based on japanese national time use survey. *2nd confernce of IBPSA*.

Yan, D., O'Brien, W., Hong, T., Feng, X., Burak Gunay, H., Tahmasebi, F., & Mahdavi, A. (2015). Occupant behavior modeling for building performance simulation: Current state and future challenges. *Energy and Buildings, 107*, 264-278. doi:10.1016/j.enbuild.2015.08.032

Yang, J., Santamouris, M., & Lee, S. E. (2016). Review of occupancy sensing systems and occupancy modeling methodologies for the application in institutional buildings. *Energy and Buildings, 121*, 344-349. doi:10.1016/j.enbuild.2015.12.019

Yoshino, H. (2013). Annex 53, Total Energy Use in Buildings - Analysis and Evaluation Methods. *Institute for Building Environment and Energy Conservation*.

Yousefi, F., Gholipour, Y., & Yan, W. (2017). A study of the impact of occupant behaviors on energy performance of building envelopes using occupants' data. *Energy and Buildings, 148*, 182-198. doi:10.1016/j.enbuild.2017.04.085

Yu, T. (2010, 12-14 Dec. 2010). *Modeling Occupancy Behavior for Energy Efficiency and Occupants Comfort Management in Intelligent Buildings.* Paper presented at the 2010 Ninth International Conference on Machine Learning and Applications.

Yun, G. Y. (2018). Influences of perceived control on thermal comfort and energy use in buildings. *Energy and Buildings, 158*(Supplement C), 822-830. doi:https://doi.org/10.1016/j.enbuild.2017.10.044

Zani, A., Tagliabue, L. C., Poli, T., Ciribini, A. L. C., De Angelis, E., & Manfren, M. (2017). Occupancy Profile Variation Analyzed through Generative Modelling to Control Building Energy Behavior. *Procedia Engineering, 180*, 1495-1505. doi:10.1016/j.proeng.2017.04.312

Zhang, T., Siebers, P.-O., & Aickelin, U. (2011). Modelling electricity consumption in office buildings: An agent based approach. *Energy and Buildings, 43*(10), 2882-2892. doi:https://doi.org/10.1016/j.enbuild.2011.07.007

Zhang, X., & Wang, F. (2017). Analysis of embodied carbon in the building life cycle considering the temporal perspectives of emissions: A case study in China. *Energy and Buildings, 155*, 404-413. doi:https://doi.org/10.1016/j.enbuild.2017.09.049

Zhao, J., Lasternas, B., Lam, K. P., Yun, R., & Loftness, V. (2014). Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining. *Energy and Buildings, 82*, 341-355. doi:10.1016/j.enbuild.2014.07.033