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Technologies for Sustainable Built Environments

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Investigating the energy performance of a multi-use venue building

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Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

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This thesis is dedicated to my mum, who still doesn't really know what my thesis is about but nevertheless offered blind support and prayers that I'd someday finish and be proud of what I had achieved. I am also grateful to my siblings for their support and encouragement.

And last but not least, to Rich, who endlessly nagged me to write.

ABSTRACT

This research documents an investigation into the building energy performance of a case study multi-use venue building that hosts several different types of events, each with their own demands of the building and its energy end uses. Such buildings have high occupant diversity factors and inconsistent occupant-building interaction leading to highly changeable demands of the building services.

The feasibility of using existing energy performance tools was initially tested against these building types. Through this approach and a critique of the body of knowledge surrounding energy performance analysis of buildings, it was argued that macro level tools cannot consider the high variability of energy use inherent in the operation of these buildings. Consequently, there is a need to develop on existing micro-scale occupancy focused Post Occupancy Evaluation and apply their learning to these buildings on which there is currently scarce literature. The next stage of this research therefore used mixed methods to monitor and analyse thirteen different events hosted in a case study building, to identify useful and wasteful energy for each different use. In doing so, this research provided rich and valuable context behind the energy consumption, to both identify drivers for energy use during different uses of the building, and also quantify energy efficiency opportunities for multi-use venue buildings.

Results identify multiple energy waste streams, centred on the numerous building actors that engage with the building, as well as a disconnect with the needs of the building occupants and the decisions made surrounding its energy management. Categorising energy waste to identify its cause and attributing energy waste directly to different actors lead to more targeted recommendations for energy management for multi-use venue buildings.

PUBLICATIONS & PRESENTATIONS

Peer reviewed journal publications

Ansari, S., Larsen, G., Shao, L. (2018). Identifying energy savings opportunities for a multi-use venue building. Journal of Future Cities and Environment 4 (1). pp. 112.

Peer reviewed conferences

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Ansari, S., Shao, L., Larsen, G. (2017) Lightening the load: analysing energy performance in multi-use venue buildings. 7th Annual TSBE Conference, Reading University 2017

Ansari, S., Shao, L., Larsen, G. (2015) Developing an energy management strategy for a multi-use venue building. 5th TSBE Annual Conference, Reading University 2015

Ansari, S., Shao, L., Larsen, G. (2014) Energy monitoring and management for a developing UK motorsport venue. 4th TSBE Annual Conference, Reading University 2014

Contents

ACRONYMS

AC	Air Conditioning
AHU	Air Handling Unit
AMR	Automatic Meter Reading
BMS	Building Management System
BPE	Building Performance Evaluation
BUS	Building Use Studies
CIBSE	Chartered Institute of Building Service Engineers
DEC	Display Energy Certificate
ECM	Energy Conservation Measure
EngD	Engineering Doctorate
EPC	Energy Performance Certificate
EUI	Energy Use Intensity
FM	Facilities Management
GHG	Greenhouse Gases
HH	Half Hourly
HVAC	Heating, Ventilation and Air-Conditioning
kW	Kilo-watt
kWh	Kilo-watt hour
kWth	Kilo-watt thermal
kWe	Kilo-watt electrical
LTHW	Low Temperature Hot Water
NCM	National Calculation Method
POE	Post Occupancy Evaluation
PROBE	Post-Occupancy Review of Buildings and their Engineering
RIBA	Royal Institute of British Architects
SBEM	Simple Building Energy Model
TRV	Thermostatic Radiator Valve
TSB	Technology Strategy Board
VT	Variable Temperature

LIST OF FIGURES

LIST OF TABLES

Chapter 1

Introduction

1.1 The problem

In response to rising concerns regarding the significant carbon emissions from the built environment sector, building performance research is expanding rapidly to improve energy efficiencies, and therefore the overall performance of buildings. Recent figures show that that public buildings accounted for approximately 2.8% of total UK CO_2 emissions that year (DECC 2016), and this figure is likely to be an underestimate as it only captures public buildings that are over a certain size. Venue buildings, such as concert and entertainment halls, conference and exhibition centres, stadiums, and smaller venues such as community centres fall within this category. Therefore, addressing the challenges of improving energy efficiencies in these building types presents considerable carbon savings.

Multi-use venue buildings host diverse and myriad events, and often have high occupant diversities whereby some days these buildings are at full capacity and on other days they may be empty (Kinnane et al. 2013). The variety of different types of events that they can host, in often large open spaces within the building, can each have unique demands on the building services and result in energy use profiles that are very challenging to predict (Grolinger et al. 2016). An active variable in this is the occupants of the building at any given time and the activities those occupants are engaged in. The multiple different interactions that occupants have, either actively or passively, through the multitude of different events hosted in these buildings are critical to the assessment of the energy performance of these building types.

To accommodate the growing diversity of requirements that occupants demand from their buildings, multi-use buildings are becoming more common, which brings into question the standardised building categories used for assessing energy performance. It also brings into question the practicality of applying tools to analyse building energy performance that were developed for buildings with a very defined and predictable use. These existing tools for building performance analysis, such as those found in Post Occupancy Evaluation (POE), are limited in their application to multi-use buildings as they cannot account for high diversity factors and resultant energy consumption profile. This is because they primarily focus on a macro-scale level of analysis e.g. benchmarking. Therefore, developing proactive energy management strategies that can meaningfully accommodate such variability can be problematic, especially with the reliance on building simulation to identify energy savings opportunities, which rely on pattern recognition.

Consequently, there is a need to find appropriate methods to analyse the energy performance of these buildings fairly, where occupant requirements of the building are not proscribed in favour of lower energy use. It is therefore essential to identify the energy that useful and conversely that that is wasted in multi-use venue buildings, in order to identify their true performance. This research has found that this can be achieved though micro-scale occupancy focused POE, where ethnography focused analysis of quantitative data can enable energy waste to be identified (Haigh 1982; Heiskanen et al. 2013).

This thesis focuses on the application of such a method on a case study multi-use venue building. As the nature of a venue building is to host an event, this research privileges the needs of those events through the needs of the occupants that host and attend them. From this position, this research seeks to further our understanding of building energy performance in multi-use buildings. The heating season was chosen for this analysis as it is the busiest time of year for the case study building, with the highest variety of different building uses. The aims and objectives of the thesis are outlined below, followed by a description of the remaining chapters.

1.2 Aim & objectives

The overall aim of this research is to investigate the relationship between occupant activity and energy performance of a multi-use venue building

1.2.1 Objective 1

This initial objective is to *demonstrate the applicability of standard methods of identifying building energy performance when applied to buildings with a high diversity factor*.

This objective explores the wider complexities in understanding energy use in buildings that have a highly flexible use. It outlines the need to probe the limitations of existing methods and tools used to identify building energy performance in their application to buildings with a diverse and transient use. This is accomplished in two ways. Firstly, though an extensive literature review examining the applications of existing methods for building energy performance analysis, and secondly through comparing the energy consumption profile of a building with a high diversity factor to energy data from a building with a more predictable consumption profile.

1.2.2 Objective 2

The second objective is to *identify energy waste and potential energy saving opportunities for a multi-use venue building.*

This objective involves direct monitoring and analysis of a case study multi-use venue building in order to identify specific areas of energy waste and therefore energy efficiencies, in order to target energy saving opportunities. A number of methods are employed in order to understand not only the energy use itself but also the wider context of how the building is currently used and managed.

1.2.3 Objective 3

The last objective of this research is to *provide recommendations for energy management and design of controls that are generalisable to buildings with a high diversity factor*.

This objective emphasises the wider impact of this research. This objective identifies commonalities in findings from both objective 1 and 2 that are applicable to wider buildings that have a highly changeable use in order to suggest adaptations in their energy management and their building controls, to enhance building energy performance.

1.3 Thesis structure

An overview of the remaining chapters is provided below:

1.3.1 Chapter 2 - Literature review

Chapter 2 outlines a multi-disciplinary literature review which critically evaluates the previous research in building energy performance. The chapter presents the wider context for improving building energy efficiencies before moving on to present literature that can demonstrate the complex challenges of analysing energy use in this building type. This is followed by a critical analysis of current methods of building performance assessment with specific focus on their application to multi-use venue buildings. Through the literature it was identified that occupant-building interaction, whether active or passive, can have a significant impact on the energy performance of buildings. Existing research was critically appraised in order to develop a method for this case study building that was robust and capable of answering the research objectives.

1.3.2 Chapter 3 – Methods and research design

Chapter 3 presents the methods that have been identified as applicable to the analysis of the case study building. These were identified through both the literature and through initial pilot studies of the case study building, including an extensive energy audit of the different energy end uses. A mixed methods approach using both qualitative and quantitative data was found to generate appropriate data that could represent the complexity of different uses of the building whilst ensuring a robust analysis that could identify the different energy efficiencies of each event

1.3.3 Chapter 4 – Analysis and results

This chapter presented the results of the monitoring and analysis with specific focus on lighting and heating use. Additionally, this chapter presented an analysis of occupant-building interaction through assigning energy waste to the different actors that engage with the building.

1.3.4 Chapter 5 – Discussion

This chapter summarises how each of the research objectives have been answered. The overall findings of the research are presented within the context of the wider body of knowledge.

1.3.5 Chapter 6 – Conclusion

The final chapter of the thesis states the overall contribution to knowledge. It then presents a critique of the methods used, the implications for wider research and the identified limitations of the research. Finally, it proposes recommendations for future research.

Chapter 2

Literature Review

2.1 Introduction

This literature review provides a thorough analysis and critique of the current body of knowledge surrounding non-domestic building energy performance, particularly around venue buildings (i.e. buildings which have an unpredictable and highly variable use) and the potential impact that end user behaviour can have on this.

As this research is being carried out in the UK, building energy performance is initially explored from a UK perspective, with specific focus on the scale of the problem and current legislation intended to improve this. This is to outline the broader context within which this research rests. The critique builds a definition of building performance and investigates existing practices around its analysis in non-domestic buildings with reference to their application to multi-use venue buildings. The main factors which can influence venue building energy performance are considered and the main stakeholders (or actors) who are able to influence this are identified.

An integral component of this inquiry is to explore the current use of post-occupancy evaluation (POE) as a method to assess building performance. In doing so it considers whether a mixed-methods approach that uses both qualitative and quantitative data, to POE could help overcome the limitations of more traditional building energy performance analysis methods and techniques, when applied to multi-use venue buildings.

2.2 Building energy performance

Examining the broader context for this research, at the time of writing the UK has put in place CO_2 emissions targets that include an 80% reduction in CO_2 emissions compared to a 1990 baseline by 2050 (Parliament of the United Kingdom 2008). At present, the operation of non-domestic buildings is estimated to be associated with around 18% of total annual UK CO_2 emissions (Department for Business Energy & Industrial Strategy 2017). Consequently, reducing energy consumption from this sector is vitally important and has become a growing area of research in recent years fuelled by changes in legislation and an increased awareness of energy related issues (Environment Agency 2012; Environment Agency 2015).

Key legislation to reduce energy consumption and associated CO_2 emissions for all new non-domestic buildings in England and Wales is regulated through compliance with Part L of the Building Regulations: Conservation of Fuel and Power (Department for Communities and Local Government 2010). Part L sets out CO_2 emissions targets that new buildings must legally meet and sets a common structure for energy efficiency calculations in buildings. However, despite this legislative attempt to improve building energy performance, there remains room for heavy criticism in its ability to truly impact building energy use (Waddell 2008). Specifically, although Part L provides a mechanism from which to calculate estimations of energy use and associated carbon emissions, it doesn’t focus on in-use performance (i.e. operational energy or carbon) and is instead a calculation of the design performance of the building. Further to this, Part L does not encourage designers to push past the minimum requirements to compliance. There is also a lack of enforcement of Part L and on-site checking post construction. Fundamentally, compliance with Part L does not go beyond a design model, and so the actual in use carbon emissions may not actually be as low as predicted.

Despite Part L providing guidance for both new-build and refurbishment works, Waddell is specifically critical with reference to Part L’s legislative capacity to reduce CO_2 emissions associated with the existing building stock, of which it is stated that 60-70% will still be in existence in 2050. As a result, Waddell states that there is a clear need for further legislation and policy surrounding energy use in existing buildings, especially as it provides a much greater contribution of the building sector’s CO_2 emissions than new buildings. Comparing this state of play in the UK with that of Australia, the adoption of the NABERS rating scheme has seen considerable improvement in the overall performance of the building stock as a whole, as the real estate sector has moved towards rewarding buildings with a better in use energy performance with a higher market value (Bannister 2012).

In general, literature concerning building energy use is focused on how building performance can be enhanced through improvements in aspects such as building design, fabric, systems, and the use of low / zero carbon or renewable technologies (Lo et al. 2012). Within this literature there has been significant development of established methods (e.g. degree day analysis and benchmarking) to improve the analysis of building energy performance (Z. Li et al. 2014; Chung et al. 2006; Day et al. 2003). For example, benchmarks have been developed for a wide variety of different types of buildings (CIBSE 2004), with increasing accuracy following the publication of Display Energy Certificates (DEC's). This is because DEC's compare actual metered energy consumption between buildings of a similar use (Centre for Sustainable Energy 2018). Alongside the growth of methods in analysing building energy performance, there has been a proliferation of research around building energy simulation which generally attempt to forecast building energy consumption, and simulate the impact of various energy conservation measures (ECMs), on future building energy performance (Bhaskoro et al. 2013; Yang et al. 2012; Pan et al. 2009; Budaiwi & Abdou 2013). Building energy simulations which consider thermal and building service performance are considered relatively mature and provide validated results (Haldi & Robinson, 2009). However, it is claimed that the interaction of occupants with building controls and systems could potentially have an even greater impact on energy performance, but is currently only simplistically considered (D'Oca et al. 2018; Hoes et al. 2009; Hong et al. 2016).

Additionally, with the literature recognising the complexities of occupant behaviour in buildings, these models of building energy forecasting and performance are also increasingly trying to predict the impact that occupants have on energy use (Hong et al.

2016; Hong, Sun, et al. 2015; Yan et al. 2015; Page et al. 2008). The overall aim of these efforts is to improve the energy efficiency of buildings.

Most literature regarding energy use in buildings is understandably focused on the building types which are most commonly represented in the building stock (e.g. offices, dwellings etc.). These building types generally have a clearly defined use for the occupants as well as relatively consistent occupancy patterns and as such could be considered to have repeatable and broadly predictable energy demands. Conversely there is a dearth of literature pertaining to the energy performance of building types which have much less consistent occupancy patterns, for example multi-use venue buildings.

For new non-domestic buildings, design teams are required to demonstrate compliance with Part L emissions targets through the National Calculation Method (NCM) which is generally calculated using SBEM (Simplified Building Energy Model) software. However, there is a large body of evidence from existing buildings in operation which routinely shows that these design models often drastically underestimate the true in-use energy performance (Bordass, Cohen, et al. 2001; Menezes et al. 2012). This discrepancy between anticipated energy consumption during design and actual energy consumption in use has led to the emergence of research surrounding the ‘performance gap’ (Bordass et al. 2004; Menezes et al. 2012).

Reasons for this gap between anticipated and actual energy performance are diverse but can include factors such as the users not being adequately briefed in how to operate their buildings in the most efficient way, energy models during the design process not accounting for the true occupancy hours of the building, and the energy modellers themselves oversimplifying the intended use of the building (Bordass, Cohen, et al. 2001). Additionally, these models may not adequately capture the diverse use of the building, something that is a particular problem for venue buildings with their changeable and often intermittent use.

It is important to emphasise that the emissions targets in Part L of the Building Regulations only consider energy associated with ‘regulated’ loads e.g. heating, cooling, ventilation, interior lighting, hot water. Regulated loads cover aspects of energy use associated with space heating, ventilation, cooling, hot water, and fixed internal lighting (DCLG, 2013). Part L does not consider other aspects of building energy use which are conversely termed ‘unregulated’ loads. Typically these cover aspects of energy use including external lighting, lifts, escalators, servers, and, crucially, the majority of small power loads, which includes all unfixed devices products and appliances that are plugged into the electricity network of a building (Dunn & Knight 2005). The latter is of interest as the category small power loads covers a whole array of equipment which is linked to occupant behaviour and can represent a significant proportion of actual in use energy consumption (Menezes et al. 2014). As such, designers are not generally required to demonstrate how much energy their building will consume when it is completed and occupied, and they are instead simply tasked with demonstrating that the design of the building complies with the emissions targets. Clearly this ‘failure’ to account for key aspects of energy use, such as small power loads, means that the compliance calculations for Part L carried out during the design process will not provide an adequate representation of actual in-use energy consumption. The omission of these loads could be seen as understandable from the perspective of the building designers as the majority of unregulated loads (particularly servers and small power loads) are difficult (or indeed impossible in the case of speculative developments) to adequately anticipate during the building design (CIBSE TM-54). However, in doing so, these models are severely limited in their ability to provide accurate estimates of in-use energy performance.

Previous research into the performance gap showed that the significant discrepancies between the anticipated consumption during the design process and actual in-use consumption can usually be attributed to a combination of the following factors: building design assumptions, occupancy and behaviour, and management and controls (Bordass et al. 2004; Menezes et al. 2012; Bordass, Cohen, et al. 2001). These will be discussed in the next section.

2.3 Buildings and energy use

Building energy performance refers to the operational energy use of a completed and occupied building (Bordass, Cohen, et al. 2001) and is often discussed in relation to the ‘performance gap’ the term for the large body of evidence that demonstrates that completed buildings routinely consume far higher amounts of energy than was anticipated during the design process, which was mentioned in the previous section (Bordass et al. 2004; Menezes et al. 2012; Bordass, Cohen, et al. 2001).

The energy performance of a building is dictated by a large number of interrelated variables which can be usefully discussed in relation to three key elements identified by Baker & Steemers (2000): building design, building systems, and the behaviour of the building occupants. This is outlined in Figure 1. Baker and Steemers attempted to quantify the relative variation each of these three aspects could have on final energy performance of a buildings by analysing data from field investigations of buildings. Acknowledging that their proposed values were high-level estimates and contain multiple assumptions they suggested a variation in in-use energy consumption of a factor of 10 between buildings providing a similar function. Considering the specific features of the building design and the performance of the building services through revisiting original energy models they were able to deduce that these two aspects are responsible for a variation factor of 5 and that occupant interaction with their surroundings could lead to variations of up to a factor of 2.

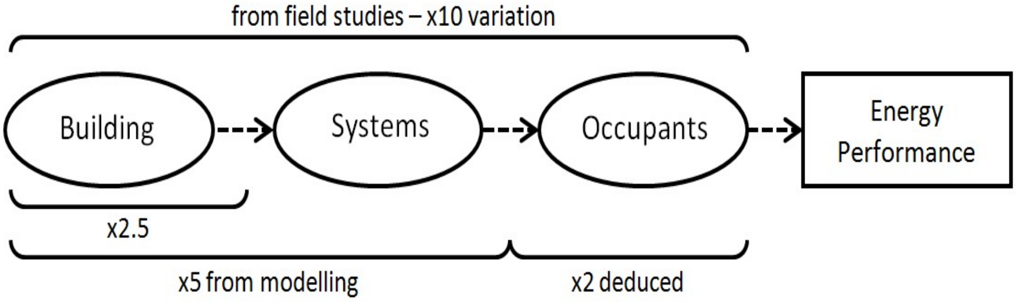

Figure 1: Diagram showing the three factors determining non-domestic building energy performance (Baker & Steemers 2000).

In addition to these three factors, Baker and Steemers then identified a potential 4th factor, which was the presence of an activity or process in the building that is a large consumer of energy. However, a question arises whereby if this large consumer of energy, for example a swimming pool, is using energy that is necessary to fulfil the requirements of the occupants then should this actually be considering detrimental to the performance of the building? In reality building energy use is primarily to meet the user's needs of the space and a building's energy efficiency, and hence energy performance, should only be negatively affected if the energy being used is in fact wasteful, for example if the swimming pool is always heated but never used by occupants.

2.3.1 Multi-use venue buildings

This thesis specifically focuses on multi-use venue buildings and the challenges associated with investigating their energy performance. By their nature, these buildings have a highly diverse use profile with intermittent and varying occupancy, occupant activity, and energy demand (Kinnane et al. 2013; Grolinger et al. 2016). The result of this is a highly irregular and unpredictable energy consumption profile when compared to other buildings with a more consistent and predictable use profile such as offices and dwellings (Grolinger et al. 2016). This is particularly problematic when predicting energy use for the purpose of accurate billing of energy to clients hiring venues (which is one of the primary uses for venue buildings), and also when modelling energy performance (Grolinger et al. 2016; Mathews et al. 2002).

Public buildings, a category in which venue buildings are encapsulated, are defined by the Display Energy Scheme as being occupied by a public authority and frequently visited by the public (Department for Communities and Local Government 2012). In terms of venues, these include buildings such arenas, theatres and halls, conference and exhibition centres, stadiums, smaller venues such as community centres, and places of religious worship. Additionally, as most public buildings are likely to have areas that are used as venue spaces e.g. school halls, the research surrounding the energy use of venue buildings can also be more widely applicable to these building areas.

The Centre for Sustainable Energy has published the latest available data from all of the public buildings over 1,000m^2 that completed Display Energy Certificates in 2010 (Centre for Sustainable Energy 2018). When compared against UK emissions data, this data shows that public buildings accounted for approximately 2.8% of total UK CO_2 emissions that year (DECC 2016). This figure is likely to be an underestimate of the true CO_2 emissions from public buildings and as DEC's now capture buildings that are over 250m^2, this figure is certain to rise (Department for Communities and Local Government 2012). Consequently, improving the energy efficiency of public buildings, and thus venue buildings, is vital if the UK is to meet its ambitious carbon emissions targets.

A study by Kinnane et al. (2013), brings special mention to DEC's and their role in shedding light on the energy use in multi-use venue buildings. This study is in support of the central argument of this thesis; that these buildings have a wide and varied use resulting in unpredictable and highly diverse energy use profiles, and in the absence of appropriate building performance analysis tools, multiple methods of analysis must be employed in order to identify and improve their energy efficiencies. The following are quotes from

Kinnane et al. (2013), that affirm the challenge of identifying appropriate strategies for energy efficiency in these types of buildings:

"Local authority buildings are often culpable of high energy consumption, given the wide range of functions operated within. The display of energy certificates (DEC) within these buildings (>1000m^2) has increased awareness of this high consumption. However, in-depth knowledge of operational consumption requires more intricate assessment." (Kinnane et al. 2013) Page 1

"Multi-purpose event spaces are common to public buildings, and are used for a wide range of functions including meetings, lectures, public consultations, exhibits, performances etc. These events are hosted regularly yet sporadically and without a routine schedule and common occupancy, making an efficient building operational strategy difficult to achieve." (Kinnane et al. 2013) Page 2

The impact of these different types of events, in terms of occupant activity and how the building is managed for them, on energy the energy performance of buildings is what this thesis aims to investigate further.

2.3.2 Multi-use venue building and energy use

Despite the significant contribution of public buildings, and venue buildings within these, to UK CO_2 emissions, there is a disproportionate representation in the building energy management literature of building types with a more typical use e.g. offices (Masoso & Grobler 2010; Kontokosta 2016; Lam & Hui 1996; Nikolaou et al. 2012). Consequently, venue buildings, being buildings with a less typical and sometimes unpredictable use, are underrepresented in literature.

Both the variability of use and the intermittency of venue use, result in highly variable energy load profile for these types of buildings (John et al. 2007). This is especially true where venues are multipurpose as this increases the variability of the energy use profile. When aiming to lower the carbon emissions of these types of buildings, the designer needs to have a clear understanding between peak and base energy loads in order to develop a low carbon design (John et al. 2007). However, without a clear understanding of the energy demands from different uses of the venue building, this becomes very challenging.

Examining buildings in use, a study by Zagar (2015), used three different statistical models to predict future energy costs of individual events at a multi-use venue. The statistical analysis used historical consumption and energy cost data alongside some basic event attributes such as event duration and type of activity. Although the study did not directly monitor a building event, it did examine energy consumption and costing of individual events. The research demonstrated the difficulty of predicting energy consumption in these spaces and showed how different types of events can have very different demands on energy. Overall, the research underlined the need to study these types of buildings to better inform financial models and thus a more robust business strategy (Zagar et al. 2015).

Unlike the research in this thesis, that examines the in-use energy performance of a multi-use venue building, a study by Grolinger et al. (2016) focused on energy forecasting for a venue building. This study used big data and two different prediction models, to predict the potential impact of changing occupant activities on the venue’s future energy use as a whole. The venue investigated was an arena used for ice sports in the US, but as the ice rink can be covered the space can also be used for other events such as basketball games, concerts, and family events. As such, the venue is not used every day and has an inconsistent and highly variable energy demand. Grolinger et al. (2016) highlight the difficulties of trying to forecast data for a venue building due to the large variation in Figure 2 from Grolinger (2016) provides an example of the variability of energy use in their case study venue building.

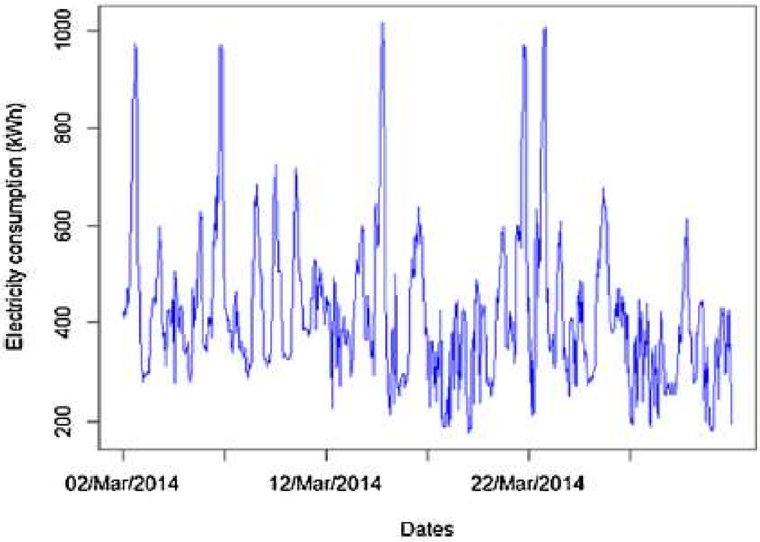

Figure 2: Example of variability in event venue consumption (Grolinger et al. 2016)

The data presented in this figure represents a single month of electricity use and there are five clear spikes in consumption that neatly correlate with events hosted at the venue building. Comparing this to Figure 3 which shows the energy consumption for a multi-family dwelling for one month, it is clear that the energy use for a venue building is much less consistent and has much larger variability.

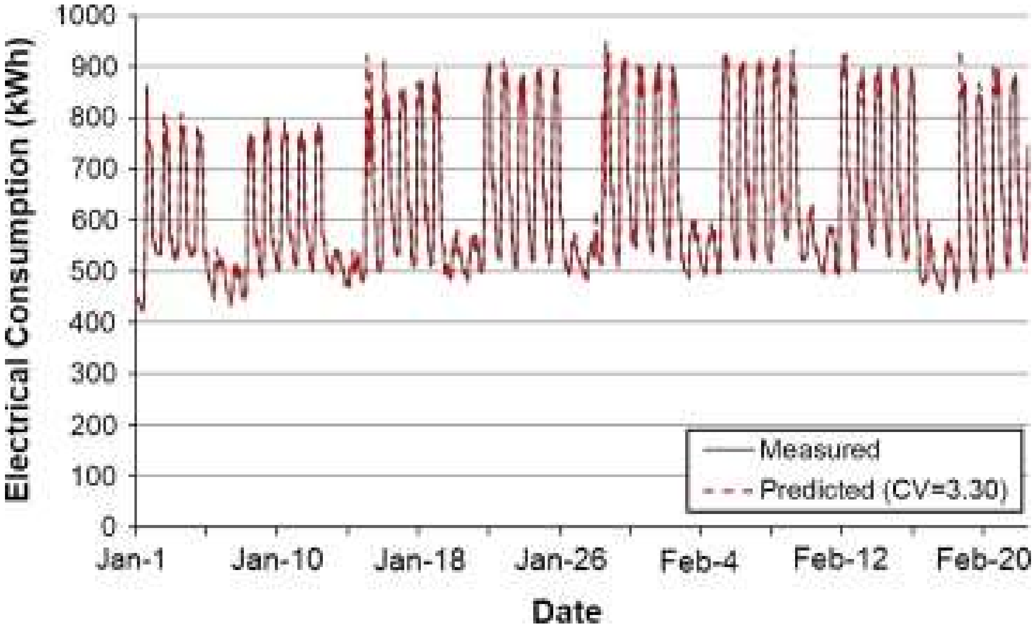

Figure 3: Energy consumption for a multi-family dwelling for one month (Jain et al. 2014)

Additionally, Figure 3 shows daily predictions for the electricity use of a multi-family dwelling. Jain et al. (2014) created these predictions based on empirical data from a multi-family dwelling that had a highly energy regular consumption profile. This achieved a level of accuracy in their prediction that is significantly better than that presented by Grolinger et al. (2016) during their attempts to predict the electricity demand for their venue building. This issue with accuracy when forecasting venue building energy use in comparison to other building types with a more regular use profile was an acknowledged limitation in the study by Grolinger et al. (2016).

Grolinger et al. (2016) also explores the impact of data granularity (daily, hourly, 15 minutes). They found that the models they developed could accurately predict peak demands but could not accurately predict total daily consumption figures. Grolinger et al. (2016) suggest that this is due to the inability of the models to account for random variations. The data used by the study includes specific attributes relevant to the different types of events, e.g. seating configuration related to maximum occupancy levels, event type, and time of year. However, the inability of the study to predict an accurate overall daily consumption figure implies that there is not enough understanding or contextual information around the energy use during each of these events. The argument that Grolinger uses to justify the use of big data and data analytics is that these can lead to new insights and better business decisions. However, despite the study managing to forecast energy use, there is no analysis to identify any energy waste or make inferences on energy performance. This is because the data is primarily focused on energy consumption and not on any physical aspects of the building's energy performance. Predictions are instead focused on the ability to forecast the cost of running events so that these can be including in recharging clients. Grolinger emphasises the importance of this for a wide variety of venue buildings, including concert halls, theatres, and conference centres.

In a separate study addressing performing arts venues, Heathfield & Bottrill (2012) used energy consumption data, collected through audits of energy bills and also two online tools created by the authors and a partner research institution to enable venues to self-report their energy use. Data was collected at building level and was used to categorise different types of performing arts buildings for the purposes of developing sector specific benchmarks. The study found no clear relationship between energy consumption and activity type. However, their benchmarks for each building which examined energy use per seating capacity could skew this analysis, as there is no understanding if all of those seats were occupied, or if the energy use that they have recorded is the representative norm for those buildings. It is possible that the venue had a quiet or busy period for events, or it had a series of events that had very high or very low energy demands, all of which would affect any benchmark figures. This underlines that their approach to benchmarking these buildings is highly flawed as it ignores the variety of different activities that are hosted at venue buildings and their different requirements from the building services, and subsequent impact on energy consumption. This therefore indicates the need to investigate venue activities and their impact on energy consumption at a more granular level.

A study by (Li et al. 2015), aimed to evaluate the impact of climate on the energy consumption of different types of buildings, including venue buildings. Three different buildings were identified to represent three different building types, these being a commercial building, a residential building, and a large venue building. Each of the buildings was first monitored and then simulated. The study was severely limited e.g. to verify the reliability of the simulated data, the cooling energy consumption for the commercial building was taken as an example to compare the measured data against the simulated energy consumption. This was not carried out for the other two building types. Knowing what we do from studies such as those by (Zagar et al. 2015; Grolinger et al. 2016; Kinnane et al. 2013), it is unlikely that a similar comparative test between the simulated results and measured data for the venue building would have produced such favourable results as those found with the commercial building. There is also no mention of any changes in building activity at the venue and the impact these have on overall building demand and consequently the building simulations. Considering these simulations present findings at an hourly interval, it is highly unlikely that these findings are reliable.

For the purposes of this research it is invaluable to examine the impact of different types of events on the highly dynamic energy use in venue building (Grolinger et al. 2016; Kinnane et al. 2013). Venue buildings complicate energy analysis through their changeable nature and existing analysis tools are potentially not able to adequately address this variability. Different types of events can use different amounts of energy and so it is important to identify what these different events are and identify their characteristics that contribute to the erratic energy consumption profiles of these types of buildings. Consequently, there is a need to develop more appropriate monitoring and analysis methods that are capable of providing a better understanding of building level performance with tangible business benefits including more accurate estimates for future energy use, for example for forecasting energy billing for clients.

2.3.3 Factors affecting building performance

Earlier in section 2.3 we saw from Baker and Steemers (2000) that there are three main factors affecting building energy performance; building design, building systems and building use. Revisiting the example of a swimming pool and defining energy waste, for venue buildings, an event held at a venue could be a large consumer of energy in the same way that a swimming pool is, but that energy use is only wasteful if there are no occupants attending the event. Additionally, venue energy use is highly diverse, the consumption profile being dependent on the use of the building, and the energy use between different venue buildings that host different types of events is potentially highly divergent.

As mentioned previously, modern building design is reliant on computer simulation to predict the impact of design options on in-use energy performance, and the effects of human-building interaction have largely been ignored or oversimplified in these simulations (D’Oca et al. 2018). For example natural ventilation strategies can be compromised by window opening behaviour which is not considered in building energy models (D’Oca et al. 2018). Similarly, models do not account for aspects such as daylighting design failures due to glare arising from occupant’s dynamic operation of blinds.

Concerning building systems, building operators and managers have the challenging task of operating buildings efficiently while meeting occupant comfort needs that are diverse, dynamic, and stochastic in nature. To manage buildings more effectively most modern non-domestic buildings have BMS systems that automate the conditioning of internal spaces and consequently the level of control that the facilities manager can have on building energy consumption is reduced.

In terms of energy efficient temperature management, some studies have tried to align heating use with occupancy more closely to avoid conditioning a building during unoccupied hours. However, some of the more engineering focused examples found in literature can be impractical. For example, using passive infra-red (PIR) based occupancy sensors to manage HVAC systems in the same way lighting can be controlled, can be impractical due to the long response time to cool or heat a space compared to lights turning on (Agarwal et al. 2010). Similarly, CIBSE provide guidelines that use concentrations of CO_2 as an indicator of occupancy from which to set ventilation set points (CIBSE 2013a). However, this too can have a long response time during which the comfort of the occupants can be compromised. Additionally, using CO_2 concentrations as an indicator of occupancy is fundamentally flawed, as the rate of CO_2 expelled into the room by occupants is greatly affected by activity (metabolic rates) and time spent in the space. Consequently, this approach is a grossly oversimplified in terms of identifying the true number of occupants in a room at any given time. Therefore, to meet occupant thermal comfort needs, conditioning a room would need to commence prior to its occupancy, meaning that there is a need to be able to predict building usage and proactively adjust systems in response to this. Predicting occupancy is convoluted for a venue building that is used intermittently for different purposes.

In terms of occupant comfort, the metrics used when predicting this have been used for almost 50 years. Fanger (1970), attempted to establish universal conditions for thermal comfort through occupant reports collected from a range of controlled climatic conditions. In doing so, Fanger proposed the use of a Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD), when trying to predict if a thermal environment would be acceptable to a large group of people (Yang et al. 2014). These metrics acknowledge that in any given thermal environment it is unlikely that all occupants will be satisfied with their levels of comfort. Use of these metrics are primarily directed at HVAC engineers in informing their HVAC design and set points, however, fundamentally this is a very engineering focused approach that distils occupant needs down to quantitative data and thus ignores the subjectivity of an individual’s comfort. Further, when examining how the data underlying these metrics was collected by Fanger, there remains debate as to the validity of the results, especially as they were collected under artificial conditions using an environmental chamber, which is not representative of occupants in dynamic real world environments (de Dear 2004).

Gökçe & Gökçe (2014) highlight the need for more sophisticated techniques in monitoring and controlling systems for building management. The study developed a heavily IT focussed energy management system that has simultaneous and consistent access to data and information extracted from different sources. Multi-dimensional analysis using time series and benchmarks then inform an optimisation of a building's energy control systems. For venue type buildings, this holistic approach to monitoring and analysis could be very useful in assessing building energy performance, especially as the devised method also uses scenarios of building use-cases, therefore allowing the IT infrastructure to adapt to different uses of the building. Different types of events could therefore be analysed separately. Although the study purports the necessity of analysing data from multiple meters and sensors around a building, it does not specifically describe each of these and it is unclear if it is consequently only the HVAC and lighting related energy consumption that is optimised later in the computations, or if small power energy consumption and associated sensible heat gains are also considered. The practicality of employing such a sophisticated system is not addressed, for example the computational time may be long considering the number of components to the system. To justify this methodological approach, the study states that the inability of current BMS to learn from previous operations and forecast the impact of control orders on the behaviour of a building can result in a loss of 10-15% in efficiency. Additionally, the study states that there is a need to have a BMS that looks at each energy related system in a building together and that not doing this resulted in an efficiency loss of 5%. These percentages are however not elaborated on any further.

In the analysis of the energy performance of a naturally ventilated library, Krausse et al. (2007) rely on the environmental sensors linked to the BMS. There is limited criticism of the location of these sensors in the building, something that may be pertinent for a naturally ventilated building that could have uneven airflow in the absence of mechanical ventilation. Both ambient temperature and average internal temperature are presented for a year, though only average internal temperatures are discussed. These are used to discuss the appropriateness of heating in response to occupancy as well as the building's response to changes in the seasons. The monitored data is then compared against the CIBSE 2002 overheating criterion as a benchmark to quantify the building's performance specific to temperature management. In analysis of the performance of this naturally ventilated building, environmental parameters such as CO_2 and VOCs relevant to air quality are not considered in this paper, something that would have added to the assessment of its overall environmental performance as a building employing this type of ventilation strategy.

Within the section of "systems", as well as referring to the operation of building systems, Baker and Steemers (2000) also refer to the design of the controls. This distinction does blur slightly with the impact that occupants have on buildings as it is through these controls that they can actively impact building energy use. However, if controls are poorly designed then this is not necessarily the fault of the building occupant. According to a Building Controls Industry Association (BCIA) publication detailing industry best practice for the design of controls for end users, controls should be easy to use, intuitive and well labelled (Bordass et al. 2007). The report states that designing controls with these features leads to higher occupant satisfaction levels and improved energy efficiencies through better active occupant-building interaction. Specific to venue buildings, to enable energy efficient use of HVAC with varying occupancies, building zoning has been suggested by some authors (Budaiwi & Abdou 2013). This would need to be factored into the design of the built form as well as the design of the building services.

2.3.4 Occupant activity and behaviour

To provide more insight into the energy performance of multi-use venue buildings, it is important to understand the role that occupants play and how they may contribute to energy waste. Findings from studies such as those by Azar & Menassa (2012, 2014) align with conclusions from wider building energy management research (Lopes et al. 2012), that there is a need to consider energy management beyond a purely technological perspective (e.g. building fabric and services) and to also consider occupant behaviour and activities. They stress a need to develop energy management strategies that incorporate human actions in the buildings, through both the occupants and the facilities management team.

Operation and management of a building, as well as occupants and their interaction with controls can significantly impact energy use. A study by Li et al. (2014), examined the actual in-use energy of 51 high performance buildings in China and the United States. It found that when examining multiple factors relating to energy performance, e.g., climate, building size, efficient technologies, occupant behaviour, and operation and management, none of these factors were decisive to a building's actual energy performance. However, changes in occupant behaviour and operation and management could significantly affect potential building energy savings.

Masoso & Grobler (2010) found that over half of an office building's annual energy consumption occurred during non-working hours and identified air conditioning systems being left on during these times as the largest contributor to energy waste, followed by occupant control over lighting and small power equipment left on after occupancy has ended as the next main contributing factor. The findings of this study emphasise that occupancy periods and small power use can have a significant impact on actual in-use energy consumption. This is an example where, as stated by Lopes et al. (2012), there needs to be a comprehensive energy management strategy in place, where the facilities team have a greater understanding of occupant needs and can therefore proactively schedule the air conditioning, and where occupants need to engage in more energy efficient behaviours.

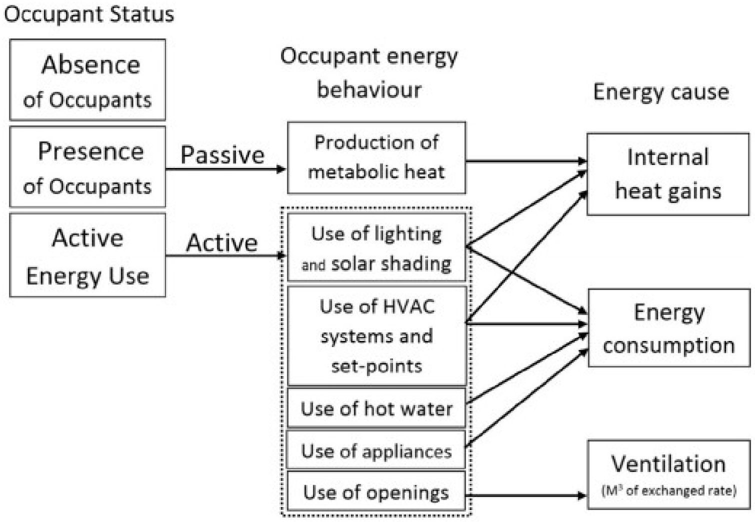

Figure 4: Occupants' types of activities affecting building energy consumption (Delzendeh et al. 2017)

As shown in Figure 4 occupants can affect building energy use in two main ways, either '*passively'* through providing internal heat gains, CO_2, and water vapour (Mahdavi & Pröglhöf 2009) or '*actively'* through interaction with the buildings services and controls. Improving the understanding of the relationship between occupants and building systems through both of these pathways is especially pertinent to assumptions in building energy simulation, improving building automation systems, and improving building performance as a whole (Zhao et al. 2014; Oldewurtel et al. 2013; Duarte et al. 2013). Additional complexity in the analysis of this relationship arises in multi-use buildings, where occupants generally have more numerous and varied interactions compared to buildings with a more consistent use (e.g. offices). Venue buildings that host diverse and myriad events are an extreme example of multi-use buildings often with flexible spaces that can host a multitude of different activities resulting in high occupant diversity factors (Technology Strategy Board 2015).

Mahdavi & Pröglhöf (2009) studied people's presence and interaction with buildings. Examining control orientated behaviour as a function of internal conditions, for example illuminance level and temperature. In monitoring the interaction that occupants had with building controls and the impact that this had on the internal environment, the authors used environmental sensors both inside and outside the building (for illuminance, humidity, and temperature). They also used a range of automatic sensors e.g. to detect presence of occupants, as well as time lapse photography to observe window and blind opening over a 9-14 months across a range of case study office buildings. Although this presented a very data rich study, there is a still a lack of context to the user behaviour when relying on quantitative data from sensors and not directly observing their behaviour. This is especially true where a change in occupant needs may result with them interacting with controls in a manner that may not be explained through analysis of each of the monitored variables. For this reason, it is argued in this research that qualitative data is essential to providing crucial context to the quantitative data and essential to identifying energy waste and subsequent appropriate energy conservation measures. In addition to the limitations in relying on quantitative data, this study by Mahdavi Pröglhöf did not monitor energy use and the impact that the occupant behaviour had on energy consumption, and instead only monitored environmental conditions through the use of internal and external sensors. As the buildings were all offices, as has been discussed in section 2.3.2, these buildings have a highly predictable use profile, so the impact on energy may be easier to identify if the impact of occupant behaviour on the internal environment impacts energy use significantly enough that is identifiable from the analysing the energy profile, however this is not quantifiable without appropriate energy readings. The study aimed to provide a basis for the development of the accurate modelling of passive and active occupant interaction with buildings. The successes and limitations of this study provides an important discussion on the need for more long-term high resolution (micro-scale) empirical data on occupant interaction to create reliable dynamic simulations of the states of occupant, building, and context.

A separate study by Hoes et al (2009) confirmed the need for more accurate representation of occupant activity in building simulations. Although both studies highlight the importance of gathering more empirical data on user-building interaction, pattern recognition in the buildings studied relied on the buildings having defined purposes, whereas as previously described for venue buildings, the purpose of these buildings is continually shifting to accommodate differing occupant needs of the space. However, there is still potential to use high-resolution empirical data from venue buildings to identify energy waste using a mixed methods approach, instead of using the data to make predictions of consumption through simulation.

Developing proactive energy management strategies for venue buildings that can meaningfully accommodate such variability can be problematic due to erratic energy consumption profiles resulting from irregular use and occupancy. Such uncertainty in energy use can limit the applicability of traditional energy analysis tools for measuring building performance. In the absence of these measures, conscientious management of building services is key to reducing energy consumption and alleviating energy related costs. Monitoring parameters such as humidity, temperature and light levels can provide a measure of the usefulness of the energy consumption by building services when analysed against qualitative data of occupant needs and activity (Hong et al. 2017a).

Building occupants are not always predictable and designers can oversimplify the behaviour of humans and their interactions with a building (Janda 2011), either in terms of their interaction with controls, the amount of small power they use, or even the times that they will occupy the building (Yan et al. 2015; Hong et al. 2016).

In using building simulation to investigate occupant interactions with buildings, Hong et al (2016), identify two different types of modelling, ‘implicit’ models, and ‘explicit’ models. They state that implicit models do not deal with occupants directly, and instead focus on the driving forces behind occupant behaviour and rules associated with physical systems e.g. opening windows and doors and switching lighting on and off. Explicit models are described as those that are based on monitored occupant behaviour. However, based on the descriptions by Hong et al (2016), it seems few direct observations of behaviour feed into these models, and instead they focus on assumed potential occupant behaviours under different conditions. Additionally, the added complexities of changing building use are not adequately associated with the level of variability found in multi-use venue buildings (Grolinger et al. 2016; Zagar et al. 2015)s.

The occupancy focused data that Hong et al (2016) identify as being necessary to be able complete occupant behaviour research centres around age, gender, and working profiles, which it could be argued do not provide a rich enough context as to why energy is being used, and potentially wasted, by the occupants. For multi-use venue buildings, this research has shown that direct observations of occupant behaviour are extremely useful in identifying instances of energy waste and which actor they are associated with. Both aspects are important considerations when developing deliverable energy conservation measures for the building.

For multi-use venue buildings, occupant behaviour and their interactions with energy end uses change to suit the different requirements of events hosted. Additionally, aspects such as occupancy times and occupant activity are only considered at a superficial level, if at all, through the use of default profiles in the modelling software which infer hours of use for the considered regulated loads (Menezes et al. 2012). A study by Haigh (1982) carried out longitudinal case studies of five UK primary schools, and found that although designers expected that school classrooms would have standard occupancy periods, in general they were only occupied for about 60% of the assumed occupied period. With as much as a 40% error in this estimate for a building that has a defined purpose and use, assumptions made when modelling venue buildings are likely to be even less accurate. Therefore, occupancy focused analysis of in-use building energy is crucial for these buildings as these limitations of the initial energy modelling process could significantly restrict any understanding of building energy performance.

Examining the multi-use aspect of buildings and the impact that this can have on building energy use, a study by Duarte et al. (2013), investigated occupancy in a case study of a multi-tenanted office building for the purposes of improving assumptions used in building energy simulations. The study monitors the varying occupancy of the building over 23 months to provide accurate occupant diversity factors. Diversity factors are hourly fractions for a 24h day. A profile for each day of the week can be created and combined to make up a representative week of general occupancy or specific equipment operation profiles in a building. Despite the case study building having a very defined and predictable purpose, it was found that occupant diversity factors were affected by days of the week, holidays, and months of the year. Although this study mainly focused on occupant diversity, it is the occupant's requirements of the buildings that also impacts on the diversity factors of these energy end uses in the building, hence impacting the variability of building energy use. For venue buildings these occupant needs, or drivers for energy use, are continuously changing between different events, and as such this contributes to the highly changeable energy consumption profile as found in section 2.3.2.

The passive engagement occupants have with buildings is important when considering the quality of the indoor environment during the design process and when setting ventilation rates and temperature set points in building management. In investigating the impact of occupant internal heat gains in venue buildings, Budaiwi & Abdou (2013) used building simulation software to model three different types of mosque in Saudi Arabia. The aim was to evaluate how intermittent and significantly varying occupancy schedules throughout the day and week could influence the internal temperatures and the impact that this could have on HVAC management. The study took data from 132 existing mosques to develop different models used for building simulations that investigate different HVAC strategies for improving energy efficiency. These were then categorised based on certain attributes e.g. periods and duration of use, floor area, capacity, built form and type of installed HVAC. Energy audits were then conducted at three of these mosques, which included energy monitoring. These readings were used to calibrate building energy models used to investigate different HVAC strategies and thus identify potential energy savings.

The energy conservation measures identified involved intermittent use of the HVAC system aligned with the predicted intermittent occupancy. The lead times for the HVAC were dependent on the prayer time, mosque size, and zoning of different areas of the building to accommodate different congregation sizes. Occupancy was not directly monitored, and so estimates for each prayer time were used based on the modelled capacity of the building and occupancy for different prayer times from existing mosques. Overall, the study identified HVAC energy savings of up to 36% (depending on the building's insulation levels) for cooling energy, adjusting its scheduling in line with occupancy, and using a larger system than would normally be specified. The study also investigated the impact of zoning the building into smaller areas for lower occupancies. Through only conditioning these areas at certain times the study estimated savings of up to 30% associated with cooling energy.

As we have seen, occupant interaction with the building services and controls is not generally considered during the design process but is of crucial importance for building energy management. The active interaction occupants have with buildings, for example through interaction with temperature settings (Combe et al. 2012) or by leaving lights on (Tetlow 2014), could potentially be more challenging for building energy managers as these can influence the efficacy of HVAC and lighting schedules. Classic examples of this include opening windows when the air conditioning (Fabi et al. 2012) or heating (Haigh, 1982) systems are operating. A number of studies have attempted to identify reasons behind these often wasteful occupant behaviours that persist despite knowledge and often training on how to use buildings more efficiently (Coleman et al. 2013; Zachrisson & Boks 2012; Chiang et al. 2014). Figure 5, taken from a publication by The World Business Council for Sustainable Development (2009), shows how consumption of different energy end-uses can be affected by occupants, and consequently the cumulative potential savings, should occupants adopt more energy efficient behaviour. Although it shows the impact of conservation behaviour for a residential setting, the findings can also be applied to non-domestic buildings. This figure also highlights the need to sub-meter services within a building to fully identify where savings can be made.

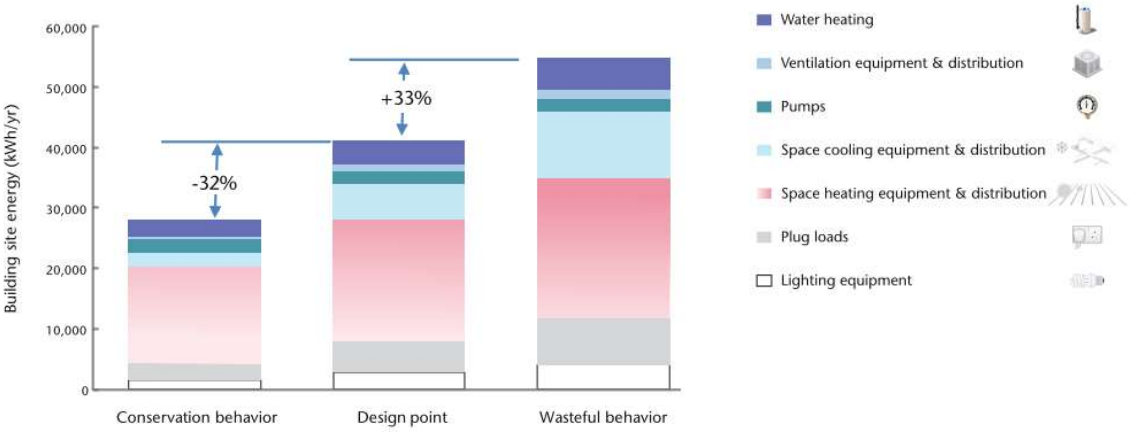

Figure 5: The impact of conservation behaviour on a residential site (World Business Council for Sustainable Development 2009)

The estimate that approximately a third of energy consumption can be attributed to energy-unaware behaviour is repeated in other studies, although Post Occupancy Evaluation studies have shown that this can vary substantially depending on the accuracy of the design model and the ability of occupants and building managers to use the building efficiently

(Tetlow 2014; Menezes et al. 2012). This further emphasises the need for building simulations to provide more realistic estimates of energy consumption.

A study by Menezes et al. (2012), showed the importance of occupant behaviour when addressing the performance gap between the designed energy consumption of the building and the actual energy consumption. Through POE, it was shown that a better understanding of buildings in use that include real occupancy patterns, can lead to better predictions of energy consumption, and consequently leads to more achievable energy savings targets. Findings from this study could also be used to support the need for further guidance for building managers post completion, as outlined in the Soft Landings process (BSRIA 2014), in order to ensure that they understand in-use energy management challenges specific to the building that they are managing.

There is a broad agreement across literature that behavioural changes are required if energy efficiency measures are to attain their full potential (Lopes et al. 2012; Coleman et al. 2013; Haldi & Robinson 2008) and that previously implemented behavioural change interventions have not achieved their potential in terms of reducing behaviour related energy consumption (Lopes et al. 2012, Chiang et al. 2014). It has been suggested that the potential energy savings available through alterations in behaviour can be as high as those achieved using technological solutions (Lopes et al. 2012), but there remains great difficulties in quantifying the impact of behaviour on energy consumption which is limiting the applicability of research in this field. It is believed that this also has had consequences for energy efficiency policies since the lack of energy behaviour quantification has limited the integration of this topic within them (Lopes et al. 2012). The difficulty in achieving energy savings through behaviour change could partially lie in the discontinuity between the different research methods employed by the social sciences and engineering disciplines. Social sciences tend to use qualitative methods such as interviews and surveys to investigate behaviour, while engineering approaches uses quantitative methods such as simulation and load quantification. In order to achieve the maximum energy savings through behaviour change it is important to consider both quantitative and qualitative approaches (Lopes et al. 2012).

In the literature offices are often used as locations for undertaking individual monitoring of energy consumption (Mulville et al. 2014; Coleman et al. 2013; Shao et al. 2017). Presumably, this is because electricity consumption (through workstations) can be more easily associated with individual occupants than in other building types. For example, Mulville et al. (2014) carried out a longitudinal study of workstation electricity consumption in two UK offices. They used plug monitors on around 90 workstations in total and monitored this over a period of around 3 months. They found significant variation in workstation electricity consumption and waste between individual occupants resulting from differences in working patterns. Their results indicated as much as 23% of electricity was being consumed outside of standard working hours and therefore was deemed energy waste. However, whether this is actual waste is debatable as there was no direct measure of whether the monitored electricity consumption was legitimate (i.e. was required for the occupant's work tasks) or was unnecessary. Perhaps one weakness of Mulville et al.'s study is that there is no measure of when an occupant was actually at a workstation and consequently identification of waste is predicated on assumed occupancy hours. Therefore, there is no guarantee that energy identified as 'waste' in this study was not actually required by the occupant. This weakness emphasises the benefit that observational data from mixed methods, case study research can provide through linking energy waste directly with an individual or actor. Mulville et al.'s study focused on an office building that has a defined purpose and where occupants can be considered to have predictable requirements of the energy end uses. For multi-use venue buildings, where occupants have changeable requirements of energy end uses, and where the occupants interacting with building controls and end uses are not always the same, it is possible that these estimates of energy waste could be significantly higher. It is also likely that the underlying causes of energy waste are more numerous owing to the multitude of interactions occupants have with these buildings.

Building on the limitations of Mulville et al. (2014), other researchers have attempted to provide a more reliable Identification of energy waste through linking energy data to actual occupancy. Shao et al (2017) carried out mixed methods research using both qualitative and quantitative data to identify energy waste in a university environment. The first stage of the research involved conducting semi-structured interviews with occupants to identify their perceptions of wireless monitoring of their behaviours, their experiences of energy use in their workplace and their preferences on energy use feedback. The next stage involved direct monitoring of individual occupants using wearable sensors (not through the researcher directly observing the occupant in the building), and energy monitoring of end uses to identify their energy behaviours. This enabled the authors to create profiles of occupancy and energy use which could then be considered together to identify instances of energy waste, e.g. where a computer was on but there was no occupancy. A major limitation of this research design is that the occupants, knowing that they are being monitored may not be engaging in their natural behaviours, and so any improvements in their energy behaviour as a result of this study may not have a lasting impact. As with Mulville et al. (2014), without direct observations of what activity the occupant was engaging in, or observations of why certain energy end uses were in use at different times, it is not possible to definitively identify energy as wasteful. An example of this can be seen in the analysis of workstation profiles, where a spike in computer electricity use outside of occupancy hours is not explained and could be useful to the occupant’s needs e.g. installing updates or running a scheduled simulation. A key part of this study was that the researchers attributed energy usage behaviour directly to individuals, with a view to providing specific and tailored feedback to each individual regarding their energy use so that more energy conscious behaviour could be encouraged. The application of this kind of tailored feedback to multi-use venue buildings would be dependent on how those buildings are managed. For example, this type of feedback would be useful to those occupants that interact regularly with the building such as the FM teams or event co-ordinators, but perhaps of less value to clients hiring the space that may only use the building for a short period of time. Therefore, understanding the context of venue building energy use and the different actors involved is crucial to the success of any energy conservation measures that are employed.

In a study by Martani et al. (2012), heating related energy, external air temperature and electricity were monitored alongside occupancy. The number of Wi-Fi connections was used as a proxy for human occupancy. The combined analysis of all of this data enabled the identification of significant energy waste for example some areas of the building were shown to be being heated when they were not actually occupied. Fundamentally this study underlined the importance of monitoring occupancy in buildings, and the impact that this can have on managing building services. Similarly to Budaiwi & Abdou (2013), energy savings opportunities that were discussed involved zoning the building to cluster together occupants during periods of lower occupancy so that only a reduced part of the building required heating. However, the study did not factor in that higher occupancy would mean more occupant related internal heat gains and thus potentially less requirement to heat densely occupied areas. Additionally, with regards to Wi-Fi occupancy monitoring, the purpose of the building is important as some occupants may not use the Wi-Fi whilst in the building. Also, although many people have Wi-Fi on their mobile phones this does not always connect automatically, and requires users to manually connect, which could be a significant period of time after they have entered the building. There could also be restrictions with people who are not regular users of the building connecting to the Wi-Fi. Consequently, this may not be an appropriate method to monitor occupancy for a venue building. Wider techniques to predict occupancy have also been developed that use video monitoring over a two week period to observe the number of occupants in a specific area of a building (Erickson et al. 2009). These observations were then statistically extrapolated over the rest of the year to provide annual occupancy. For venues there are clear limitations in this approach as occupancy is potentially too variable for this to be considered reliable.

Overall, the literature shows that occupants can significantly influence building level energy use, either passively or actively. Passive interaction with building energy use is dependent on occupancy numbers and activity, and thus through the impact that occupant related internal heat gains can have on HVAC energy loads. Active interaction is a more complicated area of research and includes occupants interacting directly with individual end uses such as small power loads and with controls for fixed building services such as lighting. In either situation, both types of occupant interaction have the potential to significantly impact on venue building energy use and must be considered during the course of this research.

2.4 Assessing building energy performance

Lewis (2012, p. xxvii), defines building energy performance as a "*quantification of the energy efficiency or energy consumption of a building, using one or more measurements, metrics or benchmarks*". This definition of building performance is not entirely correct as "energy consumption" is not interchangeable with "energy efficiency". Energy consumption is simply a measure of the energy used by a building, whether that is through combustible fuels or electricity. Measuring and monitoring the amount of energy (e.g. in the form of electricity, oil, gas, diesel, or renewable energy generated on site) that enters a building is reasonably straightforward. For example, grid fuels such as electricity and gas can be metered at the building level and delivered fuels oil, diesel, etc. are measured by the litre.

In contrast, energy efficiency is a measure of the "usefulness" of energy, whereby there is human judgement and values applied to the energy consumed to determine its usefulness in providing a service (Patterson 1996). Patterson (1996) discusses how a clearer definition of energy efficiency would aid development of energy efficiency indicators with particular focus on how they could be used at the macro policy level. Although Patterson’s paper is not specific to the analysis of energy use in buildings, the underlying questions are pertinent to defining what is meant by the energy efficiency of buildings, what is required for the analysis, and what form the output of such analysis should take. Despite the clear limitation in the definition of energy performance, what is important is that it is not enough to simply state energy efficiency, it is vital to place this within the context of its use.

In the UK, the majority of design teams will refer to CIBSE guidance for advice on best practice. CIBSE Guide F covers energy efficiency in buildings and offers the following description:

“An energy efficient building provides the required internal environment and services with minimum energy use in a cost effective and environmentally sensitive manner” (CIBSE 2004) *page 10.*

This interpretation of energy efficiency describes it as something that is not detrimental to occupant comfort or the defined purpose of the building, but a way to meet those prerequisites in the most environmentally friendly and economically feasible manner. For building energy consumption then, the usefulness of energy may be determined by the amount of end use service, e.g. lighting, that it can deliver that is actually of benefit to the occupants in terms of comfort and their ability to carry out their intended tasks. In managing the energy consumed within buildings, it is important then to question the necessity of energy used for different end uses. Consequently, wasted energy may be defined as energy use that does not fulfil a definite purpose, whereby energy is consumed without providing a service relevant to the building’s actual use (Kazmi et al. 2014). As well as the term “building energy performance”, “building environmental performance” is also used in literature in a similar way, though this term is often used when focusing on heating, ventilation, and air-conditioning (HVAC) related energy use in relation to internal environmental conditions (Krausse et al. 2007). This research extends beyond examining HVAC performance and so the term “energy performance” will be used in this thesis.

In investigating the energy performance of venue buildings, with their irregular energy consumption profiles, it is essential to refer back to the basic principles of energy efficiency defined by Patterson (1996). This enables a dedicated assessment of identifying the energy consumption that was truly useful, and therefore what was wasteful. The definition of building energy performance defined by Lewis (2012) necessitates that this energy efficiency quantification is presented within the context of its use. For venue buildings, establishing the context of the building’s use is essential to providing a description of the building’s performance. As mentioned in section 2.3.2, venue energy consumption can be highly erratic and is heavily influenced by the different hosted activities and events within the space. In order to understand why this is the case it is important to identify the causes of the variability between these events, whether that be with the equipment used, the duration of the events, or the differing levels of occupancy, and the impact that all of these variables combined can have on overall energy efficiency. This section details several different methods and techniques for understanding building energy use and the relevance of their application to venue buildings.

2.4.1 Assessing operational performance at the design stage

As can be seen with Part L of the Building Regulations, which aims to reduce building associated carbon emissions, the primary focus is on the design of the building in terms of its construction and fixed services, and not the actual in-use energy consumption. In reality, there are no legislative requirements for new buildings to achieve the anticipated energy performance in operation. However, building owners, clients or planning authorities may on occasion require design teams to make predictions of actual in-use energy consumption, and there is evidence to suggest that operational energy performance targets are becoming more common (CIBSE 2013b). In response to this CIBSE's TM-54: Evaluating operational performance of buildings at the design stage (CIBSE 2013b), provides guidance to design teams where operational energy targets are requested.

The TM-54 guidance document facilitates the assessment of a building's energy consumption in operation through development of a detailed energy model that considers all anticipated installed loads. This differs from energy modelling carried out to demonstrate compliance with Part L as it considers unregulated loads which are not typically considered during compliance energy modelling (Knight et al. 2008). A further difference is that a TM-54 energy model will generally be tested under different scenarios of use, e.g. different occupancy hours, different occupancy densities to reflect possible variable use from the occupants. This can help to designers to identify end uses with high energy consumption and help to guide the efficient use of systems.

As mentioned above, there is increasing interest, particularly from owner-occupiers, about the operational energy of their buildings and CIBSE TM-54 demonstrates that energy performance is not only dependent on how the building is designed and constructed but crucially how it is operated and maintained. It provides guidance for creating robust estimates of in-use energy consumption and highlights in particular the significant impact that operating hours can have on overall energy consumption. However, even this approach for venue buildings is limited as the variability of their use means that energy demand from electrical end uses can differ dramatically between different uses of the building, so predictions at the design stage could still yield significant error.

To overcome the shortcomings of an over reliance on energy modelling discussed above, particularly with regards to venue buildings, and subsequently improve the operational energy efficiency of buildings, it is imperative to have a clearer understanding of what constitutes building energy performance. This is to say that it is essential to ask how, where, and why the energy is used within the building to identify and take advantage of any potential energy saving opportunities.

Building energy performance assessments are useful tools for building managers to identify energy waste and inefficient operation of building systems. For example (Wang et al. 2016) modelled whole building energy consumption down to individual end uses including lighting and plug load power. They produced simulations of energy use at weekly, daily, and hourly temporal scales, and used these to diagnose when the HVAC was operating inefficiently.

However, existing methods for building performance such as benchmarks, and degree days and performance lines have limitations when applied to venue buildings. For example, degree days are calculated using a base temperature. This base temperature is chosen based on two main assumptions; the temperature rise due to internal heat gains and the target temperature of the internal space (CIBSE 2006b; Day et al. 2003). In buildings such as offices, the internal heat gains can be more readily assumed as heat from equipment and occupants can be easily predicted, with the same equipment use and occupancy profiles occurring over very predictable time frames. With venue buildings occupancy and electrical end uses can vary from day to day or even within days. Therefore, it is challenging to identify appropriate base temperatures from which to base this analysis.

It is also assumed with the use of degree-days and performance lines that the heating or cooling demand will follow the external temperature. However, in buildings that are intermittently used, it could be wasteful to heat or cool a building every day that the outside temperature indicates that the internal space should be conditioned, because the space may not always be occupied. Consequently, a more tailored approach to the assessment of the energy performance of venue buildings is necessary.

2.4.2 Benchmarking

A common method of assessing building energy performance is to compare the building's annual energy consumption to the energy consumption of similar buildings. This approach is referred to in the literature as 'benchmarking' (CIBSE 2008). Through benchmarking, the energy consumption of buildings with a similar function and purpose can be contrasted with a view to assessing actual in-use energy performance. This is usually done through providing a measure of the energy use intensity (EUI), being the energy consumed per unit floor area of a building (kWh/m^2) (Chung et al. 2006). The process of benchmarking can highlight whether a building is using substantially more energy than buildings of a similar type and this can be used as the basis of identifying instances of possible energy waste and highlighting the potential for energy efficiency measures to be implemented. Industry benchmarks such as those stated in CIBSE TM-46 (CIBSE 2008), CIBSE Guide F (CIBSE 2004) and ECON-19 (Swedish Energy Agency 2005) can be used to predict the energy consumption of similar buildings and provide standards for other similar buildings to align their consumption to. In this way similar buildings can develop a "best practice" for their energy management; they can examine if they are reaching their energy performance potential and the effect of energy savings measures at a high level can be determined. However, these categories of building types can be very broad and do not always factor in the different activities taking place in these buildings.

Although adjustments can be made to allow for changes in occupancy and regional weather, these benchmarks are still limited in their ability to predict the true energy consumption range for individual buildings. Liddiard et al. (2008) highlights potential shortcomings with the use of energy benchmarks including that they may be comprised of unrepresentative sample sizes, they are reliant on 'snapshot' data for both the assessed building and the base dataset, and, importantly, some models appear to completely ignore occupancy factors, such as occupant density and duration of use. In terms of venue buildings benchmarks are particularly difficult to apply as the use, function and purpose of the building is often continually changing.

As an alternative, (Dooley 2011) offers a metric of Wh/m^2h, where “h” refers to person hours”, on the basis of the following:

“…when considering how effectively and efficiently a building is being used the number of hours per day the building is occupied and how densely the space is populated must be considered” Page 3 (Dooley 2011)

This is a crucial development in trying to measure the human energy needs of a building, something that is ignored when classifying energy use in terms of the floor area of a building. A simple example when factoring in the occupant density is the comparison between a large and small building with the same energy use, the same occupancy and same occupant needs e.g. the same number of computers. On the basis of kWh/m^2, the smaller building with the higher occupant density will appear to be performing worse than the larger building, as per meter squared the energy use is lower. Therefore, the building that arguably has a more efficient floor plan that is conditioning a smaller space for the same number of people will appear to be less energy efficient. The metric derived by Dooley, by incorporating in person hours does not penalise buildings for having a denser floor layout or longer occupancy schedule.

With reference to multi-use venue buildings, incorporating the human element of the building is vital to interpreting their energy profiles and understanding the role of occupants in driving energy demand.

CIBSE’s TM-46 contains a range of benchmarks for a wide variety of different types of buildings (CIBSE 2008). There are three categories in this guide that could apply to multi-use venue buildings as shown in Table 1.

Table 1: Energy benchmarks extracted from CIBSE's TM-46

Building type	Reference hours per year	Maximum allowed hours per year	Electricity benchmark (kWh/m^2)	Fossil fuel consumption benchmark (kWh/m^2)	Source
Public buildings with light usage	2,040	3,672	20	105	TM-46 (CIBSE 2008)
Schools and seasonal public buildings	1,400	3,672	40	150	TM-46 (CIBSE 2008)
Entertainment halls	2,056	5,712	150	420	TM-46 (CIBSE 2008)

If there are multiple venue spaces within a building then it may be possible to develop a patchwork of benchmarks for the different areas for a given moment in time, but this jigsaw is continually shifting in time with as occupants' needs of those spaces changes. Therefore, over a longer period it becomes too onerous to compare the building against others. Additionally, EUI's do not consider the height of the room as the metric is based on floor area. This a fundamental floor in the application of this metric to building energy use. For venue buildings, there is a variety of different types of construction, and especially for some period properties the ceiling height can be much higher than seen in other building types such as homes and offices. Therefore, a metric based on building volumes would potentially be much more appropriate.

In relation to venue buildings, Heathfield & Bottrill (2012) tried to develop benchmarks for performing arts buildings using data from 157 different venues. This study presents a new type of benchmarking metric, whereby instead of utilising typical energy intensity metrics, such as kWh per m^2, for a performing arts venue the benchmark becomes energy use per performance or seating capacity. This is because existing benchmarks are not flexible enough to adequately represent the dynamic nature of a venue building and their intermittently used building services. This approach is of particular relevance to the developing argument as it begins to identify that these buildings have features, in this case changing occupancy, which are not fully dealt with by the existing approach to benchmarking.

While Heathfield & Bottrill's (2012) approach could be considered more relevant to venue buildings, their research does not take into account variation in occupant activity; for example, the different time periods of use, and the range of performance activities. Additionally, the study does not make use of any energy sub-metering to try and identify what gives rise to this energy consumption. Although the proposed benchmark metric has more relevance to venue buildings through the use of seating capacity rather than floor area, the underlying end use of the energy consumption is still not understood in sufficient detail for an energy manager to be able to improve the performance of a building. The following quote from the study responds to this by addressing the need for building specific energy analysis:

"*The most useful benchmark is one that a building develops using its own performance over time. Considering the unique built fabric and functions within performance arts buildings, this is a vital approach that will be recommended as a starting point for all for understanding building energy use efficiency."* (Heathfield & Bottrill 2012, p. 52).

However, to develop a building specific benchmark would require a very large data set providing multiple examples of very similar uses of the building in order to have a comparative understanding of what constitutes good or bad energy performance for each of these, something that as yet does not exist. Nevertheless, this statement is key to this research and is applicable not only to performing arts venues, but to all buildings that are highly dynamic in their nature, that have a changeable use (or function as stated by Heathfield & Bottril 2012), that impacts on their energy use.

2.4.3 Energy auditing

Typically attempts to assess building energy performance for a non-domestic building might start with an energy audit similar to that proposed by CIBSE TM-22 methodology (CIBSE 2006a). This involves a review of all the equipment and plant that is in use within a building (both regulated e.g. heating, ventilation, and air-conditioning (HVAC) and lighting as well as the unregulated loads e.g. small power, servers etc.) and the typical operational hours of each piece of equipment which are then used to create a profile of energy consumption that can be used to identify any energy savings opportunities. Breaking down energy loads to examine the consumption of each end-use is a valuable exercise when considering the cumulative potential savings between them (Cohen et al. 1999). Methods such as CIBSE TM-22 coupled with an understanding of occupancy schedules can identify where small power equipment, are unnecessarily being left on, and can consequently estimate the size of savings where they turned off when not required.

Previous use of CIBSE TM-22 during POEs of buildings has shown that HVAC systems are a common area of confusion for building managers which can result in unnecessary energy consumption (Menezes et al. 2012). This is either because they are incorrectly sized for their purpose, or the current settings (e.g. time schedules, temperature set-points etc.) are inappropriate for the building’s purpose. In terms of operating the HVAC system itself, most large new buildings have a Building Management System (BMS) installed to automatically control the systems based on particular operating parameters, which should in theory provide energy savings compared to manually controlled systems (Tymkow et al. 2013). However, POEs have found that these are not always operating as the facilities manager believes they are, so they could be running for longer periods than actually required leading to large amounts of energy waste (Fadzli Haniff et al. 2013). Some studies have found that buildings are frequently overcooled, especially on the north side of the building (Hong et al. 2014), or heating and cooling schedules are not always reflective of the occupancy of the building. Fundamentally, buildings are conditioned for the needs of the occupants, and these oversimplifications in managing building systems could significantly impact on occupant levels of comfort. CIBSE TM-22 type assessments can also highlight the need for technological improvements e.g. installing heat recovery systems to recover heat from waste gases, or variable speed drives (VSDs) that automatically vary ventilation rates through altering fan speeds, rather than have a constant ventilation rate that does not respond to the requirements for the internal environment. As the method considers all energy end-uses within a building, in addition to HVAC related improvements additional opportunities can be identified associated with other building services, such as lighting, where more intuitive controls or more efficient light bulbs can be suggested (CIBSE 2006a).

Aside from the advantages of measuring end-use energy consumption, several common misconceptions related to building operation can be addressed through the energy auditing processes. The example of the management of server room environmental conditions can be used to illustrate this. Historically these areas of buildings are cooled more than other parts of the building to prevent any damage to the hardware. However, studies have shown that these practices date back to the 1950’s and modern servers can withstand temperatures in excess of 25°C without any detrimental impact on performance (Strutt et al. 2012).

2.4.4 Energy metering & environmental monitoring

Effective metering and monitoring of energy end uses, occupancy, and occupant activity can provide an understanding of where, how, and why energy is used in buildings. With availability of end-use data, monitoring can enable a detailed understanding of building performance and can also identify energy saving opportunities (Wang et al. 2012). The Chartered Institute of Building Services Engineers (CIBSE) recommend that a proactive monitoring and targeting programme can help to reduce energy use by comparing it against historical data and benchmarks (CIBSE 2009a). Multi-use buildings complicate this approach as even with good sub-metered data it can be difficult to compare energy use against historical data when the user’s requirements of the building are changeable. This is exacerbated further for venue buildings as they are often used intermittently, and then for a wide variety of purposes, each with their own demands on the building’s systems and hence energy use. Therefore, the usefulness of historical data can be limited in targeting energy waste and as mentioned previously, existing benchmarks such as those found in CIBSE Guide F are limited in their application and must only be used as guides or indicators, not as replacements to actual collated datasets (CIBSE 2004).

With reference to the performance gap between the anticipated energy consumption of buildings and the actual in-use energy consumption, metering can provide useful information on what the energy end-uses are and consequently what could be done to close this gap. This is through both the inclusion of more end uses on the modelling side and the identification of waste on the building use side (Menezes et al. 2012).

The use of metering to investigate energy consumption for the identification of potential waste and to inform building managers how to operate buildings more efficiently initially seems to be a straightforward process, however buildings both new and old are proving to be notoriously tricky to monitor (Jones 2012). Despite requirements in Part L of the Building Regulations for 90% of regulated end-uses to be sub-metered (HM Government 2010), post occupancy evaluations have revealed poor compliance levels. This is in addition to extensive evidence that installed sub-meters and monitoring systems can be poorly implemented and have consequently failed to meet expectations (Jones 2012). Key issues include the accuracy of the installation, poor commissioning, and the specification of appropriately sized sub-meters. Inadequate labelling is also a major issue, but most important is the identification of a strategy that will provide useful information to improve energy performance. This is all despite the level of guidance available on how to develop and implement sub-metering strategies effectively in widely available literature (CIBSE 2009b; Carbon Trust 2012a).

Even in buildings where metering has been installed correctly, poor data management and analysis by building managers can severely limit the potential of BMS and metering data to aid in identifying and minimising energy waste leading to it being obscured within the energy demand of the building (Painter et al. 2012). With availability of end-use data, measurement based methods such as monitoring can enable a detailed understanding of building performance and can also identify potential energy savings opportunities (Wang et al. 2012). Additionally, by monitoring and analysing parameters such as humidity, temperature, and light levels, it is possible to provide a specific measure of the usefulness of the energy consumption from building services (Wang et al. 2012).

Ahmad et al. (2016) discuss the challenges of choosing, installing, and using a number of different energy and environmental sensors and monitoring techniques. Several dependant factors are highlighted including granularity of data, accuracy, cost and availability of equipment, ease of deployment, and communication protocols. In addition to this review on sensors, the expertise and willingness of the user to examine the data extracted is very important to the conclusions on energy performance that can be drawn from its analysis (Ahmad et al. 2016).

Monitoring and Targeting is a strategy promoted by The Carbon Trust to examine building energy use and to identify areas of potential savings (Carbon Trust 2012b). The underlying principles and methods are echoed in wider guidance on building energy management (CIBSE 2004). The purpose of Monitoring and Targeting is to relate energy consumption to underlying factors such as weather, to develop an improved understanding of how and why energy is being consumed. These underlying factors can be referred to as “drivers” for building energy consumption and can include myriad variables ranging from, for example, external temperature to factory production rates (Li et al. 2014; Hong et al. 2016). Different buildings therefore have different drivers and it is important to compare energy consumption to these factors to identify where energy efficiency measures can be employed without compromising occupant comfort or requirements of the building (Kontokosta 2016). For venue buildings, identifying these drivers is crucial, especially as these are likely to be different for the different events that are hosted.

Figure 6 below shows daily gas consumption (from half-hourly data) for a ‘typical’ office building over the period September 2016 to mid-November 2016 in the form of a heat pattern chart (Vesma, 2018). These charts are useful for understanding the general pattern of operation for a building’s heating system. Blue areas indicate that no gas was consumed and oranges to reds indicate increasing levels of gas consumption. Figure 25 shows that, for this particular office building, the heating system gradually became active in September.

During October, the heating system was on for regular periods each week with heating on from Monday to Friday and heating off on weekends, reflecting the typical occupancy of the office. On Monday mornings it is noticeable that the heating comes on earlier than for other days which is in response to the heating being off on weekends and therefore more energy is required to bring the building up to the required temperature on Monday mornings. This pattern of gas consumption over part of the heating season for an office is typical of office buildings which have space heating time-scheduled to be operational over general (and reoccurring) periods of occupancy.

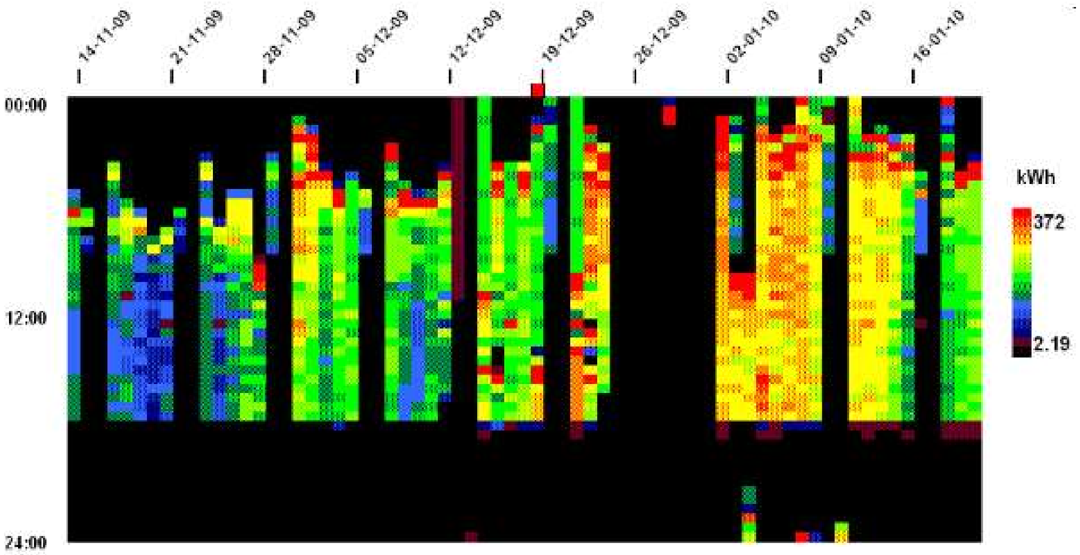

Figure 6 - Example gas consumption pattern plot for a 'typical' office building *(Vesma 2018)*

Conversely, venue buildings have much more varied and irregular occupancy and occupant activity which, as a result, will require more proactive management of the space heating system to provide efficient operation.

To have a more complete analysis of the relationship between venue energy consumption from the HVAC system and the internal environmental conditions in a building, it is pertinent to have an estimate of the heat loads. Understanding the dynamics from changing equipment use and occupancy in terms of internal heat gains and the subsequent implications for energy consumption of building services is imperative in assessing the energy performance of a venue building, as these factors are so variable. Although it is also important to quantify heat loads for non-venue buildings, these types of buildings are unlikely to experience changes in the types of equipment in use as regularly as venue buildings, and so may not influence HVAC management as greatly. By contrast, some venue buildings host events that require the temporary use of large sound or lighting systems. These can have much higher sensible heat loads than equipment typically used in other building types.

Typically HVAC systems controlled by BMS usually have one temperature sensor for each room, but this may not be sufficient due to temperature variations and stratification in venue buildings within large spaces that can sometimes be compartmentalised (Painter et al. 2012). Having additional BMS environmental sensors could enable spaces to have better ventilation management, as then an average could be taken from multiple sensors from which to base the BMS optimisation (Krausse et al. 2007). In terms of building performance, additional sensors would provide more granularity to the environmental data, analysis of which could lead to a more thorough assessment of the impact activities can have on the internal environment and consequently the implications for energy management.

To provide a more thorough analysis of thermal building performance, Hong et al. (2014), use three types of data in the analysis of a case study high performance building; energy use data, operating data of the HVAC system, and internal and external environmental data. The monitored data is used to provide analysis on different temporal scales from annual to hourly. This enabled an understanding of how, where, and why energy was being used which led to the identification of energy waste. An example of this was the observation that energy related to the AHU fans and chillers began operation around five hours earlier than other equipment. It is suggested that this could be avoided by using a different control mechanism. Consequently, this level of analysis can be directly used to identify instances of energy waste and their root causes which can then be used to suggest energy conservation measures which are targeted at a specific system or piece of equipment.

Wider building management research stresses a need to consider energy management beyond a purely technological perspective (e.g. building fabric and services), and to additionally develop energy management strategies that incorporate human actions in the buildings; through both the occupants and the facilities management team (Azar & Menassa 2014; Azar & Menassa 2012). Echoing the need for a more holistic monitoring system, Sharmin et al. (2014) recognise the benefits of expanding traditional monitoring from including energy consumption and temperature and humidity to also including indoor environmental quality indicators. The study anticipates that the additional information on wider factors affecting energy consumption and indoor air quality can be processed within the BMS to improve internal conditions whilst minimising energy consumption. However, the study does not address how this would be accomplished in reality, especially with respect to the reconciliation of conflicting factors for example, increasing ventilation to reduce CO_2 concentrations, and reducing heating demand. Additionally, the study does not show how the BMS could proactively alter the its logic to accommodate the changing needs of the occupants, something which in a multi-use venue building could change significantly with the different activities that they are engaged in.

A study by Gul and Patidar (2015), showed the importance of incorporating wider data types into building monitoring when differentiating between useful and wasted energy in a multi-use academic building that has areas that are intermittently used such as lecture theatres. This was achieved through monitoring occupancy, changes in occupant activity, and energy consumption of a multi-use academic building, in conjunction with qualitative data from semi-structured interviews from key members of staff e.g. the building manager, the control engineer of the whole building and the energy manager of the university where the study took place. These were carried out to support observations found in the quantitative data. The semi-structured interviews were crucial in providing key details that explained energy use such as hours of occupancy in different parts of the building, the use of special high energy equipment during specific periods, and occupant levels of comfort. In adopting this mixed methods approach the study provided essential context to the energy use to develop more informed decisions when identifying energy waste.

2.4.5 Occupants and the identification of actors

As can be seen in section 2.3.4, studies of occupant behaviour will often encompass multiple stakeholders including, for example, the facilities team, energy manager, and the building end users themselves. Distinguishing between these different ‘actors’ is often carried out by researchers but there is little consistency, or indeed much discussion, about how this should be carried out. Where actors are defined there is generally no attempt to ascribe responsibility of energy use or waste to them and instead this exercise is typically carried out as a way of providing standardised inputs for building simulation models. For example Hong et al. (2017); Hong et al. (2015) points out that occupant behaviour is highly diverse, complex and interdisciplinary in nature and that the application of identical energy conservation measures applied across different building types is not sufficiently understood, especially when considering the human elements of these buildings. A notable exception to this was Shao et al. (2017), which was discussed in more detail in section 2.4.5, where tailored energy feedback was provided to individuals that had participated in a direct monitoring study.

Taking a broad perspective of energy use in buildings, D’Oca et al. (2018) identifies a range of key stakeholders who can directly, or indirectly, affect the energy use of a building during its entire life cycle. Of particular relevance to this research is the categorisation of stakeholders by the authors where they draw a clear distinction between building designers, building operators, and occupants. These distinctions are in line with those identified by Baker and Steemers (2000) when describing the different factors that affect building performance. In terms of venue buildings, each of these aspects are important. Building design must allow for the variability of building use, for example through the ability to employ zoning strategies as demonstrated by Budaiwi & Abdou (2013). The building systems and their design and operation must be flexible, adaptive, and intuitive enough for venue buildings that have highly changeable occupancy, with different demands from the occupants. As has been mentioned throughout this review, the occupants themselves can influence venue buildings in several different ways and must be considered at all stages of building energy management.

Identifying the cause of energy waste, and the contribution from each of the different strategies is imperative to the identification and efficacy of a suitable energy conservation measure. A key part of identifying and targeting energy conservation measures, is to ensure that these have a relevant actor assigned to them as building energy management is reliant on the actions and needs of the occupants (Haigh 1982; Lo et al. 2012). By directly targeting occupants and identifying energy behaviours that lead to energy waste, it is possible to induce more energy efficient behaviour change (Shao et al. 2017). Therefore, it would be useful to identify the actors that affect in-use building energy performance and assign waste to them for more focused ECM. This is not currently carried out in Post Occupancy Evaluation, which is discussed in the next section.

2.5 Post occupancy evaluation

From the literature, one of the primary main ways of understanding building energy performance is through the process known as post-occupancy evaluation (POE). POE is described as a systematic process guided by research covering human needs, building performance and facility management (Hadjri & Crozier 2009). It is a process which aims to determine the performance of a building (Bordass, Cohen, et al. 2001) with a particular, and perhaps disproportionate, focus around energy performance.

Post occupancy evaluations have shown that actual in-use energy consumption over a range of building types can be as much as 2.5 times what was calculated at the design stage (CarbonBuzz 2014). As discussed previously this discrepancy could be expected as building designers will generally focus on compliance with Part L of the Building Regulations rather than attempt to make predictions around in-use energy consumption. This lack of attention towards operational performance during the design stages means that projects will often fail to meet client expectations in terms of in-use energy consumption. Once a building is handed over to the client, the project team will typically cease to be involved in the project other than to address minor defects. Consequently, there is a lack of feedback to the project team over energy performance and occupant satisfaction and this in turn can lead to a situation where poor building design, uncontrollable building systems, and inadequate considerations of occupant behaviour are repeated (Bordass & Leaman 2005; Bordass et al. 2004).

2.5.1 The history of post-occupancy evaluation

Post-occupancy evaluations (POE) will generally evaluate the performance of a building with regards to specified criteria; energy consumption and occupant satisfaction being the most prominent. Although the process was included in the Royal Institute of British Architects (RIBA) Plan of Works in the 1960s, it has only relatively recently become more established in the industry with two high profile research studies: PROBE and the TSB BPE Programme (see below). However, despite these industry-wide studies POE is not routinely carried out for building projects. Barriers to its widespread adoption within the construction industry include a lack of clarity and consistency over which stakeholders should incur the costs, and the potentially damaging consequences to a company's reputation that the dissemination of negative findings could bring (Hadjri & Crozier 2009).

Prior to a standardised approach to POE becoming established, Bordass (2003) highlights that large discrepancies between energy performance expectations and outcomes would occur virtually unnoticed. Instead, project teams would focus on producing buildings up until final completion and after handover they would rarely seek to quantify any aspects of their performance.

The term POE originated in the 1950's in evaluation of US Military facilities, mirroring their post-operational review debriefings. By 1963 the Royal Institute of British architects (RIBA) included STAGE M – Feedback in their Plan of Work based on operational research carried out during the Second World War. In today's RIBA Plan of Work, this stage of feedback is incorporated into Stage 7 "In Use", and specifically mentions POE as a key component

(Royal Institute of British Architects 2013). In academic literature, the most seminal work in POE analysed student dormitories at the University of Berkeley in California (Van der Ryn & Silverstein 1967). Later work by Markus et al. (1972) examined the in-use energy performance of a case study school from first principles and developed a representative model of how organisations within buildings operate. Adopting a mixed methods approach, Markus et al. (1972) examined the current design practice, using surveys and taking physical measurements in buildings. This involved investigating the activities of the users, the objectives of the school, the resources for initial building work, and operationally how the building was being managed. This study could therefore determine the influence of the environmental systems on the activities of the users, and how their activities influenced energy use.

2.5.2 Previous post-occupancy evaluation programmes

The first standardised methodology for POE was developed through the PROBE (Post-Occupancy Review of Buildings and their Engineering) studies which took place during the late 1990s and early 2000s (Cohen et al. 1999). The PROBE studies investigated the long-term energy performance of around 23 non-domestic buildings (Cohen et al. 1999). These buildings were chosen specifically as they were considered ‘exemplar’ designs, that is to say that their performance should be at the upper end of what could generally be expected for these building types. This project established a standard methodology for POE which effectively comprised of assessing two main aspects of performance: energy consumption and occupant satisfaction (Bordass, Leaman, et al. 2001). For evaluating energy consumption a CIBSE TM-22 Energy Assessment and Reporting Methodology (CIBSE 2006a) style assessment is suggested. This method involves reconciling actual metered energy consumption (through the main meter or sub-metering if available) with a bottom-up assessment of all significant energy consuming plant and equipment in the building. To provide context to the energy data the studies pioneered the use of occupant satisfaction surveys and developed the Building Use Studies (BUS) occupant satisfaction survey (Leaman & Bordass 2001).

The PROBE studies represented the first time that the performance of a relatively large sample of buildings were systematically studied in a standardised way. The studies provided a large amount of data and enabled the key tools of POE to be developed and refined. The headline finding of the PROBE studies was that energy consumption varied considerably between buildings of a similar type with actual in-use energy consumption regularly around twice the anticipated value (Bordass *et al.*, 2001). This discrepancy between energy performance expectations and outcomes has become widely known at the ‘performance gap’ (Menezes *et al.*, 2012a) which was discussed earlier in this chapter. Bordass *et al.* (2001) cited various reasons for the gap between ‘predicted’ and actual energy consumption. These included poor initial design parameters such as occupancy periods being longer than expected, poor build quality such as thermal bridging, and value engineering for cost savings.

Innovate UK (formerly Technology Strategy Board (TSB)) funded the largest ever POE study in 2011, investing £8m on the performance evaluation studies of around 100 recently constructed domestic and non-domestic buildings across the UK (TSB, 2013). The method for this programme essentially followed that of the PROBE studies with energy consumption assessed through CIBSE TM-22 and occupant satisfaction measured through the BUS survey.

Completing in 2014, the building performance evaluation (BPE) programme provided an even greater amount of data on building performance than the PROBE studies, data which is still be unpicked to this day. Palmer et al 2014 carried out an initial high-level meta-analysis of the data from the programme for over 50 non-domestic high-performance buildings. Importantly, their findings highlighted many of the performance problems that were originally brought to light by the PROBE studies are still major problems today, for example the difficulties in using energy metering to assess building performance (Palmer et al. 2014). This situation does not bode well for the industry as it suggests that one of the key objectives of POEs to provide feedback to design teams is not being adequately realised.

One of the key deliverables of the BPE programme was the analysis of two years of energy use data, however as the programme unfolded it became evident that the metering installed in many of the buildings was insufficient for this purpose (Palmer et al. 2014). The level of metering varied across the buildings, with some buildings not splitting up the end uses into enough detail whereas conversely some buildings had an impractical level of sub-metering providing too much detail. There were numerous examples where metering was not installed correctly, either where meters were not physically connected to the BMS, or where current transformers (CTs) were installed the wrong way round or with the CT ratio incorrectly configured (Palmer et al. 2014). Renewable energy technologies also posed problems for metering as these were not always effectively integrated with the rest of the building monitoring. In the case of PV this could mean that generated electricity could cause meters in the buildings to log negative values (Palmer et al. 2014). It was also noted that there was an overreliance on BMS systems with some buildings managers believing them to be Energy Management Systems (EMS) and expecting them to automate building systems to minimise energy consumption. Further complications with BMS included data being overwritten after seven days without building managers realising that they had to download it for further analysis (Palmer et al. 2014). The BPE programme did not specifically require POEs to monitor environmental conditions such as lux levels, internal temperatures, relative humidity etc. However, studies have highlighted that these measurements can be particularly useful when trying to identify performance problems and instances of energy waste (Palmer et al. 2014).

The BPE programme examined a range of non-domestic buildings including, schools, laboratories, offices, healthcare centres, hotels, and community centres. Of particular relevance to this research are the community centres which were identified as having highly variable occupancy and multiple uses (Technology Strategy Board 2015; Technology Strategy Board 2014). Specifically, one of the BPEs was of Angmering Community Centre in West Sussex which is used for a range of occupant activities including light and sedentary (i.e. painting classes, meetings etc.), to more intensive (i.e. dancing, aerobics and indoor sports etc.) (Technology Strategy Board 2015). The study found that whilst occupants involved in light and sedentary activities were generally satisfied with internal temperatures, occupants involved in the more intensive activities found the spaces to be too warm. In response to these higher temperatures occupants tended to open the windows, even during winter, to provide fresh air and to cool themselves down. The authors report that this could result in energy wastage during winter and they suggest that designing the HVAC strategy with different heating zones would promote better control over the temperatures in each space and could reduce energy waste. This study emphasises that multi-use venue buildings can have varying occupant activities and that this needs to be adequately considered during building design process to prevent performance problems in the completed building.

2.5.3 Post-occupancy evaluation methodology

Figure 7 below shows the activities that are generally covered by the standardised approach to POE which was initially developed during the PROBE studies and further refined during the BPE programme. The red box in Figure 7 highlights the Building Use Studies (BUS) occupant satisfaction survey which is the only direct input into the POE process containing occupant related data. As discussed in section 2.4.5, occupant satisfaction data, and occupant behaviour data more generally, can provide important contextual information to the performance data gathered from other sources. It is argued here that without this contextual data pertaining to the occupants it is in fact not possible to adequately determine whether energy is being used by the occupants to provide the necessary conditions to support their activities or being wasted.

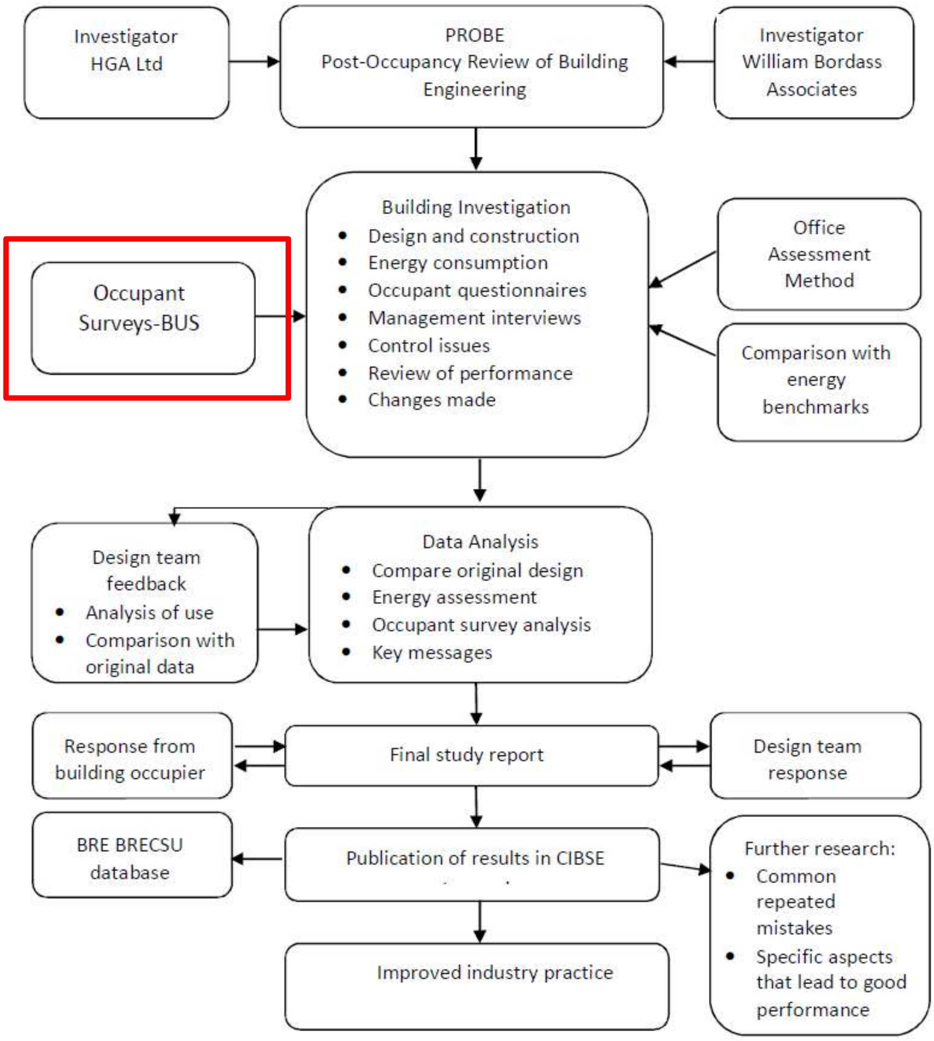

Figure 7: Flow chart diagram showing the stages and key activities during a post-occupancy evaluation adapted from (Cohen et al. 1999)

POE has generally focused on energy performance at a very broad, aggregated scale, which for the purpose of this research project will be termed “macro” scale. Conversely the term “micro” scale will be applied to studies examining building energy performance that consider energy use at the day-by-day or hour-by-hour if not finer resolution, thus examining the finer textures of energy performance. This distinction was alluded to by Haigh, (1982), when examining variation in environmental performance of school buildings.

A key benefit of POE is to identify potential problems leading to energy waste. With this focus on macro scale POE, there is less emphasis on the benefits that micro scale POE can offer. The benefit of doing POE at the micro scale is that different occupants or 'actors' engaged with the building's energy can be identified and the energy waste categorised into different sources and attributed to these actors in order to target energy conservation measures. POE currently only specifically examines occupants through occupant satisfaction surveys and does not monitor their activities or how their various actions can directly impact on energy use at the micro scale. There is evidence to suggest that unless the context of the energy use is fully understood, energy conservation measures can struggle to meet their full potential (Haigh 1982, Lo et al 2012).

2.5.4 Post-occupancy evaluation & occupants

Whilst POEs aim to tackle energy and occupant satisfaction performance problems, the emphasis during the BPE programme (and POEs in general), is on energy performance rather than occupant satisfaction or behaviour. The literature (and the BPE programme) could be considered disproportionately focused on engineering (i.e. quantitative data analysis and technological considerations) methods to identify instances of energy waste. However, arguably analysing energy use without a sufficient understanding of the context that that energy is used within can prove ineffectual. This is emphasised by studies which demonstrate that the effectiveness of technological measures to reduce building energy consumption can be undermined by the actions of the occupants (Hadi & Halfhide 2009; Lo et al. 2012). Alternatively, a case study approach can allow consideration of the context in which energy consumption was used to establish whether it was waste or 'legitimate'. Additionally, a case study enables identification at the micro level of a) the category that the energy waste relates to (i.e. whether it is associated with any of the key aspects of energy performance identified in section 2.4.6 - design, systems, and occupants) and b) the actor that is responsible for the energy waste. These two insights which a case study approach can provide over a traditional POE can be extremely valuable in targeting energy conservation measures and ensuring that the behaviour of the occupants will not reduce their effectiveness (Lo et al. 2012).

In a study by Parnell & Larsen (2005), semi-structured interviews carried out with multiple home owners revealed that if energy efficiency measures are to succeed then the occupant needs to be viewed by experts as part of the solution not part of the problem. The study found that an everyday householder centred approach improved the effectiveness of domestic energy efficiency programmes. Although this study did not look at multi-purpose venue buildings, it highlighted the importance of engaging with the user and familiarising with their needs and drivers for energy use to identify effective energy efficiency measures. In support of these findings, Heiskanen et al. (2013) examined multiple different methods of learning about energy users with a view to identifying the most effective methods that lead to better decision making. Findings from this study showed that ethnographic studies, although very data intensive, can help to identify effective energy efficiency measures that are sensitive to occupant needs. This is to say that the importance of occupants’ everyday routines and shared cultural conventions that shaped their energy use, is central to the researchers understanding of the end-user’s contexts and energy routines, and therefore central to identifying effective energy efficiency measures.

One of the first examples of utilising a case study approach to assess energy performance is from Haigh (1982) who carried out a case study investigation of five primary schools located in Essex almost 30 years ago. The schools were chosen as they provided a range of ages and construction types. The main aim of the longitudinal study was to explore the relationship between the environmental performance of the buildings (or more specifically the classrooms) and the how the teachers and pupils attempted to adjust their internal environment in response to varying conditions. Crucially, to achieve this, Haigh also employed an ethnographic approach, whereby Haigh combined qualitative observational studies with quantitative monitored internal and external temperatures. Observational studies involved Haigh sitting in each classroom and recording the occupants' activities (i.e. whether they were having a maths lessons, or sitting on a carpet listening to a story), occupancy (i.e. whether the classroom was occupied or not), specific behaviours (i.e. window and door opening), and external weather conditions (i.e. sunny, rainy, overcast etc.). In a first of the kind approach, Haigh (1982) monitored both environmental conditions and the responses of the staff and pupils to them.

This study was carried out over 30 years ago and even then, Haigh (1982) highlights that our understanding of how occupants use and control buildings is extremely limited. Rather rectifying this through gathering data from operational buildings, Haigh (1982) commented that designers instead view occupants as problems which interfere with carefully balanced environmental systems, and even blame them for the non-attainment of energy targets. Interestingly, this situation seems not to have improved to this day. Although there are a wide variety of studies emphasising the impact that building users can have on energy consumption (see section 2.4.5) designers will often restrict their ability to control their environments (and hence waste energy) (Janda, 2011) or they believe that interactions between occupants and the building systems is beyond their control (Gill 2012).

Through analysis of her results, Haigh (1982) presented an analysis arguing that air temperature was actually a relatively poor indicator of control use. She found that occupants were tolerant of large swings in air temperature and in light levels. Instead, air flow (i.e. draughts) and direct insolence (i.e. glare) were much more important factors which caused occupants to take behavioural actions to rectify their discomfort.

Interestingly, Haigh (1982) suggested that staff and pupils welcomed, and even actively sought, some variation in environmental condition which helped break up the day and even to seemingly increase concentration, although this was not actually quantitatively assessed. The occupants would also choose different conditions depending on the activity that they were carrying out (e.g. story time, maths class). Changes in response to environmental conditions, while sensible from the occupants' point of view, were often considered to result in high levels of energy waste. For example, overheating in winter as a result of heating systems not responding to radiant heating, were often met by the occupants opening windows without switching off the heating system (something which the teachers did not actually have control of in most cases).

Haigh's study is important as it highlights that even though her data showed that predictions from environmental models were valid on the broad scale they ignored day by day or hour by hour events at the micro-scale which could have a significant impact on environmental performance, for example window and door opening, raising and lowering blinds, and adjusting lighting controls. The study shows the additional value that the context of individual behaviours gathered through observation can have when analysing the environmental performance of buildings. Haigh (1982) suggests a need for control systems with internal logic that can complement the users, but with additional energy goals. This study emphasises the need for different control opportunities for spaces with multiple inhabitants, such as classrooms, offices, and venue buildings.

Although Haigh's method may now seem crude when such sophisticated sensors exist to enable researchers to analyse building environments, her observations were vital to her analysis of the quantitative data. Similarly, Mandel (2010), found that direct observations of occupants was crucial in her analysis of how occupants interacted with library spaces.

As mentioned previously in the discussion on POE, determining occupant satisfaction is an important part of providing context to energy data and for determining possible interventions. Through analysing occupant satisfaction data from 177 (Leaman & Bordass 2007), BUS surveys suggest that occupants tend not to act in anticipation of discomfort, but instead react and take action at points when a ‘crisis of discomfort’ has been reached, a finding that echoes Haigh (1982)’s previous work. They also suggest that individual occupants will have a range of different tolerance thresholds and as such will respond differently to changing conditions.

Data from the PROBE studies Leaman and Bordass (2001) identified lack of perceived control as a key determinant of occupant dissatisfaction. They suggested that occupants are effectively ‘satisfiers’ who may accept conditions that designers and thermal comfort models may suggest are unfavourable as long as they can take control opportunities to relieve this discomfort. They also suggest that occupants can still be satisfied if they do not have local control as long as the facilities team (or whoever is responsible) react quickly when requested to restore comfort once a problem has been reported

A more recent example of utilising a mixed methods approach with POE comes from (Painter et al. 2016). Painter (2016) used objective physical measurements, observational data, and self-reported “experience” data to highlight the benefits of integrating multiple data sources through a case study example of occupant interaction with a novel type of building glazing. Continuous measurements were taken of illuminance levels as well as a log of the use of glazing controls by the occupants. Other data such as self-reported feedback in the form of a diary or interview or observed data in the form of images were taken at 30-minute intervals. Painter linked the data from the various sources in order to identify underlying relationships and to derive a better understanding of the different factors that contribute to occupant experience and behaviour. Although the research did not focus specifically on energy and the identification of energy waste, the mixed methods research employed in this study are applicable to developing an improved understanding of occupant-building interaction and the subsequent parallels in energy research.

In a study by (Kinnane et al. 2013), a Post Occupancy Evaluation was carried out for a public venue building in Dublin. The study looked at a Dublin City Council event space and carried out a Post Occupancy Evaluation (POE). The venue building itself is described as having high energy consumption, with a significant portion of this dedicated to space heating. Despite this, complaints of thermal discomfort are high. The study aims to analyse the space heating strategy of the building and the thermal comfort of the occupants. To do this the study used mixed methods, so collected both quantitative and qualitative data. This included a quantitative study of metered temperature and humidity to assess the indoor thermal conditions within the venue, a quantitative study of metered gas and electricity data to assess the energy performance of the venue, and a qualitative study of occupant perception of the indoor venue environment via an occupancy survey. As the study's primary focus was occupant comfort, the occupant responses to temperature, humidity and air movement were of particular interest to the researchers.

The study found that despite the indoor temperature remaining in the range of 19.8^{o}C to 21.8^{o}C, 48% of the occupants complained of being cold or very cold. The researchers found that this likely to do with the heating strategy of the building and the building form, whereby warm air was not diffused effectively over the occupied areas and was instead stratifying in the two storeys of the open plan building and being extracted before it could mix with the spaces below. To determine this the study also carried out carried out a computation fluid dynamic model, which supported the findings from the survey. This study by Kinnane et al is of particular interest to this thesis as it not only investigates a venue building, but it also outline the need to interrogate multiple different type of data in order to determine the performance of the building. Despite defining that the venue building was a challenging environment to analyse, the study did not investigate the impact of these different events and the varying activities of the occupants on their levels of comfort and the internal environment. Consequently, findings from the study suggest that changes are being made to how the building is being heated as a result of the research, but it does not say if these strategies are being proactively tailored to the changing needs of the occupants.

The POE's discussed in this section demonstrate that occupancy and energy use are closely linked. Each of them was carried out with a focus on understanding the impact of occupants and their activities on energy use and identifying how useful or wasteful energy consumption was. In particular, Haigh (1982) produced micro-scale observations of occupant activities and their interactions with controls to demonstrate the variability of occupant behaviour in the same space and the impact this could have on energy use. For venue buildings with such variation in occupant activity it would be valuable to adopt Haigh's approach to monitoring occupants in order to identify their impact on energy use in these buildings, and to provide key context in differentiating between useful and wasted energy.

2.6 Identifying the gap in literature

Existing and common analysis tools for building energy performance have a limited application when applied to multi-use venue buildings. Compounding this, there is limited available literature that examines multi-use venue buildings as case studies. Where these studies have been attempted there is little success in accurately identifying energy waste, subsequent energy savings opportunities and appropriate energy conservation measures.

Existing studies using Post Occupancy Evaluation (POE) on multi-use venue buildings are lacking in the detailed analysis of building energy. This is especially true when considering the potential impacts on energy use from the different uses of the building. Instead, POE's examining venue buildings have examined energy but not the internal environment (Zagar et al. 2015), others use mixed methods but don't drill down into the detail of individual events and their needs from building services.

As seen through Patterson (1996), energy consumption does not necessarily equate to energy performance. This is because presenting consumption alone, as is repeatedly done through macro methods of energy performance analysis such as benchmarking that present consumption per m^2 to generate an energy use intensity (EUI) metric, does not provide any judgement on the energy efficiency of the building (Chung et al. 2006; Technology Strategy Board 2015; Dooley 2011). That is to say that the useful energy consumption for a building has not been adequately distinguished from the wasteful energy consumption, and also that the human element of building energy use has been ignored (Dooley 2011).

The aim of this research is to investigate the relationship between occupant activity and energy performance of a multi-use venue building. From the literature it is apparent that to achieve this it is vital to have both a measure of energy consumption and how useful that energy consumption was. Vital to this judgement is the reason that the building exists – to meet the needs of its occupants. The needs of the occupants therefore need to be identified in assessing the usefulness of the energy used by a building and not reduced a to overly simplified engineering principles such as that devised by Fanger (1970) when trying to predict define occupant levels of comfort.

In order to do this, analysis of multiple sources of both qualitative and quantitative data that is sensitive to the needs of the occupants as carried out by (Painter et al. 2016; Haigh 1982; Kinnane et al. 2013), will be essential to examining these buildings and identifying energy waste. Identifying energy waste is important because it would allow facilities/energy managers to identify appropriate and effective energy conservations measures to improve energy efficiencies. Although new methods may not have been developed in this research, the overarching use of both qualitative and quantitative methods to identify energy savings for different uses of a multi-use venue building has not been found in the review of literature.

2.7 Summary

This review of the literature investigated the current body of knowledge surrounding building energy performance with a specific focus on multi-use venue buildings. Through interrogation of industry literature, it was found that venue buildings could account for significant CO_2 emissions and that subsequently addressing the energy use of these buildings could lead to potentially significant CO_2 savings. Despite these potentially substantial savings, it was found that these buildings are underrepresented in literature with the majority of research in this sector instead focusing on buildings with a more fixed and consistent use, such as offices.

The three main factors affecting building performance were identified as building design, building systems, and building occupants (through both passive and active interactions). Additionally, it was identified that there are different stakeholders who can affect the energy consumption of a building during its life cycle. With reference to this research the main stakeholders (or actors) were identified as building designers, building operators, and occupants. An opportunity was found that by categorising energy waste into different categories and by assigning energy waste to different actors there is potential to improve the energy management of the building as well as the efficacy of identified energy conservations measures.

Through examining the multitude of existing tools and methods available to analyse building energy performance, it was found that these have a limited application when investigating multi-use venue buildings. The main reason for this is that these methods cannot sufficiently account for the variability of multi-use venue building energy use. Integral to this dilemma is the need to adopt a more mixed methods approach in building performance analysis that can account for the complexity of occupant-building interaction that is continually shifting on a temporal scale.

The review investigated the use of post occupancy evaluation as a useful tool to examine in-use energy performance. However, the focus of this tool tends to be at a macro level of analysis, and as such does not consider the finer more detailed intricacies of building energy efficiencies at a micro level. Applying a mixed methods approach to a micro scale analysis of buildings, which crucially included key contextual information surrounding the activities of occupants, was identified as valuable approach in identifying instances of energy waste for buildings such as multi-use venue buildings.

Chapter 3

Methods and Research Design

3.1 Introduction

Chapter 2, the Literature Review, critiqued existing literature on building energy performance, with a specific focus on multi-use venue buildings. It also found that through mixed methods post occupancy evaluation it is possible to identify effective energy efficiency measures that do not compromise on occupant comfort or their requirements of a building. Fundamentally, the chapter found no examples in the literature where mixed methods were effectively used in a multi-use venue setting to analyse the energy performance of multiple different event types and the impact these have on building energy performance. This chapter outlines a method that builds on those identified in literature with a view to answering the aim of this research: To investigate the relationship between occupant activity and energy performance of a multi-use venue building.

This chapter initially explores research philosophy and theoretical approaches to research, presenting a robust argument for the methods chosen to address the research problem. It then moves on to describe the method that has been developed to achieve:

Objectives 1: *to demonstrate the applicability of standard methods of identifying building energy performance when applied to buildings with a high diversity factor*, and

Objective 2: *to* identify *energy waste and potential energy saving opportunities for a multi-use venue building* of this research.

These methods are based on findings from the literature review in chapter 2, and from pilot investigations carried out in a case study multi-use venue building, which forms the focus of this research.

The chapter describes the methods applied to investigating the energy efficiencies of 13 different events hosted in the case study building that are each investigated as separate case studies. As the research adopts a mixed methods approach, both the qualitative and quantitative methods employed are described in detail with relevant analysis of different equipment used. The last section of this chapter details how identified energy efficiencies of different events are analysed in conjunction with the different actors that engage with the case study building, in order to recommend suitable and appropriately targeted energy conservation measures as required for completion of objective 3: *to provide recommendations for energy management and design of controls that are generalisable to buildings with a high diversity factor*.

3.2 Research philosophy & approach

Identifying appropriate research methods is essential in addressing the objectives outlined in chapter 1. To explore relevant methods, it is important to consider the wider approaches and strategies in research to ensure that those selected are appropriate to answer the research questions. One example of how to represent the components of research as a whole is presented in Figure 8, the “research onion” (Saunders et al. 2009). Although this representation is not the only framework of research available, it does provide a general overview of research that would enable the researcher to place the following arguments of the thesis into a wider context. Wider examples of research frameworks will not be discussed as a comprehensive critique of the extensive literature in research philosophies is beyond the scope of this chapter.

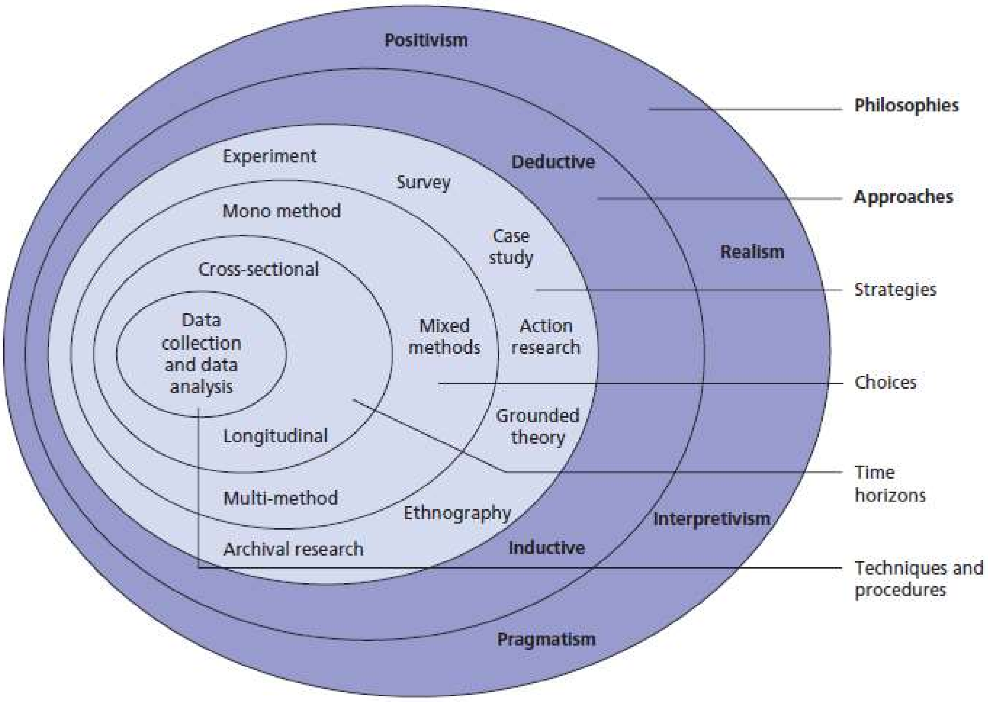

Figure 8 - The "research onion" ***(Saunders et al. 2009)***

Whilst open to critique, the overarching the research philosophies identified in Figure 8 are the positions of ontology (the study of what exists and what is real), axiology (the study of value), and epistemology (the study of knowledge and understanding). It is important to note that this research does not aim to choose between ontology, axiology or epistemology, especially as it intends to investigate the relationship between the physical (ontological) and the human understanding (epistemological), including their expectations and interactions, of these types of buildings. Chapter 2 detailed the need to distinguish between what energy was useful and what energy was wasteful in determining the energy efficiency and thus energy performance of a building. The researcher's valuation (axiology) is therefore crucial in interpreting the data to place a value on what is identified as useful or wasteful energy. Referring back to Figure 8, this research would adopt the philosophy of pragmatism whereby the position embraced is dependent on the question being asked (Creswell 2009).

As such, adopting a pragmatist view point lends the research naturally towards mixed methods, using both quantitative and qualitative methods (Creswell 2009; Robson 2011).

The overall approach of this research does not rigidly define between the deductive and inductive as shown in Figure 8. Although the research has a clear set of objectives to achieve the research aim, which potentially implies a more deductive approach with a defined and rigid set of methods, in order to identify appropriate techniques and procedures and time frames for the research, a more inductive approach is used. This means that data is interpreted as it was collected to help develop an understanding of what should be explored in greater detail.

With reference to objective 2: *identify energy waste and potential energy saving opportunities for a multi-use venue building*, a case study strategy is used in this research. This involves the empirical investigation of energy use within the real-life context of a multi-use venue building. As with the research of Painter et al. (2016), described in chapter 2, this requires multiple data sources to facilitate an investigation of the case study from different perspectives in order to develop a more holistic understanding of the underlying relationships. As such, case study research covers a range of research methods and techniques, to collect a variety of different types of data covering differing lengths and levels of detail to investigate a phenomenon (Amaratunga et al. 2002). The case study strategy in this research is two-fold, whereby not only is a building chosen as a case study, but also individual events held in the building are studied as individual case studies.

The case study building is studied as a whole for objective 1 to demonstrate the need to examine the building at a finer level of granularity in order to understand the energy use and hence identify waste. The individual events studied for objective 2 are examples of its different uses that are analysed to both demonstrate the variability of building use and the variety of different energy waste sources. These individual events are not directly compared against one another because each of the different events have unique demands of the building; instead their individual energy use is analysed within their unique context to have a greater understanding of why and how the energy was used and therefore what energy savings could be identified for each of them. However, findings from the analysis of some of the events could inform the analysis for other events, an example of which is the time the building took to reach the target temperature with different external temperatures.

As argued through chapter 2, in order to investigate the energy use in a building that has a highly changeable use, it is necessary to analyse a wider variety of data in order to have a more holistic understanding of why that energy is being used and potentially where savings could be achieved. To provide sufficient context to the energy use, it is therefore necessary to analyse both quantitative and qualitative data. Referring back to Figure 8, this is termed “mixed methods”. Specifically, in this research, analysis of both quantitative and qualitative data is converged to provide a comprehensive analysis of the research problem. Mixed methods are useful for this research because the use of both quantitative and qualitative methods aids the interpretation of the data and provides generality through the use of one source of data contextualising other source of data (Creswell 2009; Painter et al. 2016). Most importantly the use of mixed methods enables triangulation of the data, where multiple independent sources of data corroborate the research findings, through convergence of the data to answer the research problem. In the context of building energy use, mixed methods can provide an effective means of providing essential qualitative context (e.g. why energy was used) to quantitative data (e.g. how much energy was used), in order to have a better understanding of overall building performance.

Moving towards the centre of Figure 8, this research will use both longitudinal and cross-sectional data. Initially, longitudinal data covering at least one year will be used to contribute to achieving objective 1 of this research. Cross-sectional data will be used to address objective 2 of the research, covering one day per individual event as a case study as mentioned above. The remainder of this chapter details the most central layer of Saunders' "research onion", Data collection and data analysis. Each method of data collection is described, and the techniques used to analyse said data are outlined.

3.3 The case study building

The case study building is a concert hall and a Grade II listed building situated on the University of Reading's London Road campus in the UK. The large auditorium area is used for a multitude of events including concerts, lectures, examinations, exhibitions, and ceremonies. It is used intermittently throughout the year and the frequency and intensity of its use varies seasonally. Each event can have different requirements of the space (in terms small power equipment, lighting schemes, occupant numbers, duration etc.), and can therefore place different demands on the building services.

The day to day running of the building is managed by a team of porter's who also manage all other buildings on this campus. Their role is to ensure that buildings are secure when empty, to provide support to clients hiring the space in terms of access, arranging the hall in the right configuration for their events, and demonstrating how to use the lighting controls.

The Events team are the main point of contact for clients hiring the space. For large events and for events where new clients are using the space the events team are often present in the hall to facilitate the client where needed e.g. to introduce them to the different areas of the building and lighting system. For smaller events and when the Events team are not present in the building, the Clients are left to manage and use the building as they see fit after a brief introduction to the lighting controls by the Porter. The client then primarily contacts the Porter if they require assistance e.g. further guidance on how to use the lighting controls or queries related to access.

The BMS manager is located at a separate campus but is responsible for the day to day heating scheduling of the building. Heating requirements are communicated through the Events team via a calendar of event bookings. The BMS manager does not actively visit the building for the purposes of energy management and only intermittently monitors building energy use. He is responsible for managing BMS systems of buildings across campus.

The Estates team are the furthest removed from the day to day running of the building and mainly engage with it in terms of wider University energy billing and reporting. Some analysis of building related energy is carried out but this is high level and inclusive of other buildings on campus.

Figure 9: The interior of the case study venue building

3.3.1 Construction

The venue building was opened in 1905 and is brick built with 19 large single glazed sash windows, a barrel-vaulted ceiling running along the centre of the hall, and an externally pitched roof. The main hall in the building shown in Figure 9 measures approximately 35.0m by 14.6m, with a maximum ceiling height of 10.3m. Since its construction, an extension has been built to accommodate changing rooms and toilets, though the main auditorium remains unchanged. No original drawings of the buildings have been found by the researcher, however detailed drawings from surveys and of the construction of the extension exist that were used by the researcher to understand the building's construction and to verify their measurements of building dimensions. Floor plans and sections of the building are provided in Appendix A. To interpret the construction, the researcher sought expert advice from an architect who advised on the most likely construction materials of a building this size and age. It was advised that the masonry construction most likely consisted of solid brickwork with no cavity. The level of insulation in the roof is not known, however previous investigation (see Figure 10) in this area by contractors has indicated that this is minimal.

Figure 10: Photograph of the interior of the roof void in the Great Hall from previous audit work by contractors showing no obvious insulation

3.3.2 Heating ventilation & air-conditioning

The building is naturally ventilated, however, none of the 19 windows can be opened. Occupants increase the fresh air rate through opening the external double doors to the rear of the hall indicated in Figure 11. The building is primarily heated through two natural gas-fired boilers located in the basement plant room, each with a maximum heat output of 115kW$_{th}$. The load factor of the boiler is unknown. The boilers operate concurrently rather than in duty/ standby configuration and supply heat to the space through local radiators via one variable temperature (VT) low temperature hot water circuit (LTHW). Accordingly, space heating for the building is not controlled zonally. Radiators serving the main hall do not have temperature regulating valves and are concealed behind wooden panelling. In other areas of the building such as the changing rooms, radiators are fitted with thermostatic radiator valves (TRVs) which have been set to varying levels of heat output. These TRV’s can be operated by anyone using these areas of the building. Natural gas is only used for heating as hot water is provided through electric water heaters. The heating system is controlled through a building management system (BMS). The heating set point for the building is 20^{o}C, with the BMS responding to the lowest temperature detected from environmental sensors placed around the building. Because the heating system’s LTHW circuit operates based on the lowest temperature in the building and is not zonally controlled, operation of the manually controlled TRV’s is crucial to the risk of these areas overheating whilst other areas of the building such as the main hall struggle to reach the set point temperature. Additionally, the BMS sensors are not positioned at the standard height of 1.5m in the main auditorium area and are instead positioned at least 2.5m from the finished floor level. The heating operates based upon the assumption that the building is occupied from 9am to 5pm and the heating schedule is manually changed through the BMS to heat any events that fall outside of these hours. To allow for the building to reach temperature the BMS has a self-learning optimiser that factors in internal and external temperatures and increases pre-heat times from a programmed minimum. Through analysis of the BMS code provided by the BMS manager and through pilot analysis of heating use and temperatures, the following governing logics were identified:

- Logic 1 – if the temperature is below 0ºC at midnight on an event day then the heating comes on at midnight
- Logic 2 – the design of the heating controls system / BMS optimiser are programmed to bring heating on for 4 hours prior to occupancy in November and 5 hours prior to occupancy in December, with adjustments to this preheat time calculated based on internal and external temperatures and the desired temperature set point. The key point here is that based on the design assumptions regarding external temperatures, in most situations the design pre-heat time of 4-5 hours for these months should be sufficient.

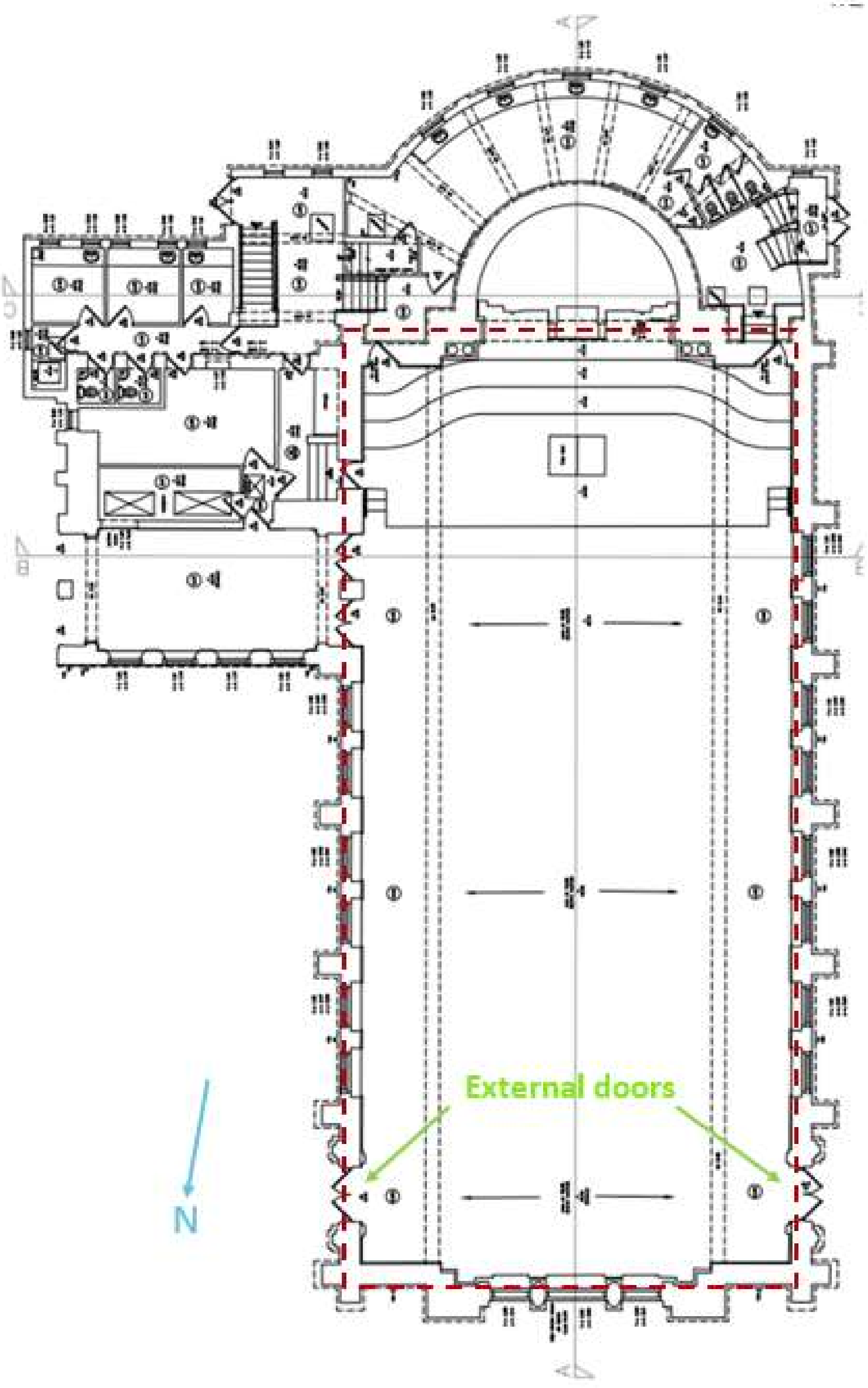

Figure 11 - Layout of the ground floor of the Great Hall showing the main hall outlined in red and the location of external doors used for additional ventilation and access.

There are 5kW$_e$ air-conditioning (AC) units, the condenser units for which are located in the basement, which supply cooling to the main hall through low level vents on the stage. The cooling duty (kW$_{th}$) of these systems is unknown. The AC units are not controlled through the BMS and are instead manually operated by the porters on request by the building user who are not always present during events, as their role also concerns wider buildings on campus. The events monitored for this research did not use these cooling units and so their energy use was not investigated.

3.3.3 Electricity

Artificial lighting is the main permanent electrical end use in the main hall and is supplied through a variety of fittings. These are listed in Table 2 and their locations are also indicated on Figure 12. Lighting is controlled through manual switches. There are no passive infra-red (PIR) sensors to control lighting based on occupancy in any part of the building. The large windows allow natural light into the space and light fittings do not have any daylight dimming or manual dimming capability.

Table 2: Light fittings in the main hall

Lighting fixture	Bulb type	Number of bulbs	Installed load per unit (kW)	Total installed load (kW)
Chandeliers & wall lights	CFL 11W	98	0.011	1.08
Fluorescent strips in cove	T5 80W	18	0.080	1.44
Floodlights	MH 400W	8	0.400	3.20
Stage spotlights	Hal 150W	8	0.150	1.20

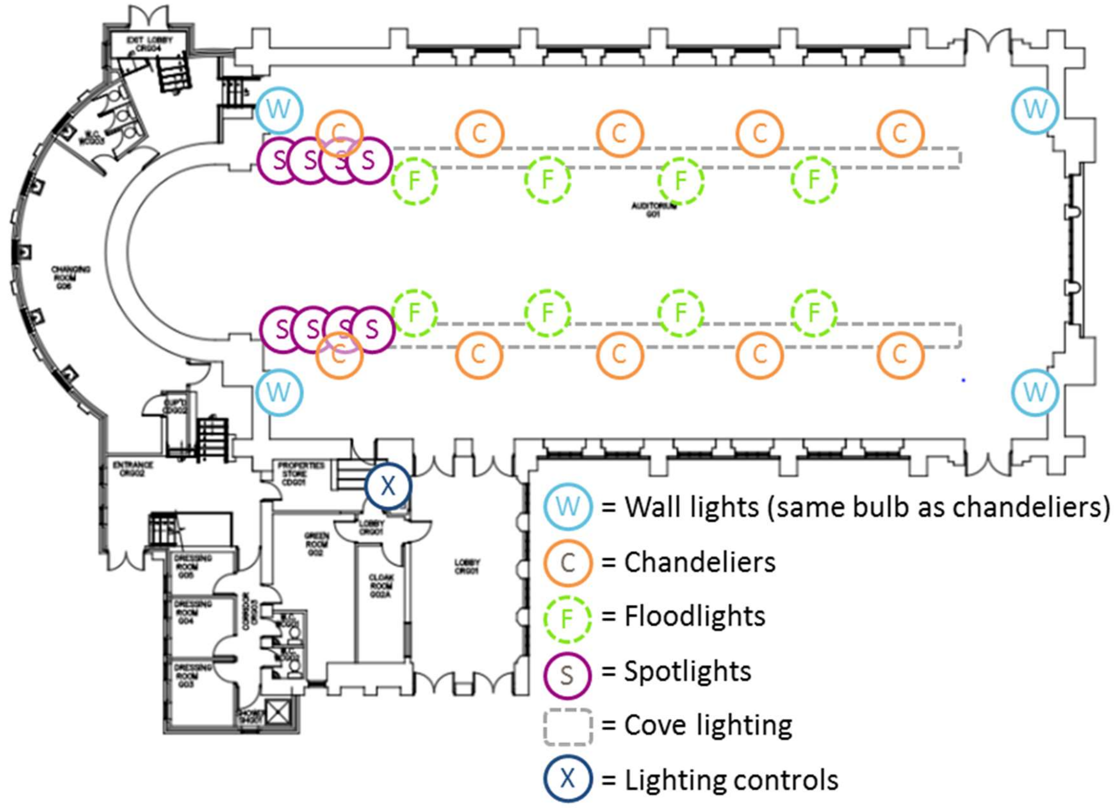

Figure 12: Layout of ground floor showing locations of the main types of lighting and lighting controls.

The main hall has some permanently installed small power equipment such as fire alarm and security systems, wireless routers, and a small audio visual system. However, during events it is typical for small power equipment to be introduced to the space by the event organisers for a variety of uses e.g. additional audio equipment, fridges, and additional lighting. Further electrical end-uses are found in the rest of the building such as a humidifier for the organ and electrical point-of-use hot water heaters for hand washing facilities. A list of energy end uses that are permanently in the building and have been identified through an energy audit process can be found in Appendix B.

3.3.4 Energy metering

The building has a metered gas supply, shown in purple on Figure 13, that is only used to supply the two gas-fired boilers. Data for the gas meter is stored on the BMS and is available at half hourly resolution. As of August 2016, the main electrical incomer to the building, shown in red on Figure 13, has been separately metered and is able to provide five-minutely data at building level. There is no separate sub-metering for any of the building's electrical end-uses. Electricity and gas consumption data is stored on the BMS and continuously logged by the energy management team at the University.

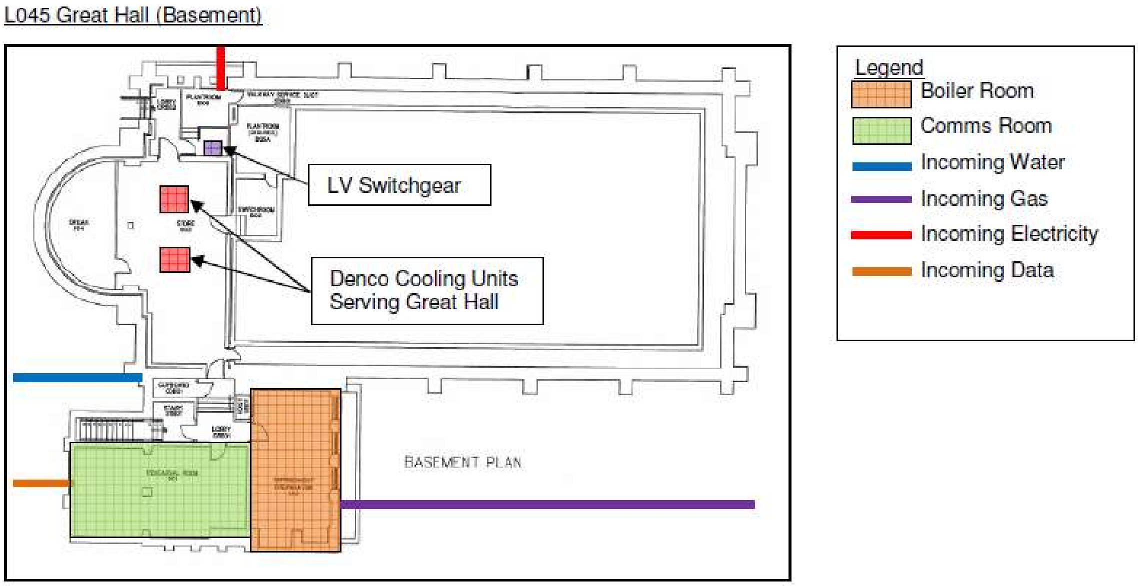

Figure 13 - Plan of the basement level of the case study building showing the supply of services

3.3.5 Occupancy & activity

Occupancy and occupant activity for the building is highly variable and event specific. Outside of the hours that it is used for events the building is unoccupied. The maximum seated capacity is approximately 600 people, however for some events this can be lower depending on the set up of the room. Levels of activity by the occupants can also vary. Some events such as dances can have very high levels of occupant activity whereas other events, such as concerts or lectures, can have more sedentary occupants. The impact on internal heat gains from occupants and requirements for additional ventilation is consequently event specific. Lighting and small power requirements also vary between different event types and are dependent on client requirements. Some events, although appearing to serve that same purpose can have very different lighting and small power demands, for example, concerts can either have lots of small power equipment in the form of audio equipment, or can have no small power as instruments are acoustic. Therefore, it is important to analyse drivers for energy use for each separate event.

3.4 Sensing & data collection

Chapter 2 presented a critique of literature and identified the need for a more holistic understanding of the different factors impacting building energy performance. Integral to this is a better grasp on the impact occupants have on energy use and a more appropriate judgement on the energy that is useful or wasteful for their needs. Chapter 2 also identified the need to utilise multiple data sources, both quantitative and qualitative, when identifying the building energy performance of multi-use venue type buildings, rather than a wholly engineering based approach. An argument was developed through the critique of literature, that multi-use venue buildings are an extreme example of buildings with flexible use, and that current tools and methods of building performance analysis are limited in their application for these types of buildings. Therefore, a method of monitoring and analysis was required to identify the energy efficiencies of these kinds of buildings.

Fundamental to the process of assessing building energy performance is monitoring and targeting (Carbon Trust 2012b). Monitoring and targeting (M&T) refers to the process of collecting energy data through either fixed or temporary metering, analysing this data, and establishing appropriate targets for energy reduction through the implementation of energy conservation measures (Carbon Trust 2012b). Clearly, M&T does not save energy or cut costs unless the information is acted on; for that to happen effectively, systems such as those described earlier must be in place. It does, however, introduce systematic procedures for the long-term ‘tracking’ of energy use and identification of areas for improvement. This is achieved by establishing current consumption and comparing it with historical data and benchmarks for similar users. As a result, future targets can be set and ongoing performance can be compared against them. It also allows identification of trends in consumption and areas for improvement by providing information for energy management action. Once a monitoring system is in place it can alert users to irregular patterns of consumption, which may be due to a planned change in activity or to other issues with the building usage or plant (BRE, 2012).

Automatic meter reading (AMR) is an important tool for this, as when implemented correctly, it can provide half hourly or higher resolution data over a period of time allow trends in consumption to be identified (Jones 2012). High resolution data can be used to analyse demand patterns and assess energy performance over multiple time frames e.g. daily, weekly monthly or seasonal patterns. A viable metering system is essential for this as problems with these can impede the ability of building managers to understand these patterns in energy demand and therefore manage their buildings efficiently. Once an operative metering system is installed, it can prove useful in not only identifying avoidable energy waste, for example through fault detection, but also in quantifying the efficacy of employed savings measures, providing real-time feedback on energy consumption for building users, and informing performance targets (Carbon Trust 2012b).

As stated in section 3.2, this research utilises mixed methods, whereby both quantitative and qualitative methods are used. The different methods employed in this research are outline in Table 3.

Table 3- Qualitative and quantitative methods used in this research

Qualitative methods	Quantitative methods
Semi-structured interviews	Energy auditing
Observations of occupant behaviour	Energy monitoring
	Environmental monitoring
	Observation and quantification of occupant activity level

Echoing the research design of Painter et al. (2016) and Haigh (1982), using both quantitative and qualitative data would allow some data to be collected and analysed in order to understand a measurable and objective reality alongside data that are understood to be subjective and contextually dependent (Creswell 2009). This context is crucial to understanding why energy is used differently between the different events monitored, and essential in the ability to identify energy waste from the quantitative data. As mentioned in section 3.3, this research uses both longitudinal and cross-sectional data to examine the building's energy use. The main types of data and the time frames over which they were collected are shown in Figure 14. To partially address objective 1 of this research, longitudinal data in the form of gas and electricity consumption, and weather data that are typically used in standard building energy performance methods, was used to illustrate the complexities of applying these techniques to the case study building. In particular, the energy use data was used to demonstrate the highly changeable energy demand of the building, the need to examine this at a higher level of granularity, and the need for additional data to provide valuable insight into what gave rise to such a changeable energy use profile.

Specifically, as well as visualising energy consumption data to identify its variability, degree day analysis was used to investigate building gas consumption.

Thus this, as well as the findings from the literature review, demonstrated the need for objective 2, whereby a number of cross-sectional studies of multiple building uses were conducted in order to understand the energy needs of each of these events, thus distinguishing between useful and wasteful energy.

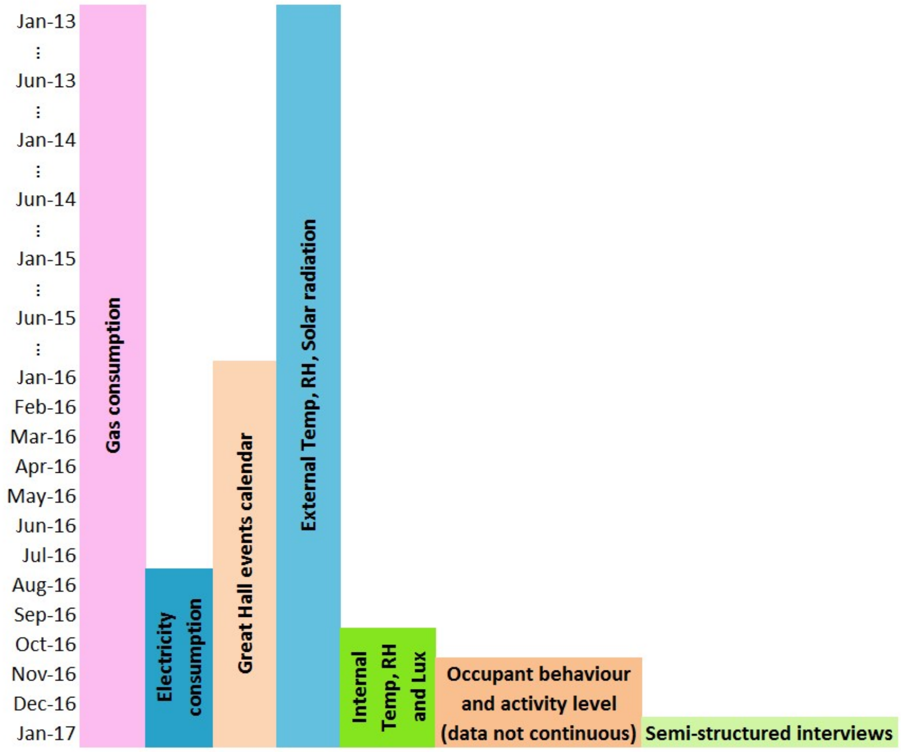

Figure 14: Data time horizons

These cross-sectional studies examined discrete events in the building's calendar to understand how the different events and occupant activity influenced the internal environment and energy use, and what energy waste could be identified. The cross-sectional data covers the period from November 2016 to January 2017. In terms of what is classified as an event in this research, this refers to the whole 24-hour day in which an event was held, and this 24-hour period is presented in the monitoring and analysis for each event. Each event was treated as a separate case study. In total, thirteen individual events were monitored. In line with the philosophy of pragmatism employed in this research, in order to refine the monitoring techniques and ensure that sufficient data were collected at the right resolution, a number of events were monitored as pilot studies prior to the monitoring of the thirteen events presented in this thesis.

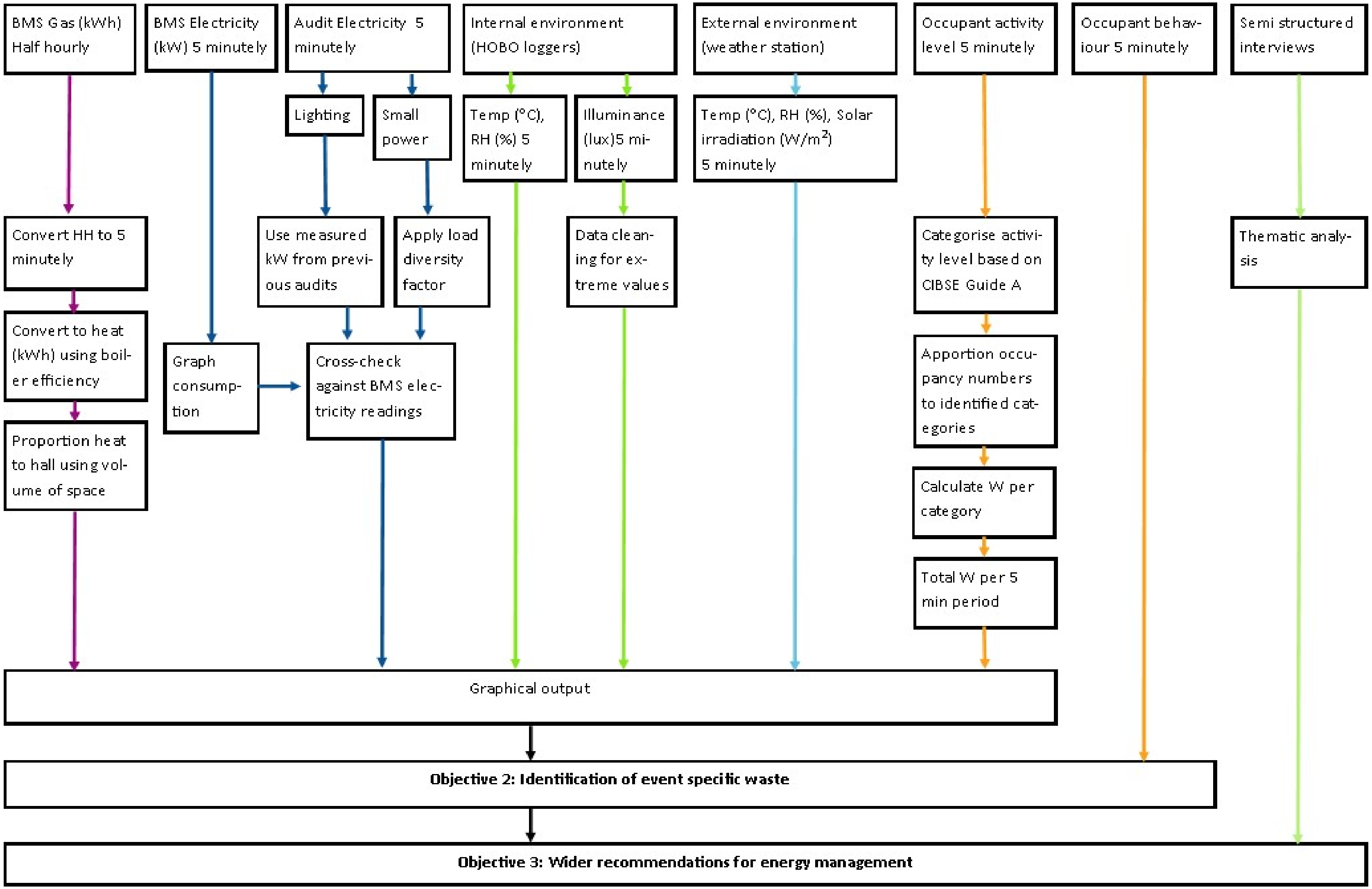

Figure 15: Data pathways for individual data streams collected for the cross sectional studies, showing data collection, data processing and route to achieving Objectives 2 and 3.

The monitoring programme focused on the heating season, which was also the busiest time of year for the building with the most variety of event types being held. Therefore, this was an intense period of monitoring that could enable the researcher to examine the impact of multiple events on the energy use of the building within the same season. The focus of the monitoring presented was in the main hall (outlined in Figure 11) of the building. Figure 15 details the collection and processing of different data streams relevant to accomplishing objective 2 and how they feed into objective 3. In addition to metered energy data and environmental conditions, direct observations of occupant activity levels and behaviour were used to provide essential context to the analysis. This approach echoes that by Painter et al. (2016); Haigh (1982), where observation of occupant activity was crucial to their interpretation of the data.

In terms of occupied hours for each event, this was taken as the hours from when any occupant(s) arrived to the hall and engaged in tasks relevant to hosting the main event for an audience later that day, to when the hall was vacated and no longer in use. In order to have an accurate record of building activity and the timings that electrical end uses, such as lighting and small power were used, the researcher ensured that they were the first occupant of the building on each monitored event day. It was ensured as far as possible that the researcher had a good line of sight to all entry and exit points to the building to monitor occupancy, and also knowledge of lighting and small power use in other areas of the building. This necessitated the need to walk around the building at specific times during an event e.g. an intermission during a concert. At other times it was possible to sit at the back of the hall and observe the event as backstage areas were unoccupied e.g. during a concert performance. The direct monitoring of occupants and their interactions with the building is based on monitoring carried out by Haigh (1982), which is described in Chapter 2.

3.5 Qualitative methods

3.5.1 Semi-structured interviews

Semi-structured interviews have been extensively used in building performance analysis research in order to provide essential wider context to the way in which buildings are used (Hargreaves 2011; Shao et al. 2017; Painter et al. 2016; Pegg 2007; Gul & Patidar 2015). To follow the research applications that these authors have used, and to inform understanding of the different uses and users of the case study building, and how it is maintained, semi-structured interviews were carried out with four key groups that regularly interact with or have a key interest in the building. These included a member of the Estates department's energy team, a BMS manager, two members of the Events department, and a Building Attendant.

Questions were tailored towards the roles of each interviewee and their individual interactions with the building, with a view to providing context to the quantitative data collected and also to aid decision making around any potential energy conservation measures suggested as an output from this research. In addition to this, the interviews also helped to verify observations of how the building was used and managed. However, as the interviews were intended to explore the different worldviews of the interviewees, the responses were used with caution. Examples of the types of questions asked are found in Appendix C.

Each interview was recorded and then transcribed by a transcription agency employed by The University of Reading. These transcriptions as well as the original audio recordings were analysed using thematic analysis, whereby common patterns in responses were identified as well as a broad overview of each interviewee's opinions towards the building and their interactions with it. Direct quotes were also used to inform the researcher how the building was used and managed. The output of this aided interpretation of the direct monitoring and contributed to the recommendations provided to attain objective 3 of this research.

The responses were not analysed statistically as this was not important to the aims and objectives of the research. Instead, the key actors interviewed provided context and background knowledge to the energy use and energy management practices used. This is similar to the approach by Gul and Patidar (2015), who also interviewed key staff members of a multi-use academic building to provide them with vital context to how energy was being used and what their energy concerns were. In a similar manner, in this research, where appropriate the interviewee's needs from the building were also recorded so that the researcher could suggest appropriate energy conservation measures following analysis of all data from each of the monitored events using a mixed methods approach as outlined above.

3.5.2 Observations of occupant behaviour

During initial pilot studies, observations of occupancy followed the example presented by Haigh (1982), and observations were only noted when there were changes to the occupancy in the room. However, as some events have rapidly changing occupancy's, and because behaviours such as door opening often occurred only briefly, a more standardised method of noting down occupancy and activity was iteratively developed through the pilot monitoring to in order to cover the complexity of occupant activity over time.

Occupancy was noted every five minutes by direct observations of entry and exit points to the building along with a brief description of occupant activity. This resolution was chosen to monitor the variety of occupant behaviours that can occur at the microscale e.g. opening and lowering blinds, opening doors, and adjusting lighting controls etc. These need to monitor at the microscale was also stated by Haigh (1982) in describing the monitoring of school classrooms and the numerous interactions that occupants had with different building controls. Additionally, a five minutely resolution aligned with the highest resolution available from the electricity metering, and so having as many data streams as possible at the same resolution enabled these to be overlaid on top of each other within the time frames in which they occurred. At specific times during an event e.g. an intermission during a concert it was necessary for the researcher to walk around the building to make continued observations of occupancy. At other times it was possible to sit at the back of the hall and observe the event as backstage areas were unoccupied e.g. during a concert performance. Occupancy numbers were cross checked with event organisers who had details on ticket sales and total seating capacity for different events, to verify the researcher's counting method.

Observations of occupant activity were noted in order to calculate occupant related internal heat gains (described in section 3.6.4). Additional observations were also made relating to occupant clothing to provide context to the data e.g. whether occupants chose to keep their coats on or took jumpers off and how that related to their level of activity and the temperature and humidity in the hall at that time (Haigh 1982). Direct observation of occupant interaction that was critical to providing context to quantitative data was also noted when necessary. An example of this could be the time that chandelier lights were turned on and if this was because lighting was required to perform a task, or if this was because the chandelier lights being on was visually pleasing to the occupants, an occupant trying to only turn on specific lights in the hall, or an occupant leaving an external door open.

3.6 Quantitative methods

3.6.1 Energy auditing

Following the method set out in CIBSE's TM22 (CIBSE 2006a), a systematic walk through of the building identified electricity end uses in its different areas as well as providing an understanding of the heating system operation. Locations of significant energy consuming plant and equipment (e.g. lighting, small power, boilers, pumps etc.) and any relevant observations were noted down on the building plans alongside identified power ratings.

Acknowledging that the power rating specified on an individual device, appliance or piece of equipment does not always equate to the actual energy demand from that end use, further checks were carried out to experimentally determine their demand. This was especially pertinent for end uses where the energy rating was not easily identified e.g. the chandeliers in the Great Hall had multiple different types of bulbs in use.

3.6.1.1 Electricity

Validation of the building level electricity meter was carried out through switching on and off an end use with a known power consumption over a fixed period of time. Physical readings were taken from the meter and then from the BMS to confirm that the meter was correct.

Where it was not possible to definitively identify the power rating of a particular piece of equipment, this was experimentally determined by turning off all lighting, equipment and heating that could be turned off and then individually turning on specific end uses for a defined period of time. The building's baseload power consumption was read directly from the main meter before individual end uses were turned on. This was subtracted from the electricity reading during the time an end use was turned on, enabling an assumption of average power consumption by that device. The baseload reading was also verified against the minimum historical electricity reading found in the available data. This audit was limited to the fixed services in the building as the changing use of the building necessitates additional small power equipment to be brought in for use during some events.

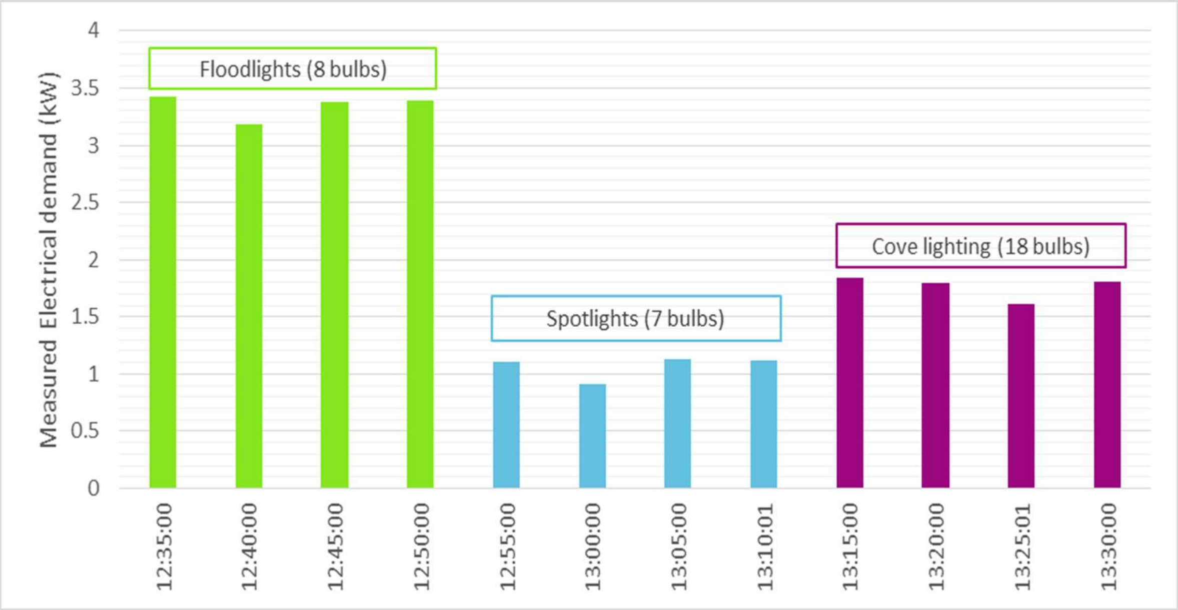

Figure 16: Energy auditing of different lighting using building level electricity meter. Each lighting end use was turned on for a period of time that was sufficient to ensure that the building level meter had captured its electricity demand, before being turned off and then another lighting end use was turned on.

Figure 16 shows the electricity demand observed from multiple lighting electrical end uses during the verification process. During this process, all known end uses in the building were switched off and individual end uses then in turn switched on for 20 minutes periods. The associated increase in demand was measured using the building level meter. The baseload consumption that had been previously determined was subtracted from this data so that the data only represented the increase in demand associated with individual end uses. It can be observed in Figure 16 that there are fluctuations in the measured energy demand from individual end uses. Although every effort was made by the researcher to switch off every known electrical load in the building, it is possible that some of the loads contributing to the baseload power had an oscillating demand and therefore contributed to fluctuations in the electricity data. Additionally, it is known that the wiring to some of the lighting end uses is faulty, leading to some bulbs to occasionally flicker on and off. This would also lead to fluctuations in the measured data.

The data from this monitoring during the verification was used to validate estimations of electricity consumption from individual end uses during the monitoring of each event. Appendix B details the energy end use breakdown for the building that was collated through this process.

3.6.1.2 Heating

Space heating for the Great Hall is provided through a low temperature hot water (LTHW) system with wet radiators located in occupied spaces which act as heat emitters. The LTHW system is heated through two $115kW_{th}$[1] gas-fired condensing boilers located in the basement plant room. These boilers are not original and were installed as part of a retrofit. When operational, the gas-fired boilers heat water held in a primary circuit which circulates through the boilers. Heat is transferred from the primary circuit to a single secondary distribution circuit through a plate heat exchanger which hydraulically isolates the primary and secondary circuits. This is a common solution in building services design for retrofitted heating systems as it prevents dirt and debris in the original secondary circuit from entering, and potentially damaging the newly installed boilers. The heated water is pumped around the secondary distribution circuit using pumps and the heat is transferred to the occupied spaces of the buildings through radiators.

The heating schematics indicate that the heating system is designed to operate on a flow and return temperature of 82^0C / 71^0C respectively. This is a typical flow and return temperature for buildings which use wet radiator systems as heat emitters. Spot checks of the instantaneous flow and return temperatures for the heating circuit on the BMS indicated that the flow and return temperatures are generally close to the design parameters.

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[1] The $115kW_{th}$ boiler heat output was identified through the manufacturer's technical specification available online and through reviewing the heating schematics.

Consequently, the gas-fired boilers are not operating in condensing mode because the return temperature is too high. Condensing boilers can deliver heat at a high efficiency (i.e. greater than 95%) as they can recover latent heat from the exhaust flue gases and use this to heat the return water before it enters the boiler. However, the condensation of flue gases requires the return temperature to be low enough for this to be possible (it is generally maintained that the return temperature needs to be below 60^0C if this process is to work effectively (Tymkow et al. 2013)).

For the purposes of this project this is an important observation as it is necessary to convert the gas consumption data into the heat for space heating during each event. This was achieved by multiplying each half hourly gas consumption reading by the estimated gross boiler efficiency of 88%.

The Great Hall has a gas meter which monitors consumption for the gas-fired boilers only. There is no other gas consuming plant or equipment in the building. The gas meter has an automatic meter reading system (AMR) fitted which transmits half hourly gas consumption data to the BMS. The AMR records pulses from the meter which indicate when one m^3 of gas has passed through the meter. The BMS converts the raw m^3 data into kWh and half hourly gas consumption data (kWh)

Analysis of the gas data shows that, on occasion, the average power (kW_{th}) can exceed the stated kW_{th} output of the boilers due to two factors:

1) The assumptions made of the boiler efficiency. This has been found as 88% based on the manufacturers literature for when the boiler is not operating in condensing mode.
2) Assumptions on the calorific value, temperature, and pressure (volume) of the supplied natural gas.

To validate the gas meter readings with the data available from the BMS it was necessary to take manual meter readings daily for a period of two weeks and then compare these with the BMS data. As the manual meter readings were in cubic meters (m^3) of natural gas and the BMS data was in kWh it was necessary to convert the manual readings into kWh. To convert from gas in m^3 to gas in kWh it is necessary to first multiply the reading by a ‘volume correction factor’ of 1.02264 which accounts for the temperature and pressure of the natural gas (OFGEM 2000), and then multiplied by the calorific value of natural gas which for 2016 was quoted as 39.6 MJ/m^3 (Department for Business Energy & Industrial Strategy 2017) To convert from MJ to kWh the result is multiplied by a conversion factor of 3.6. The volume correction factor is an industry standard, and the calorific value of natural gas can vary between energy suppliers but can be found on monthly energy bills. To ensure that the validation process was as accurate as possible, calorific values were taken from the latest bill for the Great Hall.

This validation process revealed that the kWh data recorded by the BMS were underestimated by a factor of 100. This was apparently because the AMR system was not commissioned properly to recognise the decimal places (i.e. the meter correction factor) on the physical meter. Consequently, it was necessary to multiple each half-hourly BMS reading by a factor of 100.

Analysis of HH gas consumption in this way verified that the maximum demand of the boilers (from HH gas consumption data) is 98.88% of the manufacturers stated output from the gas boilers, when the boilers are not operating in condensing mode.

As the events take place in the main hall and the LTHW heating system provides heat to the whole building it was necessary to estimate the proportion of heat that was only used for the main hall. To achieve this the internal volumes of the various areas of the building served by the space heating system, were calculated by using information on the available

CAD drawings. The ratio of the main hall volume to the total building volume was then calculated. This ratio was then used to multiply each half hourly heat reading to have an estimate of heating energy delivered to that space. It is recognised that greater accuracy in the heat output to the hall area could be achieved through physically measuring each radiator within that space, however it was not possible to access these as they are behind fixed wooden panelling.

To enable the half hourly heat readings for the main hall during an event to be compared with the electricity, internal conditions, and observational data which was recorded in 5 minutely intervals, it was necessary to convert the heat data into 5 minutely increments. This was achieved by simply apportioning the half-hourly heat data equally into six 5-minute increments. This is recognised as a limitation of this approach. Five minutely periods were chosen as this level of high frequency data collection is required when more detailed information about energy usage is needed (Guerra-Santin & Tweed 2015). This high frequency data can also be coupled with information about comfort, indoor and outdoor conditions and building operation. For multi-use venue buildings, this high frequency of data collection would provide a detailed understanding of multiple interacting variables.

3.6.2 Energy monitoring of events

Each event uses energy to support both the running of the event and also the comfort of the occupants e.g. lux levels, heat, equipment use. The energy consumption associated with each event comprises of electricity consumption and gas consumption. Electricity consumption is associated with lighting, small power, heating pumps and on demand hot water amongst other end uses in the building.

Gas consumption is associated solely with providing internal space heating. Monitoring the heat energy consumption associated with each event relied entirely on the buildings' total gas consumption recorded by the BMS. Gas consumption data was stored at half hourly intervals.

Electricity monitoring for each event was carried out using a ‘bottom-up’ continuous audit process, whereby the energy demand for each individual end use was systematically identified as described in TM22 (CIBSE 2006a) and also carried out in studies by the Technology Strategy Board (2015), Menezes et al. (2012), and (Liddiard (2014), The instances and duration of their use was noted for each event through direct observation by the researcher (analogous to work by Haigh (Haigh 1982) (see section 2.5.4. Observations of instances of equipment and systems use were continually noted every five minutes throughout the duration of the event to align with the highest resolution of electricity consumption data available from the building level electricity meter.

The aim of this process is to be able to facilitate the comparison metered energy data (electricity and gas) with direct observations of equipment and systems use as well as instances of occupant behaviour. This can enable the researcher to make evidence-based inferences about the impact on overall energy use of from the event and occupant behaviour.

To facilitate these comparisons energy data (electricity and gas) and the bottom up energy audit data is over-laid in chart form. An example is shown in Figure 17. These charts show time along the x-axis over the 24 hour period of the event day, with the primary y axis (axis on the left of the chart) showing metered electricity data in kWh and the secondary axis (shown on the right of the chart) showing metered gas data in kWh. The total building electricity demand (obtained from the building’s electricity meter which stores data at 5 minutely intervals) the electricity data is shown as the blue line. Total building gas demand (obtained from the building’s gas meter which stores data at 30 minutely intervals) is shown as the purple line. Fluctuations in electricity and gas demand correspond to different systems being operational to provide the requisite internal conditions for the occupants. The bottom up audit results/ observations are shown in orange in this case lighting loads in the main hall. Note that for the reasons given above the total building energy data will always be higher than the bottom up data.

A worked example of how lighting electricity consumption in kilowatt hours was calculated for each 5 minutely period is shown below:

- Lighting end use: 10 x chandeliers, 8 x Floodlights
- Measured power demand from audits, see section 3.6.1.1 (kW): 10 x 0.1, 8 x 0.4
- Number of 5 minutely periods in an hour: 12

Total electrical demand in one 5-minute period = ((chandelier measured power demand x number of chandeliers) + (floodlight measured power demand x number of floodlights)) / number of 5 minutely periods in an hour

$$= ((10 \times 0.1) + (8 \times 0.4)) / 12$$

$$= 0.35 \text{ kWh}$$

As the power demand from each individual lighting end use was measured through the audit process, all power losses e.g. control gear losses, have already been considered and do not need to be factored into this calculation.

Some judgement was applied by the researcher when recording the use of individual lighting end uses during each 5 minutely period, whereby if a lighting end use was turned on for a short period of time e.g. less than 1 minute, this was not recorded. This is because the finest temporal granularity to the calculations was 5 minutes to align with wider data sources and to allow for a manageable monitoring process by one researcher. Recording a lighting end use that was turned on for a short period of time would result in overestimating the electricity consumption from that lighting end use during that 5 minutely period. For the purpose of estimating internal heat gains from lighting, 100% of the consumption was converted to sensible heat, following guidance in CIBSE TM-54 (CIBSE 2013b).

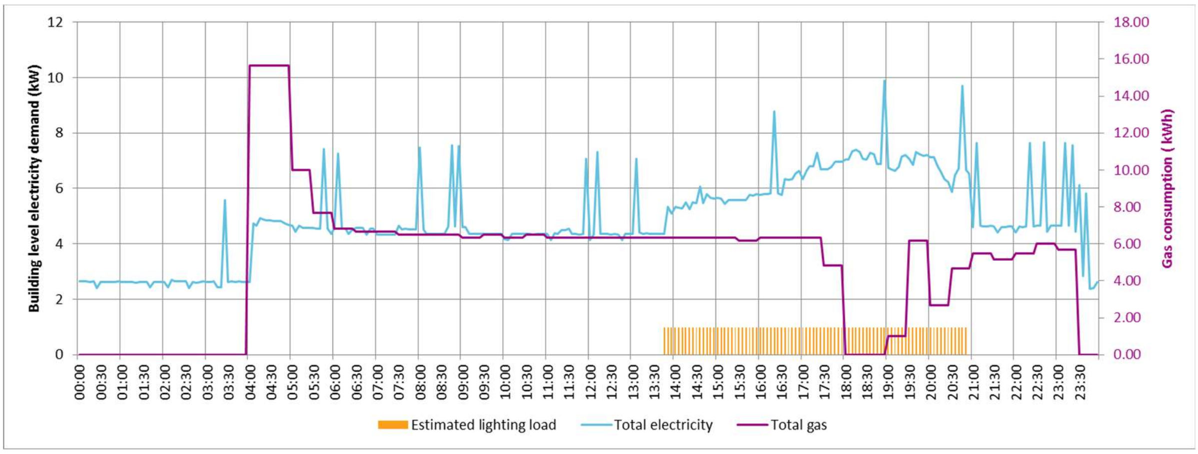

Figure 17 – Example of electricity demand (blue) and gas consumption (purple) from building level meters on an event day

An example of how inferences (making connections about energy use and behaviour) can be seen in Figure 17 where at 13:45 there is an increase in electrical demand of 1kW that corresponds to observations of lighting use amounting to an estimated electricity demand of 1kW. Additionally, there is a clear increase in electricity demand of approximately 2.3kW at approximately 04:00 that aligns with gas consumption. From the bottom up audit process, it was estimated that the electrical demand from the heating pumps is 2.5kW. For clarification these are the main heating system pumps located in the plant room which drive the heating system. This is based on one primary pump and one secondary pump running at 80%, a setting that was directly observed on each of these pumps. As this is an estimate based on these observations, and because these pumps are not directly sub-metered, error between the estimate and building level metering is to be expected. From 14:30 to 21:00, the building level electricity demand also includes small power equipment that the users had brought into the building for this specific event. Consequently, the changing electricity demand from the heating pumps with the fluctuations of gas consumption are masked by this increase in electricity demand from other electrical end uses in the building.

During events it is common for additional equipment to be used. Some of this is already present in the building e.g. audio equipment. However, additional equipment is often brought in by the event organiser e.g. additional audio-visual equipment, fridge.

Small power use was monitored to provide a measure of their internal heat gains and to provide explanation for the electricity consumption recorded by the building level electricity meter. It was not possible to directly monitor small power use using plug monitors. In the absence of plug monitoring, observations of small power devices and equipment in use were recorded for every 5-minute period of a monitored event. During the monitoring this involved recording the time that each individual small power end use was turned on and turned off, each 5 minutely period that it was in use, and what the average power rating for each device was, which was located on their name plates. The energy consumption from these end uses was calculated based on the average power rating for devices and an appropriate load diversity factor that was applied to account for the variability in their energy consumption. Diversity factors were applied based on figures provided in CIBSE TM-22 (CIBSE 2006a) and CIBSE TM-54 (CIBSE 2013b). To plot this data against other data collected for these events the consumption from small power was calculated for each 5 minutely period that it was observed to be in use. This enabled a profile of small power consumption to be compared against the building level electricity meter profile. It also enabled a profile of internal heat gains from small power equipment to be compared against space temperature.

A worked example of how small power consumption in kilowatt hours was calculated for each 5 minutely period is shown below:

- Small power equipment: 2 x catering urns,
- Small power demand (kW): 2 x 3.6
- Load diversity factor: 20%
- Number of 5 minutely periods in an hour: 12

Total electrical demand in one 5-minute period = (number of catering urns x power demand for catering urn) / number of 5 minutely periods in an hour

$$= (2 \times 3.6 \times 0.2)/12$$

$$= 0.12 \text{ kWh}$$

This process was repeated for each small power end use and a total small power consumption calculated for each 5 minutely period calculated by summing the consumption from each small power device or piece of equipment that was observed to be in use during a given 5 minutes. As with lighting use, some judgement was applied by the researcher to determine when small power use should be recorded if its use was for less than 5 minutes. For the purpose of estimating internal heat gains from small power, 100% of the consumption was converted to sensible heat, following guidance in CIBSE TM-54 (CIBSE 2013b).

The building level electricity consumption also includes end uses that are not in the main hall such as a fridge, hot water heaters, and lighting and other small power for the remainder of the building. Therefore, for each event this consumption is higher than the sum of lighting and small power consumption that was calculated for end uses observed to be use in the main auditorium. Therefore, it was imperative that during the monitoring of each individual event, the researcher also had knowledge of wider electrical end uses in use so that these could be accounted for in this verification process. It should be noted that the building level electricity consumption also includes end uses that are not physically located in, or related to the operation of, the main hall, such as hot water heaters for handwashing in toilets, internal lighting for other spaces in the building and other small power equipment such as a fridge. Therefore, the total electricity demand recorded by the main building meter (and shown in the chart as the blue line) across the event day is higher than the sum of the lighting and small power loads that were directly observed to be in use in the main hall. Therefore, during the monitoring of each individual event, it was imperative that the researcher also had knowledge of all other electrical end uses that were using energy in other parts of the building so that these could be accounted for in this verification process.

3.6.3 Environmental monitoring & data analysis

The environmental monitoring involved data collection for both external and internal conditions.

3.6.3.1 External environmental sensors

External weather data was obtained from the University of Reading's weather station. Data was downloaded as excel files and covered the period January 2013 to January 2017 to align with the available data for gas consumption (i.e. space heating) data. The data consisted of solar irradiance (W/m^2), dry bulb temp (ºC) and relative humidity (%). Data was downloaded in 5 minutely intervals.

3.6.3.2 Indoor environmental sensors

The internal environment was monitored using environmental sensors shown in Figure 18. Each sensor is pre-calibrated by the manufacturer and capable of logging temperature, relative humidity, and lux levels. Table 4 shows the accuracy, range, and resolution of the sensor for each of the parameters it measures as stated in the manufacturer's technical specification.

Figure 18: HOBO internal environmental sensor and logger

Table 4: Manufacturer data table for HOBO environmental sensor for temperature relative humidity and light levels

Sensor	Range	Accuracy	Resolution
Temperature diode	-20° to 70°C	± 0.35°C from 0° to 50°C	0.03°C at 25°C
Hygrometer (RH)	5% to 95% RH	±2.5% from 10%RH to 90%RH	0.05% RH
Light sensor (Lux)	10.76-32280 lux typical; maximum value varies from 16150 to 48420 lux	± 2 mV, ± 2.5% of absolute reading	0.6 mV

Due to the size of the monitored areas of the case study building and the spatial range covered by the sensor, specifically with relevance to lux, multiple sensors were required to ensure sufficient coverage of the hall. Examining the resolution and accuracy of the sensors as shown in Table 4, it was recognised that the error between the sensors needed to be experimentally identified in order to ensure that the analysis was based on the true environmental conditions of the case study building, and not resultant from sensor error.

This was identified prior to installation in the case study building, by placing them in an environmentally controlled chamber set at 20°C for at least 48 hours to allow both sensors and chamber time to settle and for readings to stabilise. Readings were taken every 30 seconds. The range of readings between sensors was identified and any sensors that showed significantly different readings were excluded from the main monitoring programme. The analysis of this data showed that readings from the sensors were within 2% error of each other for temperature, and within 1.2% error of each other for relative humidity.

3.6.3.3 Indoor environmental sensors & their comparison to the BMS sensors

The BMS also records temperature data from 6 sensors around the building and stores it for 3 weeks. A HOBO sensor was placed directly adjacent to a BMS sensor for several days and readings from each compared. Figure 19 shows raw temperature data from the BMS sensor and the HOBO sensor. The HOBO sensor was set to sample temperature on the hour every hour for 6 days. The sampling rate was chosen to align with the sampling rate and timing of the BMS sensor. It shows that the readings from the BMS sensors were consistently higher than those from the HOBO sensors. Figure 20, shows that this difference was on average 0.3oC, or approximately 2%, higher for the monitored period. This is within the manufacturer stated accuracy range of ± 0.35°C.

Figure 19: Monitored temperature readings from a HOBO sensor and BMS sensor showing the difference between readings from the two sensors under the same environmental conditions.

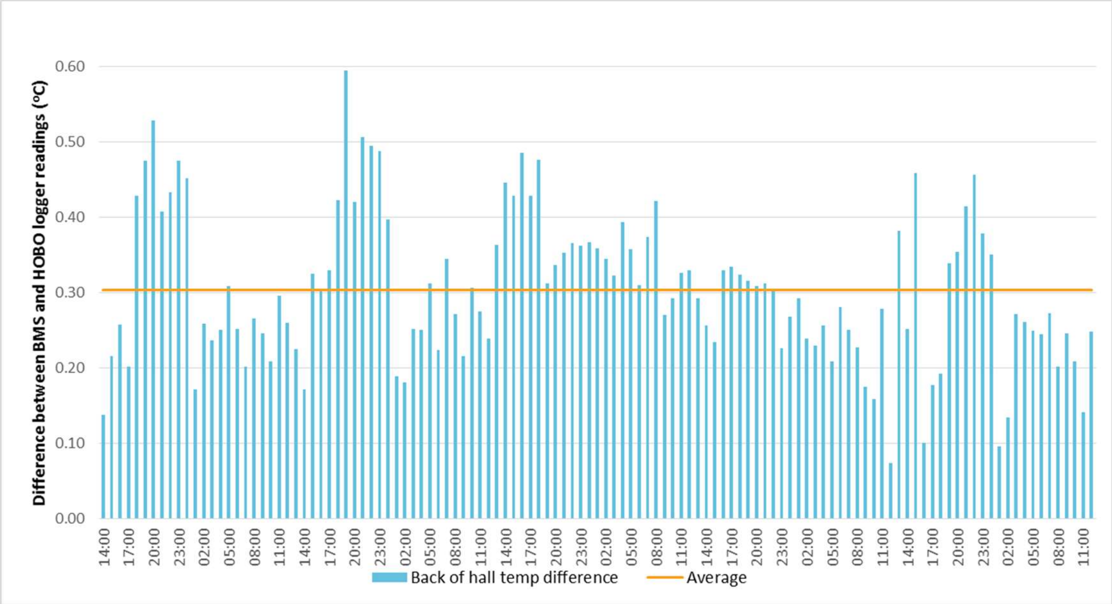

Figure 20: Measured temperature difference between a HOBO sensor and BMS sensor under the same environmental conditions.

3.6.3.4 Indoor environmental sensor placement and data collection

For the main monitoring programme, the sensors were positioned around the hall as shown in Figure 21. Examining the dimensions of the Great Hall and the location of windows and radiators behind wooden panelling, it was important to choose locations for environmental sensors that would be representative of the surrounding area. The sensors were placed at a height of 1.5m per industry recommendations and literature (Krausse et al. 2007; CIBSE 2016), and on wall panels known to not have radiators behind them. Some sensors were also placed near doors to monitor temperature and humidity changes with door opening. For the sensors to cover as much of the internal area as possible the sensors were placed 5m apart from each other. There was not an appropriate location for sensors to be placed in the centre of the hall.

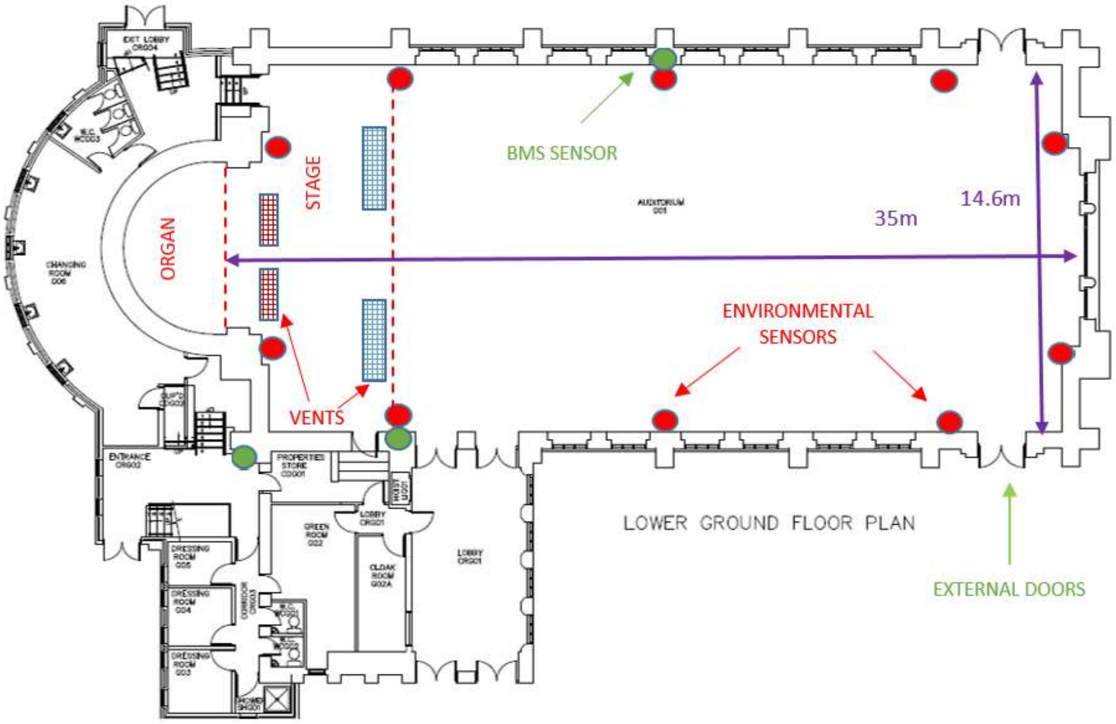

Figure 21: Building floorplan showing basic dimensions of the auditorium, location of external doors within it, and location of supply (blue) and extract (red) vents on the stage for the cooling system. The location of BMS sensors (in green) and additional environmental sensors (red circles)

Readings were taken every minute and data manually downloaded from the sensors weekly. Very high lux levels were noted for some of the sensors at specific times of day. This was found to be due to incident, very bright sunlight directly on the sensor. This data was cleaned from the sample as it was not representative of the ambient light level in the building, and the last sensible reading carried forward.

In order to analyse this data against the energy consumption data, data was grouped into five 1 minutely readings and averaged in order to provide 5 minutely readings. Where there were gaps in the data e.g. from the logger running out of memory, the last reading was carried forward to cover the time period, though it was ensured that this never occurred during an event that was monitored.

3.6.3.5 Building air exfiltration

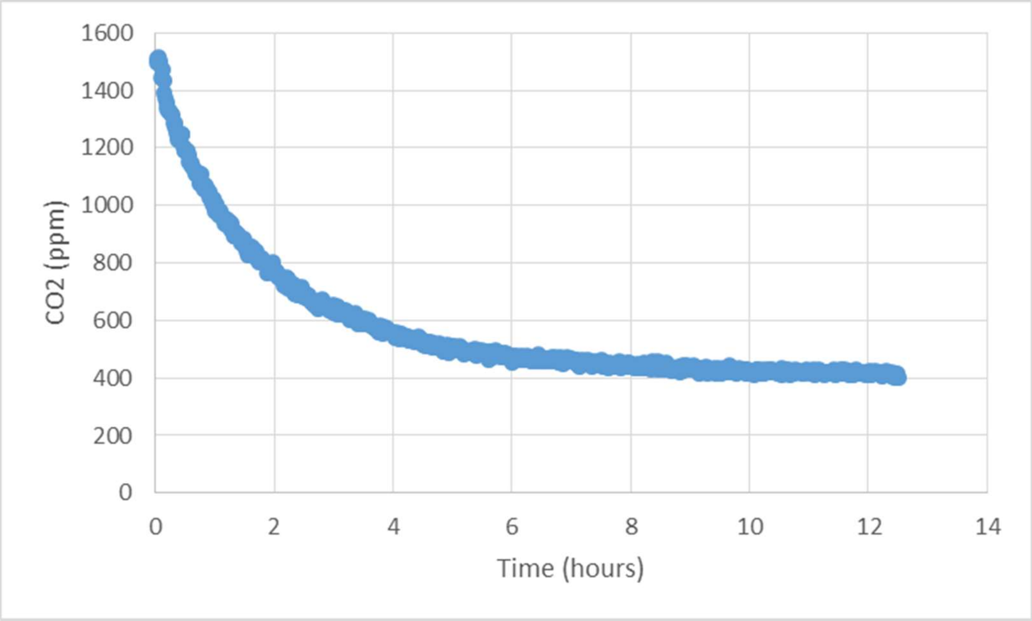

Figure 22 - Measured exfiltration of CO2 from the case study building under controlled conditions

In order to understand the thermal properties of the building and to have an estimate of the thermal losses, in addition to estimates for U values for the different construction elements, it was also necessary to measure the building's exfiltration rate. This was measured using four CO_2 sensors that had been calibrated to external background CO_2 levels prior to being evenly distributed throughout the main hall area. The loss of CO_2 from the building through gaps in the building fabric is indicative of the air lost through the same means and consequently heat (Awbi 2008).

By closing all external doors immediately following a large event, the sensors were able to log the decay of CO_2 through gaps in the building fabric. Figure 22 shows the results from the analysis of these readings. Over the same period of time the temperature in the hall fell from 22.2°C to 19.6°C.

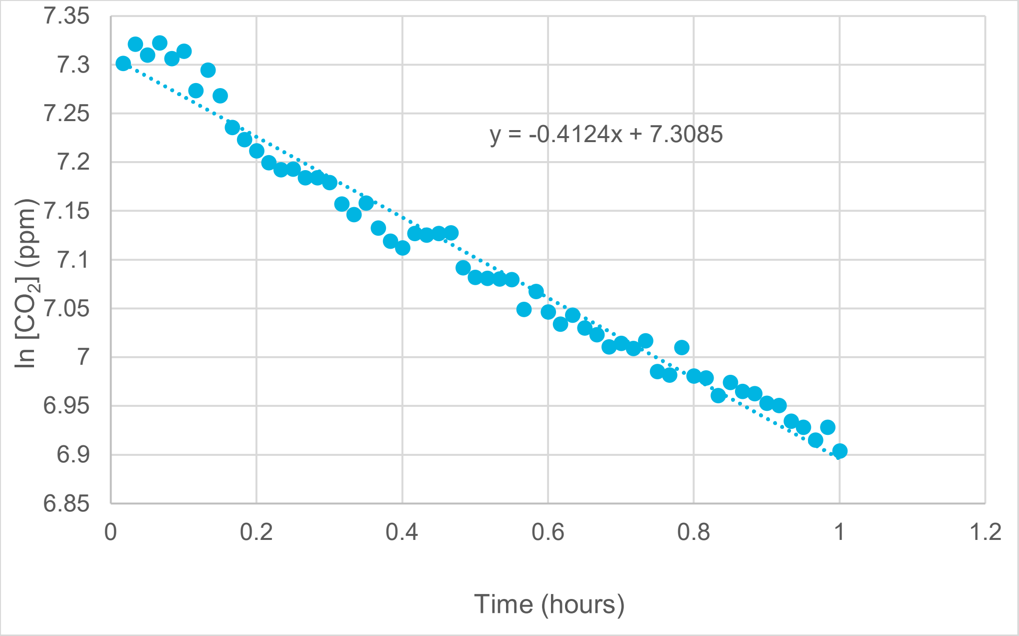

Figure 23: Chart showing the natural log of CO2 exfiltration. The gradient of the line shows that there are 0.4 air changes per hour (ACH)

From this data, the air changes per hour (ach) were calculated to be 0.4ach. It is recognised that this measure of air changes per hour is under controlled conditions with all windows and doors shut and no additional sources of CO_2. When the building is in use, this is much more dynamic as the occupants continuously emit CO_2 and use doors. However, this measurement is valuable in contributing to a wider understanding of the heating requirements of the space.

3.6.4 Quantification of occupant related internal heat gains

Occupant internal heat gains were calculated in kilowatt hours based on guidelines from CIBSE Guide A, which are shown in Table 5 (CIBSE 2013a). The guide provides estimates of sensible and latent heat gains from occupants engaging in a range of different activities.

Table 5: Examples of sensible, latent and total heat gains per person for different activities taken from CIBSE Guide A (CIBSE 2016).

	kW	kW	kW	kW	kW	kW	kW	kW	kW
	Seated inactive (matinee)	**Seated inactive (evening)**	**Walking/ standing (e.g. dept store)**	**Walking /standing (e.g. bank)**	**Seated light work (restaurant)**	**seated moderate work (eg office)**	**Light bench work**	**Moderate dancing**	**Heavy work**
Sensible	0.078	0.082	0.097	0.098	0.09	0.093	0.116	0.132	0.19
Latent	0.022	0.023	0.044	0.044	0.036	0.037	0.093	0.117	0.25
Total	**0.1**	**0.105**	**0.141**	**0.142**	**0.126**	**0.13**	**0.209**	**0.249**	**0.44**

During the monitoring of individual events, as well as observing the occupancy number in the hall in five minutely periods, the type of activity that the occupants were engaging in was also observed and noted. The number of occupants engaging in certain activities were recorded based on CIBSE Guide A's categories of occupant activity as shown in Table 5. Where an activity did not exactly fit a category, the type of activity that was most fitting was selected. Thus, it was possible to calculate the total kW of energy emitted by all the occupants for an event. An example of how this was calculated using the categories in Table 5 for 5 people seated doing light work (restaurant) and 2 people walking standing (e.g. dept. store) for a five minutely period is as follows:

Occupant activity related internal heat gains = ((sensible + latent heat gains for seated light work (restaurant) (kW) x number of people observed engaging seated light work (restaurant) + ((sensible + latent heat gains for walking standing (e.g. dept. store) (kW) x number of people observed engaging walking standing (e.g. dept. store)) / number of 5 minutely periods in an hour

$$= ((0.126 \times 5) + (0.141 \times 2)) / 12$$

$$= 0.076 \text{ kWh}$$

This is useful in providing context to the monitored temperature in the hall and the rate of that temperature change during different events. Overall, this calculation of occupant related internal heat gains based on direct observations provides insight into the passive impact that occupants have on the internal temperature. However, this approach is limited as it assumes that people have a very similar body mass and does not take into account the role of different items of clothing worn by the occupants and the ability of different types of clothing to impede heat transfer from the occupant to their surroundings. Because of this limitation, and because some of this estimated heat from occupants (as with heat from other sources) continually leaves the building through exfiltration, through the building fabric and through open doors etc., this estimate of heat from occupants will only be used as an indicator of the internal heat gains from occupants. The actual monitored temperature will be used to analyse the passive impact that these occupants heat gains have on the internal environment.

3.7 Data interpretation & the identification of energy waste

The analysis methods used above for each of the different types of monitored data were used to enable the interpretation of these multiple sources of data using triangulation, which was introduced in section 3.2. The use of mixed methods to find energy waste is to compare the energy supplied with the energy needs of the user.

This process is described in more detail in the next chapter on Results, whilst discussing individual examples of energy waste. As with any complex events/buildings, the determination of waste involved assumptions and experiences which could change from one assessor to another and any item of specific assessment could always be improved, though we believe the overall approach and the demonstration of the approach as presented are sound.

Quantitative data was graphed over a 24-hour period, to show how the different monitored variables evolved over the course of an event day. Through this presentation of the quantitative data and using the qualitative data to illustrate the context of its emergence, it was possible to evaluate the energy use and hence distinguish between useful and wasteful energy in order to identify energy saving opportunities.

3.7.1 Lighting energy waste

For lighting, the same method of calculating energy consumption from multiple lighting end uses was used to calculate the energy wasted. For example, if the use of 10 chandeliers and 8 floodlights were observed to be superfluous to the occupants needs for a 20-minute period, their energy consumption was categorised as wasteful and this energy waste was calculated as follows:

- Lighting end use: 10 x chandeliers, 8 x Floodlights
- Measured power demand from audits, see section 3.6.1.1 (kW): 10 x 0.1, 8 x 0.4
- Number of 5 minutely periods in an hour: 12
- Number of 5 minutely periods in 20 minutes

Total wasted lighting energy = (((chandelier measured power demand x number of chandeliers) + (floodlight measured power demand x number of floodlights)) / number of 5 minutely periods in an hour) x 4

$$= (((10 \times 0.1) + (8 \times 0.4)) / 12) \times 4$$

$$= 1.4 \text{ kWh}$$

3.7.2 Heating energy waste

For heating, there were two main methods used to calculate energy waste. Firstly, where heating use was observed and heating was no longer needed by the occupants, e.g. they had left the building but the heating was still on, the total heating energy consumption after the occupants had left was classed as wasteful.

Secondly, heating energy waste was calculated from the changes in temperature in the hall. The method to do this is shown in section 3.7.2.1. This was used in two ways, firstly where the chosen set point temperature had been exceeded, and secondly where the temperature in the room dropped due to external doors opening.

3.7.2.1 Calculating heat energy from temperature measurements

The BMS is programmed to turn the heating off once the set point temperature is achieved. However, as the heating system is based on hot water moving through radiators, and because internal heat gains from occupants and equipment continue to contribute to the internal temperature, it is possible for this set point temperature to be exceeded even after the heating has turned off. Where the internal temperature exceeded the set point temperature, this temperature difference above the set point for the period of time that it occurred was converted into kWh in order to calculate the energy savings opportunity if the set point temperature was not exceeded. This is shown in Figure 24 below. Effectively this quantification of energy is the heating energy that could be offset by internal heat gains.

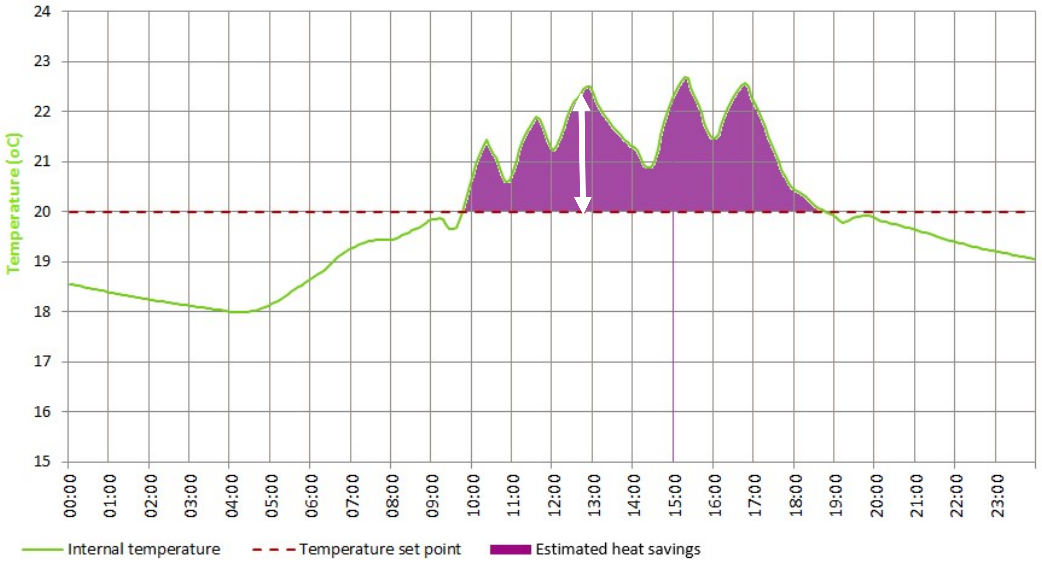

Figure 24: Example of monitored temperature exceeding the set point temperature. The white arrow identifies the temperature difference between the set point temperature and the monitored temperature for a single 5 minutely period. The shaded area is representative of the heating energy use that could be avoided.

Similarly, these calculations were also used where a temperature drop e.g. due to an open door led to a temperature drop. In this situation the temperature in each 5 minutely period that the door was open was calculated into kilowatt hours of heating energy.

It was assumed that the air was dry and at standard atmospheric pressure, and that the density of air changed with changing temperature. Thus, the mass of air was calculated from the measured volume in the hall using Equation 1, the Ideal Gas Law equation.

Equation 1: Ideal gas law equation expressed as a function of temperature and pressure

$$\rho_{dry\ air} = \frac{p}{R.T}$$

Equation 2, the specific heat capacity equation was then used to calculate the heat in kWh in the temperature difference between the set point temperature and the observed temperature exceeding the set point for each monitored 5 minutely period.

Equation 2: Specific heat capacity equation

$$Q = mc\Delta T$$

By quantifying the energy in the increase in temperature for a single 5 minutely period it was possible to summate the kWh of heat for the period that the temperature exceeded the set point. This then provided an estimate of the energy use from the heating system that could be avoided if the set point were not exceeded.

3.7.3 Assigning energy waste to actors

To provide judgement on what caused the waste and hence provide insights for appropriate energy conservation measures it was necessary to categorise the different types of waste that had been identified. This was done in two main ways. Firstly, the identified energy waste was grouped into categories relating to their sources as follows:

- Lighting – inflexible controls and occupant behaviour
- Heating – Poor BMS scheduling, Inappropriate set points, occupant behaviour

Secondly, the energy waste was grouped into categories pertaining to the different actors that interact with the building as follows:

- Building designer
- Building lighting designer
- Clients
- Events team
- BMS manager
- Porter

Consequently, it was possible to not only identify the energy waste but also target those responsible for the energy waste with a view to identifying more targeted energy efficiency measures. Exactly what waste is attributed to each actor is described in the results section through the identification and categorisation of energy waste. This approach aligns with that recommended by the Carbon Trust in their guidance on monitoring and targeting energy savings (Carbon Trust 2012b).

3.8 Summary

This chapter initially investigated research philosophies relevant to this research, identifying that this research adopts the position of pragmatism and utilises a mixed methods approach to investigate the case study building and the multiple events held within it were investigated as individual case studies. It then described the overall research design and timelines of available data used to achieve the research aims and objectives. The case study building was described in detail in terms of its design and construction, its building services, and the variability of its use. The remainder of the chapter concerned specific methods of monitoring and analysis used to understand building energy performance, initially through a macro scale using degree day analysis, and then at a micro scale concerning the monitoring at 5 minute intervals and subsequent analyses of the individual events examined as case studies. Most of the methods described in this chapter concern the monitoring programme devised to analyse these case study events. Each method used is described in detail with analysis of relevant equipment, to ensure that their limitations are understood and factored into any analysis of data that is collected by them. The methodology developed is to identify energy waste of these individual events treated as individual case studies in a multi-use event building, then pool the data from multiple events to identify patterns of main causes of energy waste in such buildings. Finally, this chapter detailed how the data would be analysed in order to understand the energy efficiencies of the building based on the different types of energy waste identified and which actors were responsible for them in order to provide appropriate and targeted recommendations in response to the requirements of objective 3.

Chapter 4

Analysis and Results

4.1 Introduction

The previous chapter outlined the methods and techniques identified in literature and through initial audits of the case study building. This chapter provides analysis and results from application of these methods and techniques to the case study building. This is with a view to answering objectives 1 and 2 of this research. Section 4.2 focuses on objective 1 and examines the variability of the buildings energy use and the application of existing methods for building performance analysis. In doing so, a brief comparison is also made to the energy use of buildings with a more regular use profile. Section 4.4 focuses on objective 2 and identifies energy waste from a number of different uses of the building that were monitored and examined as separate case studies. This section is divided into two main parts, lighting, and heating, to separate the analysis from each of the case study events into these two main energy end uses of the building. Section 4.5 also focuses on objective 2 to provide a high level analysis of the monitored events, the different categories of waste identified and what can be inferred from this and the different actors involved in the building to understand the its energy performance.

4.2 Variability of building use

In order to achieve objective 1 of this research, which is to *demonstrate the applicability of standard methods of identifying building energy performance when applied to buildings with a high diversity factor*, a high level analysis of the case study building's calendar and annual gas consumption was carried out. The aim of this was to demonstrate not only the variety of different uses of the building but also to show the irregular impact that these events have on the building's gas use. Due to a building level electricity meter only recently being installed, an analysis of the building electricity consumption was not carried out over the same period as there was no historical data to support this.

As described in section 2.3.2 venue buildings tend to have an erratic occupancy profile when compared to other buildings, such as offices. Consequently, any predictions of energy use carried out during the design stages, for example using methods such as CIBSE TM-22 or CIBSE TM-54, may be ineffectual when applied to venue buildings. Figure 25 below shows the impact of events on daily electricity consumption for the Great Hall. All known events are indicated in either orange for those that were identified in the building's room booking calendar, or purple for those events that were actively monitored by the researcher in order to achieve objective 2 of this research. As not all uses of the building come through on the central room booking system, it is highly likely that some of the peaks in consumption that are not indicated in Figure 25 as events, are event days that were booked through another means. From this data it is not possible to identify any energy waste, it is only possible to see the variability in building electricity use caused by different building activity. Therefore, it is necessary to investigate energy use at a more granular level.

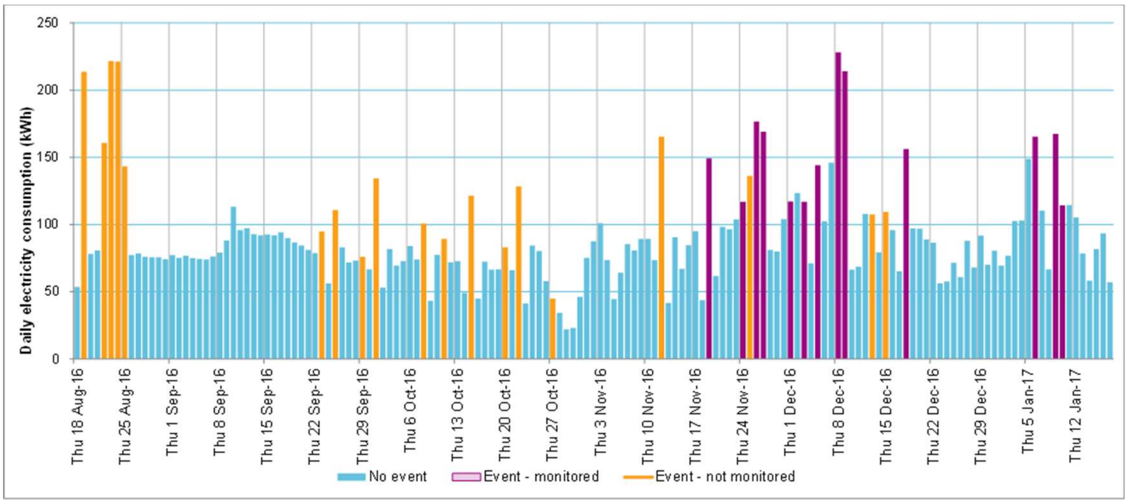

Figure 25: Daily electricity consumption profile for the case study venue building for 5 months.

Figure 26 and Figure 27 below show gas consumption pattern plots for the Great Hall in January 2015 and October 2015 respectively. As can be seen, the Great Hall has much more varied and erratic space heating consumption profiles when compared to the 'typical' office building shown in Figure 6. The chart for January shows that space heating would often start in the very early hours of the morning (around 01:00 to 02:00) and switch off at around 17:00. However, this could vary with heating sometimes not switching off at all during the day and sometimes coming on much later in the day. There were no days during January when the heating remained off all day.

The use of heating in the very early hours of the morning was discussed with the BMS manager during the semi-structured interviews and subsequent dialogue with him when further analysis of the data had been carried out. The BMS manager advised that this use of heating was an exception to the University’s usual practice around scheduling heating, and was because he had been informed that there would be an event held that day and wanted to pre-heat the space to ensure that it was at the desired target temperature by the time guests arrived. In addition to this, the BMS manager also provided some extra context to the heating use throughout the week and context as to why in Figure 26 the heating is consistently on in the very early hours of the morning and sometimes overnight at the weekends and on a Monday morning. The following is a quote from the BMS manager when discussing the heating schedule:

“… the BMS is configured to optimise the heating so we'll have a core time of say eight o'clock till six o'clock typically for buildings now, Monday to Friday, but obviously the heating will be off over the weekend, so the building temperature can drop down to a night set back temperature typically 10 or 12 degrees so we don't let the buildings drop any lower than 10 or 12 so Monday morning the heating needs to optimise on quite early depending how cold it is so if it's minus 5 degrees outside, it possibly needs to come on…Like one o'clock in the morning, by the time we get to Thursday or Friday only needs to come on perhaps four, five or six o'clock in the morning or if it's very mild outside it doesn't need to come on. So we have like an optimum start programmes with warm up periods which allow heating to come before eight o'clock in the morning, so it's supposed to be self-learning and it's supposed to adjust depending on room temperature, outside air temperature so it should vary from day to day depending on those temperatures.” (BMS manager)

“whatever the booking time is, the idea is that it is up to temperature by the start of whatever the function is, concert or practice or whatever so it should be up to temperature by that start time. So we'll put the start time in, say might be 6:00pm till eleven o'clock at night or something like that so we'll put it in a 6:00pm typically in that case we might put it on two or three hours earlier if it's cold, give it a better chance of warming because even with the warm up period of say five or six hours it might not make it.” (BMS manager)

With this vital context from the BMS manager it is possible to then explain the occurrence of gas use in the very early hours of the morning during this month. It also describes how the BMS manager’s priority is to ensure that the building is at the desired temperature before the building is due to be occupied.

Figure 26 - Great hall gas consumption pattern plot for January 2015

The chart for October 2015 below again emphasises the irregularity of the heating operation for the Great hall. Although the space heating is apparently generally scheduled to commence at 06:30 there are two instances (the 7th and the 27th) when the heating comes on much earlier (around 03:00) and there are multiple instances when heating comes on in the early afternoon and remains on until late evening. Instances where the heating is on until the late evening are likely to be due to evening events being held in the Great Hall, though without wider data sources, such as calendar data, it’s not possible to definitively identify these as such.

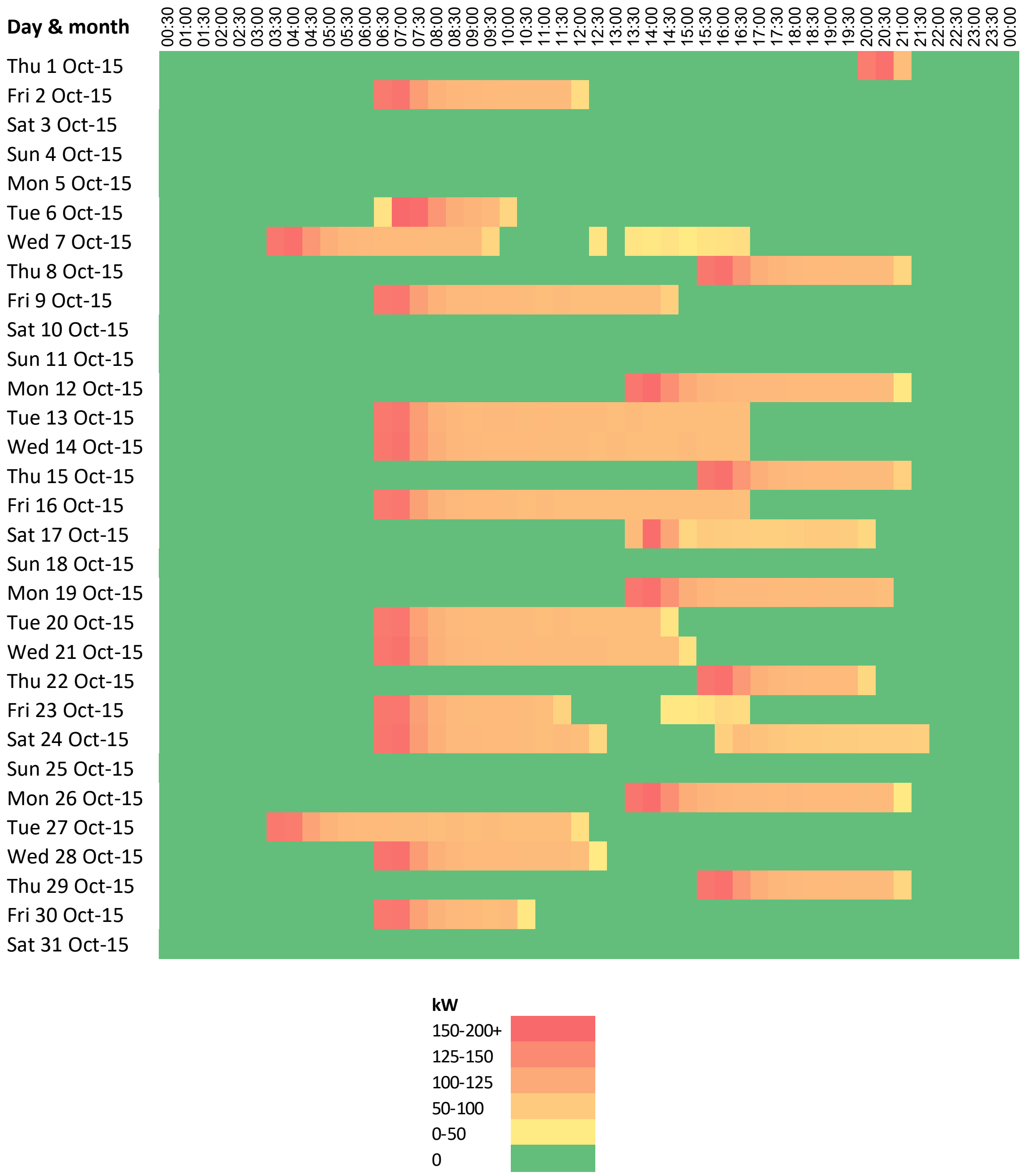

Figure 27 - Great hall gas consumption pattern plot for October 2015

Taking the gas consumption data for the calendar year of 2016, and applying this to the Gross Internal Floor area, as used in TM-46, the fossil fuel consumption energy use intensity for the Great Hall would be 179.8 kWh/m^2. Comparing this against the benchmarks in Table 1, this would position the building closest to the category of "Schools and seasonal public buildings". Arguably there is such a spread in data between the benchmarks for these building types, and a high level of ambiguity in the description of the building type categories, that in reality it would be very difficult to base any measure of performance of the Great Hall against any of these benchmarks.

Using consumption as a benchmark for performance can only be applied to buildings that have a very defined and regular use pattern, where the needs of the occupants are very similar between buildings that have the same purpose and the equipment within those buildings serves the same purpose to the occupants. These benchmarks for each building type are generated based on average consumption. However, by relying on consumption alone there is no quantification of energy efficiency, and so there is the possibility that the benchmarks that buildings are compared to, are buildings that are actually wasteful. What is key here is that by relying on consumption alone and with ambiguity in what is included in each building category, there is little information on what each benchmark is composed of. Venue energy use is highly diverse, the consumption profile dependent on the use of the building, and the energy use between different venue buildings that host different types of events potentially highly divergent. There are therefore two reasons why simply using consumption as an indicator of performance for venue buildings is inappropriate; firstly, that there needs to be an estimate of venue energy efficiency through differentiating between useful and wasteful energy; and secondly, that some buildings may simply have a higher energy use intensity because of the types of events that they host. Consequently, if any comparisons of venue building energy performance are to be made, these should only be based on energy efficiency and not consumption alone.

We know from semi-structured interviews with the BMS manager and events team, and from Figure 26 and Figure 27, that the heating for this building, is used every weekday regardless of the intermittency of its occupancy, and also used later on some evenings and weekends depending on when events are scheduled. Plotting the annual gas consumption data against degree days as shown in Figure 28 and Figure 29 reveals an R^2 value of 96.7% which would infer that the building's heating system is being operated well. However, this analysis belies the reality on the ground where the building is being heated during periods when it is unoccupied.

Additionally, Figure 28 shows gas consumption for a whole year. Surprisingly, and despite the University's heating policy, this chart shows that there was gas consumption in June. Examining the data in more detail, this consumption was only for the first three days of June. It was queried initially with the Estates team, who advised that the consumption was accurately recorded and that there had not been a fault with the BMS or data logging. This, along with the verification of the gas meter during the pre-monitoring audits of the building carried out by the researcher confirmed that this data was accurate and represented true gas consumption in the Great Hall.

It was then queried with the BMS manager who advised that this was a result of the BMS self-optimising and that the heating system had come on automatically. Fundamentally, this is an example of the building's heating scheduling not being managed in line with the University's policy where the heating is turned off completely in summer.

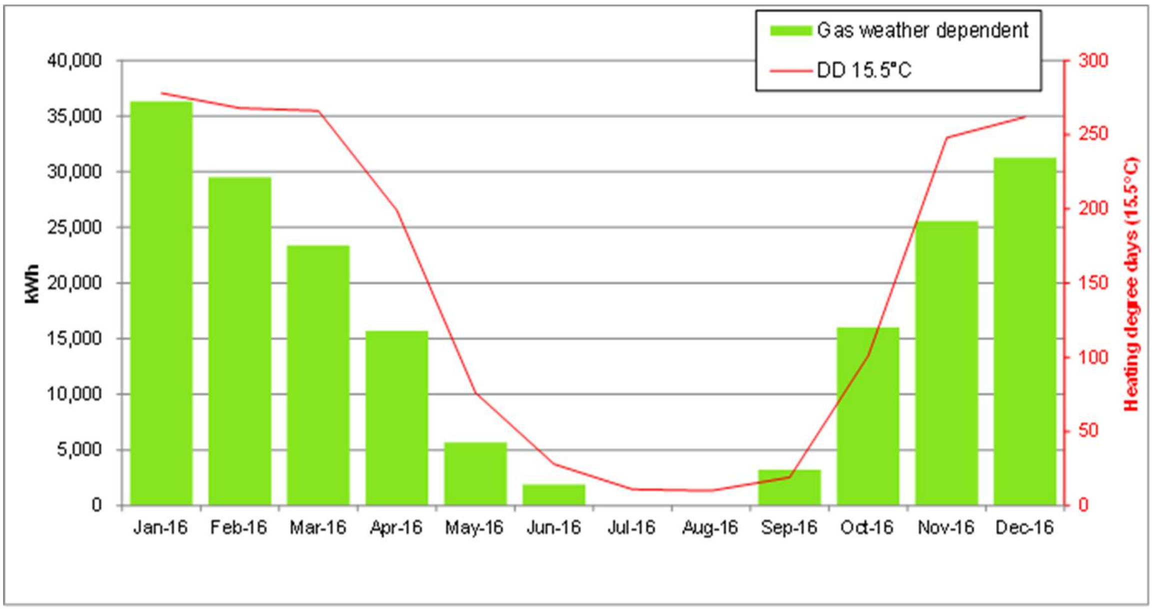

Figure 28: Great Hall gas consumption data compared against external temperature using heating degree days to a base temperature of 15.5°C.

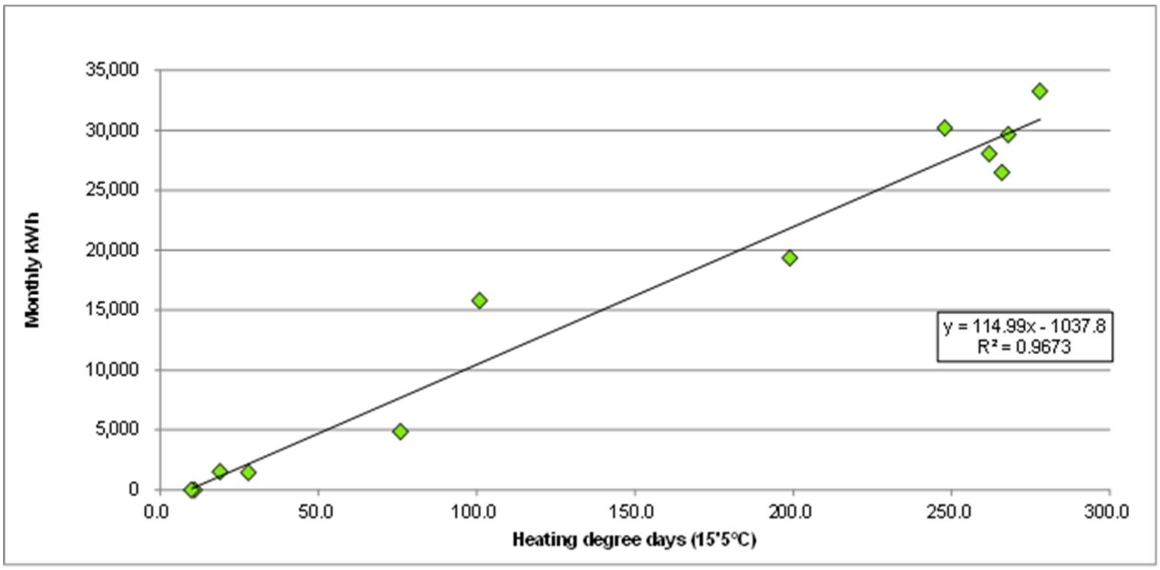

Figure 29: Performance line of Great Hall gas consumption data against heating degree days to a base temperature of 15.5oC

For the sake of consistency with studies found in literature that conduct degree day analysis on building heating use (Bordass, Cohen, et al. 2001; Marshall et al. 2015; Galvin 2013), a base temperature of 15.5°C was chosen for this analysis. As can be seen here the straight line plotted on Figure 29, meets the y axis at a negative value. Typically, the line should meet the y axis at a positive value to identify the minimum heating requirements of the building. An example as this where the line meets the y axis at a negative value, indicates that the building balances at a base temperature lower than the assumed 15.5°C (CIBSE 2006b; Day et al. 2003). There are several reasons why this might be the case including where a building is highly insulated, or where a building has high internal heat gains. For this reason studies now also use variable base temperature degree days in the analysis of energy performance (Zhao & Magoulès 2012). To investigate this further for the case study building, it is necessary to carry out more detailed monitoring to understand the thermal properties of the building and its minimum heating requirements under different conditions. These factors will be analysed in the next section where the energy consumption of specific events hosted in the Great Hall are examined as separate case studies.

4.3 Overview of monitored events

Thirteen individual events were monitored by the researcher during the winter heating season of 2016/17. The focus of the monitoring was in the main hall of the building as outlined in the Methods chapter. In terms of what is classified as an event in this research, the whole 24-hour day in which an event was held is presented in the monitoring. In all events lighting was used to make the hall visually appealing as well as to provide useful levels of light, however the use of individual lighting fixtures at different times of day could be questioned.

Table 6: Timings for each event

Event	Event start	Event finish	Event duration	Occupancy start	Occupancy finish	Occupancy duration
Concert 1	11:15	22:00	10:45	09:30	22:20	12:50
Lecture 1	14:30	20:45	06:15	08:00	20:45	12:45
Concert 2	12:50	22:00	09:10	07:45	22:20	14:35
Concert 3	10:05	17:35	07:30	08:00	18:15	10:15
Lecture 2	12:20	21:05	08:45	09:00	21:25	12:25
Ball	14:00	23:10	09:10	11:00	23:45	12:45
Carol Service 1	15:20	20:15	04:55	10:20	20:30	10:10
Graduation day 1	07:40	17:05	09:25	07:15	19:50	12:35
Graduation day 2	07:50	16:50	09:00	07:00	16:50	09:50
Carol Service 2	10:10	21:15	11:05	09:40	21:45	12:05
Exams day 1	07:55	17:20	09:25	07:50	17:30	09:40
Exams day 2	08:00	17:20	09:20	08:00	17:20	09:20
Exams day 3	13:15	17:25	04:10	13:10	17:25	04:15

Table 6 shows the overall timings for each event. In terms of occupied hours, this was taken as the time from when any occupant(s) arrived at the hall and began to engage in tasks related to hosting the event for an audience later that day, to when all occupants had vacated the hall. Overall, each event was unique in terms of hours of occupancy and / or times of day that the hall was in use. This is outlined further in Table 7, where an overview of the different events monitored outlines the differences in occupancy, activity and energy end uses between events.

Table 7: Overview of the events monitored

Event	Maximum number of people	Event description
Concert 1	280	Held in November. Evening concert with afternoon rehearsals. No small power use. High levels of lighting use. Performers sang or played acoustic instruments. Clients in control of energy end uses
Lecture 1	63	Held in November. Evening lecture with guest speaker and seated audience. Medium use of small power in the form of audio-visual equipment. Low-medium use of lighting. Clients in control of energy end uses
Concert 2	300	Held in November. Evening concert with afternoon rehearsals. No small power use. High levels of lighting use. Performers sang or played acoustic instruments. Also had a bar for the interval period. Events team in control of energy end uses
Concert 3	240	Held in November. Evening concert with afternoon rehearsals. No small power use. High levels of lighting use. Performers played acoustic instruments. Clients in control of energy end uses
Lecture 2	298	Held in December. Evening lecture with guest speaker and seated audience. Medium use of small power in the form of audio-visual equipment. Medium use of lighting. Clients in control of energy end uses
Ball	180	Held in December. Evening dance involving all occupants with high levels of occupant activity. High levels of small power, mainly audio equipment. Low levels of lighting use. Events team in control of energy end uses
Carol Service 1	430	Held in December. Evening carol concert. Low – medium use of small power equipment in the form of audio equipment. Audience members engaged in a range of activities from being sat quietly to singing. Events team in control of energy end uses
Graduation day 1	605	Held in December. Five separate graduation ceremonies held throughout the day. Hall reached maximum occupancy. Medium – high levels of small power in hall for filming and audio. High levels of lighting use. Clients in control of energy end uses

Graduation day 2	592	Held in December. Five separate graduation ceremonies held throughout the day. Medium – high levels of small power in hall for filming and audio. High levels of lighting use. Clients in control of energy end uses
Carol Service 2	220	Held in December. Evening Carol concert with high levels of small power use in the form of audio-visual equipment and electronic instruments. Low levels of lighting use. Audience members engaged in a range of activities from being sat quietly to singing and stood dancing. Clients in control of energy end uses
Exams day 1	209	Held in January. Two exam sittings in the day. No small power use. High levels of lighting use. Clients in control of energy end uses
Exams day 2	102	Held in January. Two exam sittings in the day. No small power use. High levels of lighting use. Clients in control of energy end uses
Exams day 3	42	Held in January. One exam sitting in the day. No small power use. High levels of lighting use. Clients in control of energy end uses

Lighting use varied between events and throughout some of the events. This is discussed for each individual case in section 4.4.1. The ball had the highest levels of small power as additional sound systems and electronic amps for musical instruments were used. The heating system was in use for all events. The cooling system was not used for any of the monitored events; however, it was observed that during one particular event, the ball, that external doors were opened to allow colder fresh air intake. This particular example is discussed in more detail in section 4.4.2.1.

4.4 Energy use

This section provides analysis of the energy use from each event and explanation of where the researcher has identified energy waste for each of these. Waste is identified as energy use that exceeded the needs of the occupants.

Table 8 provides measured and calculated energy use for heating, lighting and small power use based on metered data and observations of equipment and devices and lighting in use.

Where energy consumption has been calculated, the methods to do this have been described in section 3.6.2.

Table 8: Overview of energy use from each monitored event. Total gas and electricity are presented from the building level metering. Lighting and small power electricity consumption is for the main hall area of the building only

Event	Total Gas use (building) (kWh)	Total estimated Heat (hall) (kWh)	Total Electricity use (building) (kWh)	Total lighting use (hall) (kWh)	Total small power use (hall) (kWh)
	Measured	Calculated	Measured	Calculated	Calculated
Concert 1	1,191	823	150	58	0
Lecture 1	1,462	1,010	117	7	3
Concert 2	1,240	857	176	60	5
Concert 3	906	626	169	66	1
Lecture 2	1,771	1,224	117	18	10
Ball	1,286	889	118	9	15
Carol Service 1	1,884	1,302	144	23	7
Graduation day 1	421	291	228	84	4
Graduation day 2	311	215	214	85	5
Carol Service 2	1,736	1,200	228	40	21
Exams day 1	1,303	901	164	68	0
Exams day 2	1,508	1,042	167	67	0
Exams day 3	1,450	1,002	114	28	0

The building total electricity use shown in the table above also includes end uses that are not in the main hall such hot water heaters, additional lighting, a fridge, and other small power for the remainder of the building. Therefore, the consumption shown will be higher than the sum of the hall lighting and small power as explained in section 3.6.2. The energy consumption in this table is for the full 24 hours of a specific event day. It can be seen from this table that both electricity and gas consumption varies significantly between the different events.

4.4.1 Lighting energy use

For lighting, the potential energy saving opportunities were calculated by first calculating the energy consumption in kWh of each lighting end use as described in section 3.6.2. The sum of energy consumption from each different lighting end use that was identified to be wasteful through analysis of all the monitored data, including the qualitative analysis of occupant needs, was then calculated for each 5 minutely period. This was so that this wasteful energy use could be graphed on the same chart as illuminance, occupancy, external solar irradiance, and the calculated lighting load. The sum of the wasteful energy over a 24-hour period is presented in the discussion for each different event that was monitored.

4.4.1.1 Concert 1

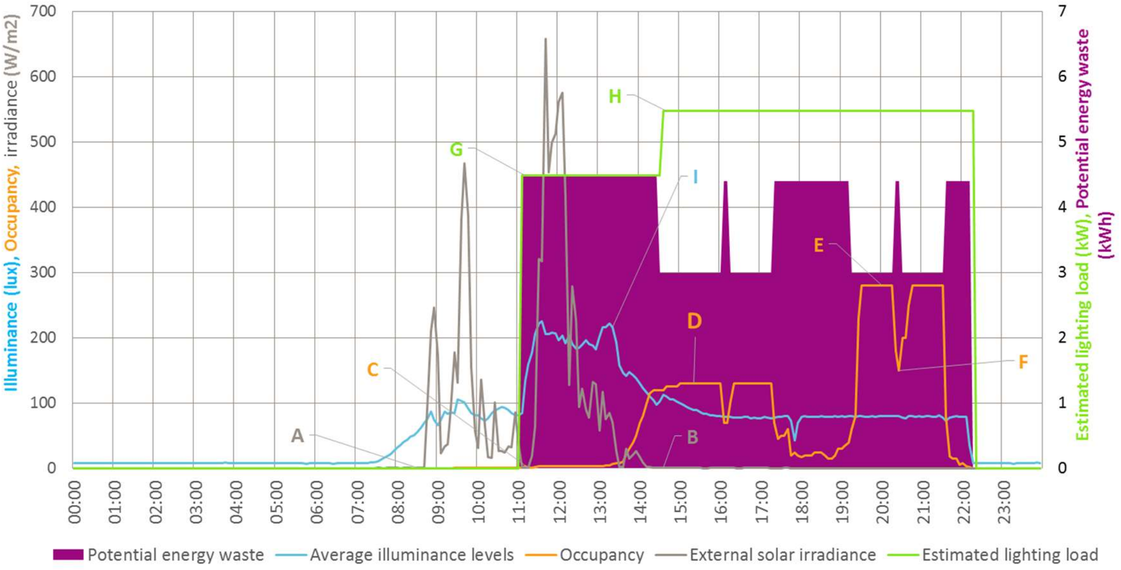

Figure 30: Estimated lighting use, lighting waste, measured illuminance and external for Concert 1. Specific points of interest are as follows: A – Sunrise, B – Sunset, C - Event organisers arrive to set up the hall, D – Rehearsals with a brief break, E – Main concert with irradiance guests, F – Intermission, G – Floodlights and stage spotlights turned on, H - Chandeliers turned on, I – Light levels begin to fall due to external weather becoming more overcast.

Figure 30 shows the estimated lighting load that was calculated as described in section 3.6.2. Also shown in this chart are the measured internal illuminance levels and the external solar irradiance levels. The different profiles for illuminance and irradiance is due to three main factors. Firstly, the sensors used to monitor illuminance do not discriminate between natural and artificial light. An example of this can be seen between 11:00 and 12:00, where the illuminance levels rise due to both artificial lighting being turned on and a rise in solar irradiance. Secondly, the difference in the two profiles is also a result of the building's form and orientation and also the location of windows. The orientation and plan of the building is shown in Figure 11. The path of the sun is such that for certain times of day the level of illuminance due to natural light is lower than that recorded outside due to the location of the windows. Thirdly, intermittent cloud clover meant that there were large variations in the level of solar irradiance, which would have been different for the case study building and the location of the external solar irradiance sensor located at the university weather station.

Concert 1 started at 19:30, with rehearsals earlier in the day. On arrival of the event organisers at 11:00 the floodlights and stage spotlights were turned on. Additional lighting in the form of the 10 chandeliers was switched on at 14:25 to compensate for low levels of natural light due to changing weather conditions. The purple shaded area in Figure 30 shows the potential energy waste that could have been avoided, which amounts to 42.6kWh or approximately 73% of the total estimated lighting energy used that day, had the artificial lighting been aligned to the required average illuminance levels for occupant tasks. Interestingly, illuminance levels before the lights were switched on at 11:00 were similar to those once the sun had set around 16:05, indicating that the use of artificial lighting before 14:25 was unnecessary, and thus wasteful. Likewise, the use of floodlights and stage spotlights during breaks and the intermission period was also wasteful as these were only required to illuminate the performers on stage. During the break, the performers left the stage. Turning these end uses off at these times could have provided a saving of around 154kWh of electricity. Additionally, during the rehearsals and performance, it could be argued that the measured illuminance levels of 80 lux were not necessary for the entire hall as the area the audience were located in did not need to be as brightly lit as the stage area. At approximately 17:50, prior to the evening performance, the event organisers were observed attempting to adjust lighting levels so that the audience area was less illuminated than the stage area. However, the current lighting control system meant that this was not possible. The switches for the chandeliers and floodlights, both of which were used during this event, serve pairs of luminaires which are not always adjacent. As a result, the lighting set up is not flexible enough to allow only certain areas of the hall to be lit to a defined level of illuminance and enable the occupants to achieve their preferred lighting design. Assuming a greater flexibility in lighting controls, switching off the six chandeliers and six floodlights directly above the audience during performance times could amount to an additional saving of 9.2kWh of estimated lighting related energy waste. In addition, if the lights could be dimmed for certain tasks or activities, further savings could be attained though it is not possible to estimate the potential savings here as there are no measurements of dimmed lighting that could facilitate these calculations.

4.4.1.2 Lecture 1

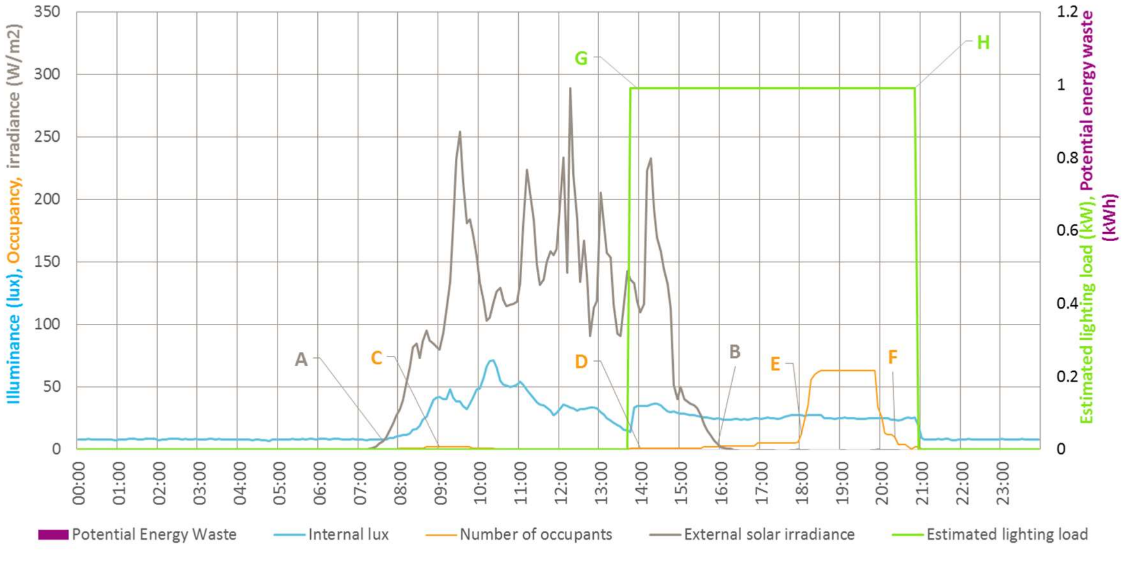

Figure 31: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Lecture 1. Specific points of interest are as follows: A – Sunrise, B – Sunset, C – Porter arranging

chairs (no artificial lighting used), D – Event organisers arrive to set up, E – Guests start to arrive, F - End of evening event, G – Event organisers turn on chandeliers, H – Porter turns off lights.

There was no obvious lighting related energy waste during this lecture. During the morning building users generally relied on natural light rather than using the artificial lighting, this was mainly the porter arranging chairs for the main event later that day. Event organisers arrived prior to the sun setting at approximately 13:45 and turned on the chandeliers. Although natural daylight was available, monitored average illumination levels were decreasing, and event organisers were installing audio visual equipment that may have required higher levels of illuminance to complete their task. The lighting design for this event also included pre-charged coloured LED light boxes which meant that there was less reliance on the existing lighting infrastructure. During the lecture itself, as a projector was being used, it was advantageous to have lower levels of lighting so that the audience could see the screen clearly.

4.4.1.3 Concert 2

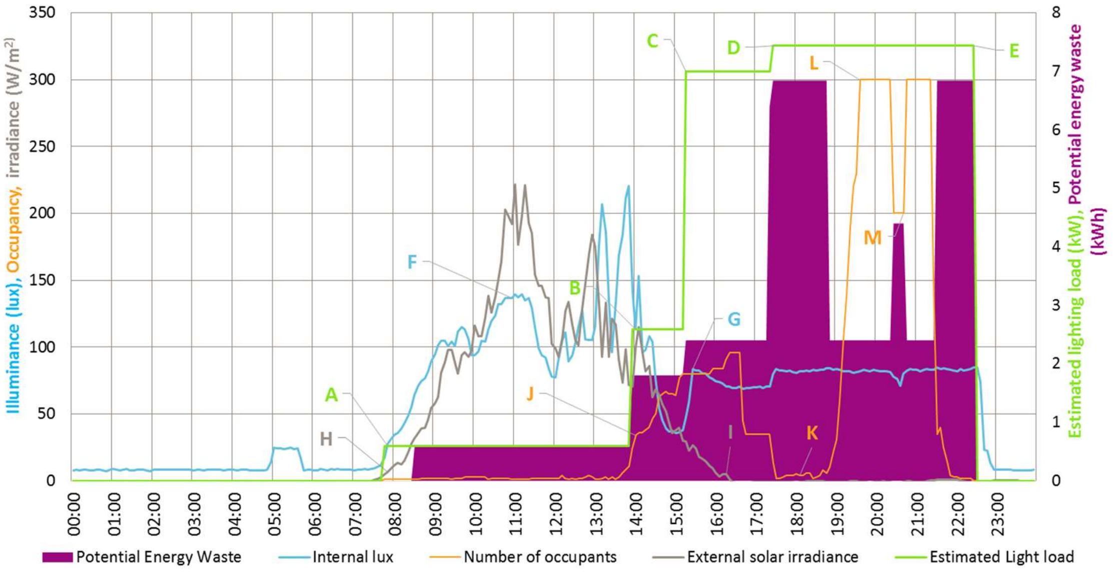

Figure 32: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Concert 2. Specific points of interest are as follows: A – Porters turn some chandelier lights whilst setting up, B – Cove lighting turned on, C – Floodlights and stage spotlights turned on, D – Remaining

chandelier lights turned on, E – All lights turned off by porter, F – Illuminance levels fluctuate in response to natural light, G – Illuminance levels increase with additional lighting, H – Sunrise, I – Sunset, J – Performers arrive for rehearsals, K – Performers leave for break, L – Main evening event starts, M - Intermission

Concert 2 consisted of an evening event with an afternoon rehearsal. The porter arrived just before the sun rose to arrange chairs in the room and to turn on the chandeliers, followed by the event organisers at 13:00 to arrange the stage area for the musicians. As the musicians arrived the event organisers turned on the cove lighting. Just prior to the rehearsal starting the floodlights were turned on. The event organisers had tried to only put the floodlights on over the stage areas, however were unable to do so as the lighting controls were not flexible enough, and so the length of the hall was illuminated using this end use. Use of both floodlights and stage spotlights was only necessary during the rehearsals and evening performance, thus outside of these times their use was wasteful. Additionally, during breaks and the evening intermission lower light levels were required. In total, it was determined that more than 34.8kWh or approximately 58% of lighting related electricity savings could have been made that day.

4.4.1.4 Concert 3

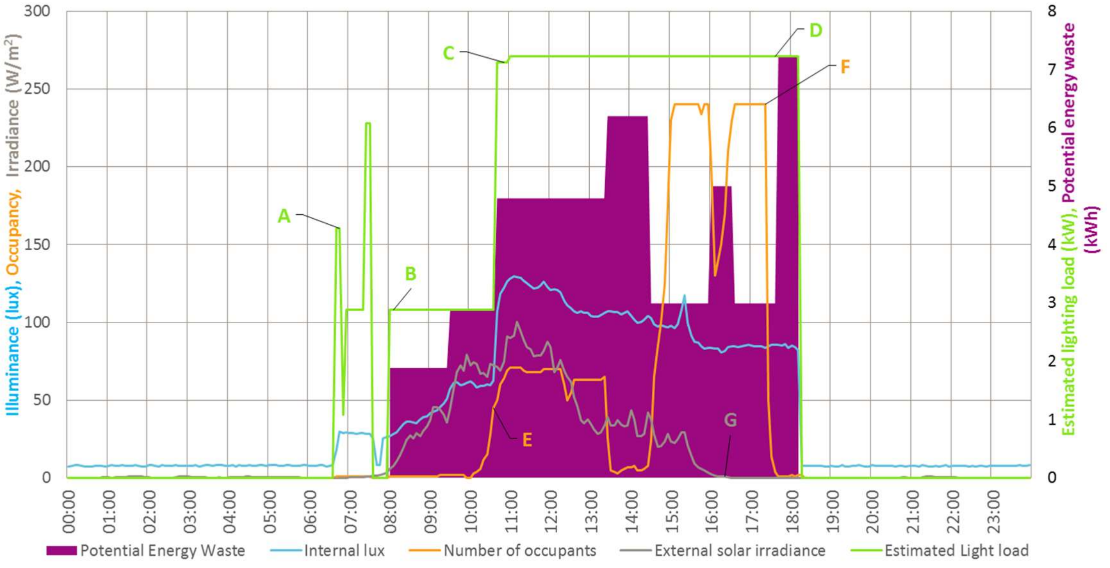

Figure 33: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Concert 3. Specific points of interest are as follows: A – Porter testing lights, B – Porter turns on cove lighting and chandeliers, C – Event organisers arrive and turn on stage spotlights and floodlights, D – All lights left on after event, E – Performers arrive for rehearsals, F – End of evening performance, G – Sunset

During Concert 3 all of the available lighting types were used. Throughout the day the necessity of these lights varied with changing occupant activity and levels of natural daylight. In total 41kWh or 62% of lighting related electricity was calculated as wasteful. In the morning, as the porter was setting up, the use of the cove lighting is considered unnecessary as the light from the chandeliers should have been sufficient. Additionally, while the porter was carrying out their tasks, natural light levels rose so that illuminance levels were suitable for their activity, meaning that all artificial lighting could have potentially been avoided. Once the event organisers arrived at about 10:45, all lights were turned on, despite natural light levels being adequate, and remained on until the porter turned them off at the end of the day, irrespective of how the space was being used. As was the case for Concert 1 and 2, the use of floodlights, cove lighting and stage spotlights was avoidable during break and intermission times. The inflexibility of the lighting controls meant that floodlight and chandelier use was not limited to the areas of the hall where the performers were positioned during performances and rehearsals. This meant that all 8 floodlights were used instead of the 2 that the building users wanted to use, and all 10 chandeliers were used instead of the 4 that the building users wanted to use. This further accumulated to lighting related waste as the entire hall was illuminated instead of part of it. Despite most of the lighting being turned on by the event organisers, the lights were left on at the end of the day until the porter turned them off, which constituted further waste.

4.4.1.5 Lecture 2

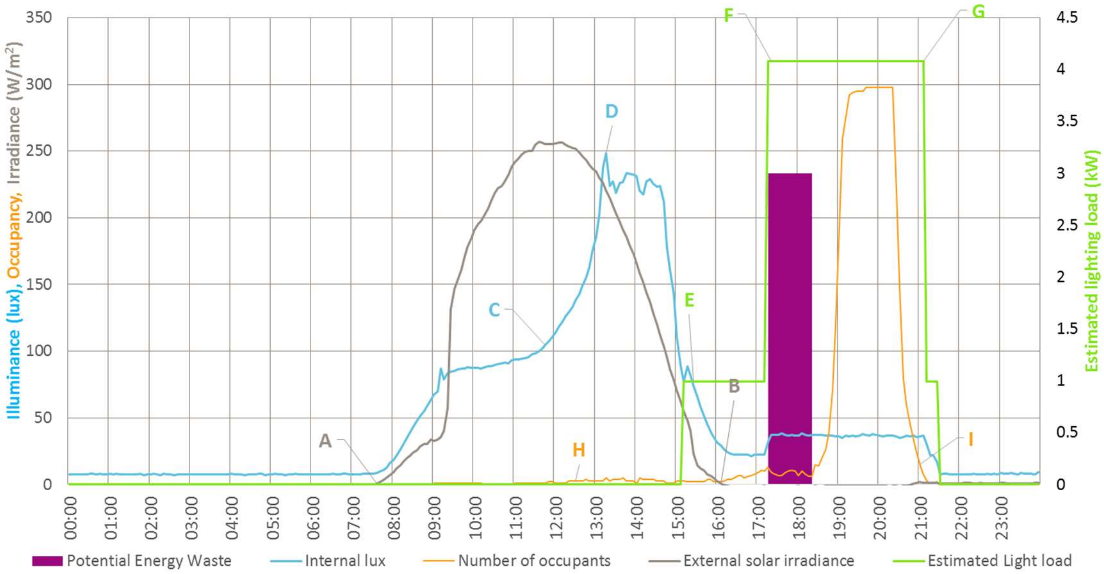

Figure 34: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Lecture 2. Specific points of interest are as follows: A – Sunrise, B – Sunset, C – Orientation of building and position of the sun with respect to windows limits impact of solar irradiance on internal illuminance levels, D – Internal illuminance levels peak as sun moves round to windows into the hall, E – Chandeliers turned on, F - Stage spotlights and cove lighting turned on, G -Stage spotlights and cove lighting turned off, H – Event organisers arrive to set up, I – Guests leave at end of lecture

As a clear bright day, the external solar radiation was not inhibited by cloud cover. Therefore, by examining the different profiles of external solar irradiance and monitored internal illuminance, it is possible to see the impact that the building form, orientation and location of the windows have on natural light entering the building throughout the day. During this event, it was observed that at certain times bright sunlight was directly incident on certain loggers at the back of the hall causing illuminance readings to spike. These readings were cleaned from the data in order for the general trend to be observed and plotted on the same chart (see section 3.6.3.4). Event organisers arrived in the hall at approximately 12pm, at which point natural light levels were sufficient for them to set up the room. Artificial lighting, in the form of the chandeliers, was only turned on once natural light levels began to fall at 15:00. The main identifiable source of lighting related waste relates to the stage spotlights and cove lighting which were turned on over an hour before they were actually required by the occupants. Use of these lighting end uses over this period of time was calculated to amount to 3.5kWh or approximately 19% of lighting related energy used that day.

4.4.1.6 Ball

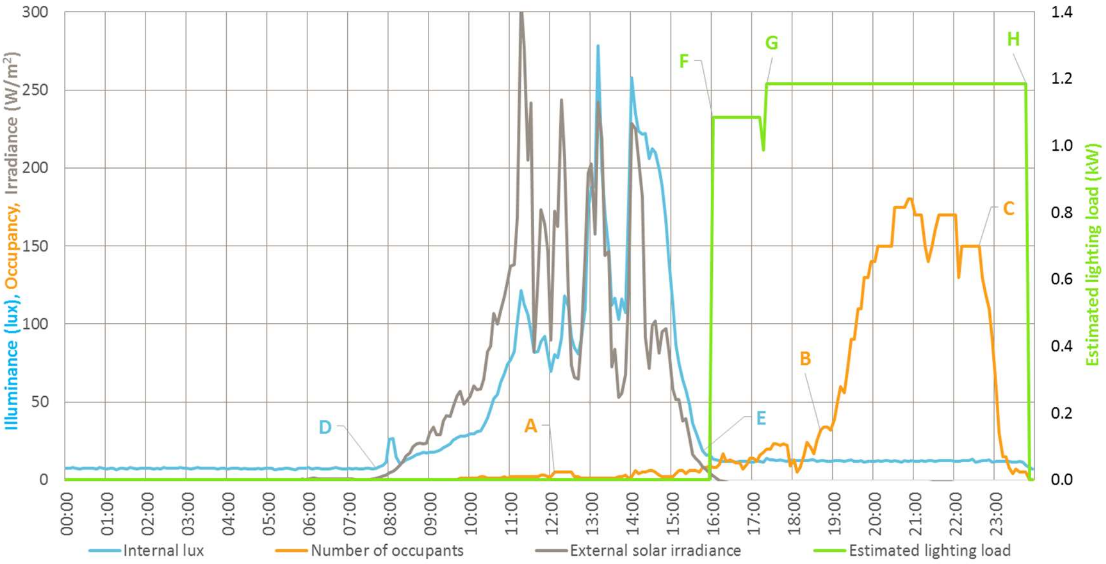

Figure 35: Estimated lighting use, lighting waste, measured illuminance and external irradiance for the Ball. Specific points of interest are as follows: A – Event organisers arrive, B – Evening guests begin to arrive, C – Guests begin to leave, D – Sunrise, E- Sunset, F – Some stage spotlights and some chandeliers turned on, G – More stage spotlights turned on and some chandeliers turned off, H – All lights turned off.

Throughout the day organisers for the ball relied on sunlight whilst they were setting up the event. Artificial lights were only turned on after the sun had set. In addition to the artificial lighting already present in the building, as part of the lighting design, event organisers also used pre-charged battery powered LED lights that were able to change colour. In terms of energy waste, very little lighting waste is obvious. Lights were turned off soon after the event finished and levels of lighting in use throughout the event were very low with levels of illuminance at approximately 10 lux, part of which was due to the use of pre-charged coloured LED lights.

4.4.1.7 Carol service 1

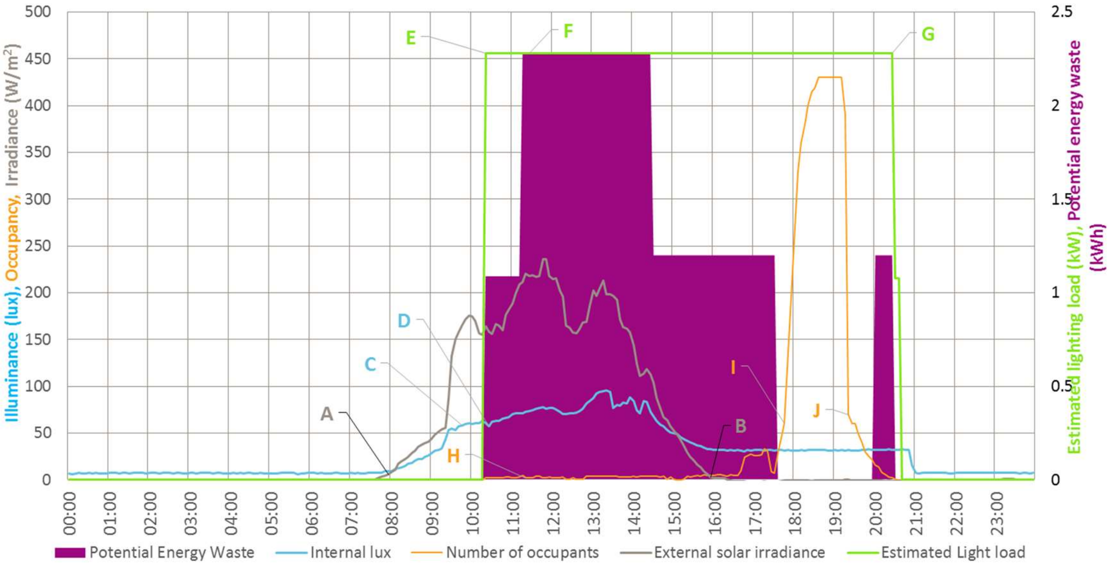

Figure 36: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Carol Service 1. Specific points of interest are as follows: A – Sunrise, B – Sunset, C – Rise in internal illuminance levels with natural light, D – Little increase in internal illuminance levels with artificial lights use, E – Chandeliers and stage spotlights turned on, F – Lights left on, G – Lighting turned off at the end of the day, H - Event organisers arrive to set up, I – Guests arrive for evening performance, J – Guests leave after performance ends.

During this Carol Service, the main sources of lighting were the chandeliers and the stage spotlights. These were turned on at the start of the day by the porters and members of the facilities team that were setting up some temporary steps by the stage. Because of the nature of their work the use of the stage spotlights was justified, however the use of the chandeliers in the hall during this task was considered unnecessary, especially as these lit the whole hall and not just the area of the hall where the stage steps were being built. All of the lighting remained on for the rest of the day, irrespective of occupant requirements or levels of natural light. At point F on Figure 36, the stage spotlights and chandeliers were all left on despite there being adequate natural light and also no real need from the occupants to have a higher level of lighting based on their tasks. Once natural light levels started to fall, the use of chandeliers by the event organisers would have provided useful lighting levels, however the use of the stage spotlights could still be considered wasteful. This is also applicable after the event ended when event organisers were closing the event down. It total, the behaviour of the facilities team and event organisers contributed to approximately 12.7kWh of lighting energy waste or 54% of the total estimated lighting energy that was used that day.

4.4.1.8 Graduation 1 and 2

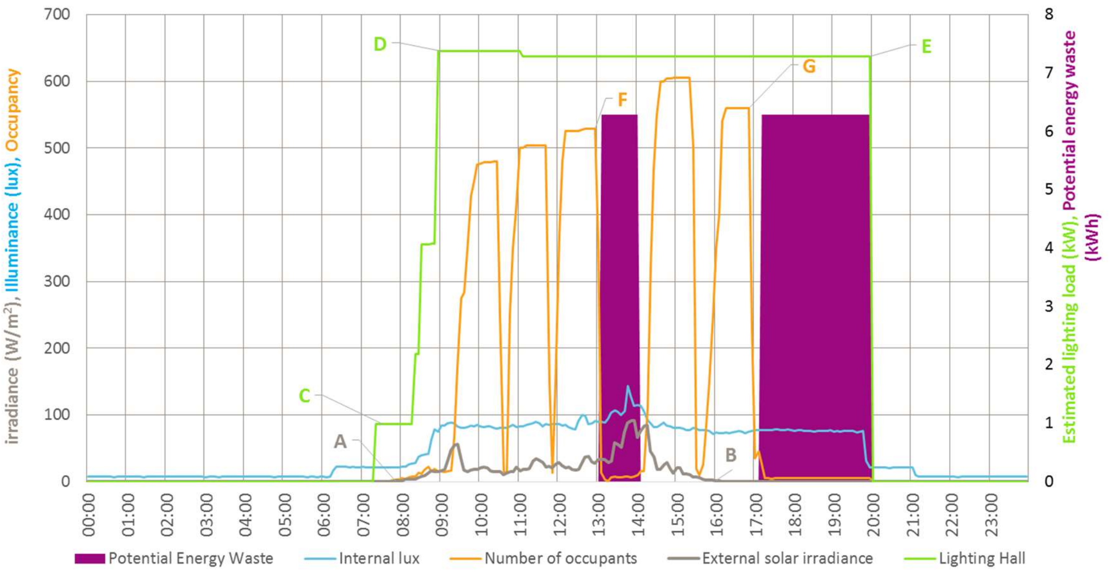

Figure 37: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Graduation 1. Specific points of interest are as follows: A – Sunrise, B – Sunset, C – Chandeliers

turned on, D – Floodlights turned on, E - All lighting turned off, F – Start of lunchbreak, G – End of last graduation ceremony.

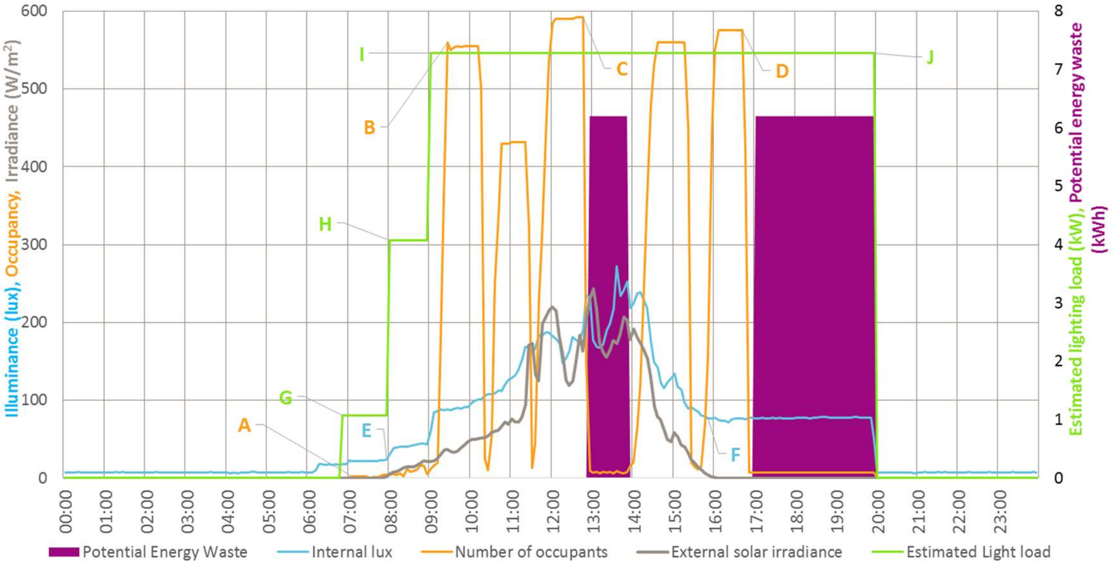

Figure 38: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Graduation 2. Specific points of interest are as follows: A – Event staff arrive, B – First ceremony begins, C – Lunch break, D – End of last ceremony E – Sunrise, F – Sunset, G – Chandeliers on, H – Cove lighting and stage spotlights on, I – Floodlights on, J – All lighting turned off

Of all of the different events monitored, the two graduation ceremonies were most similar to each other, with event organisers following a set lighting design for each of the days. Both of the graduation ceremonies showed very similar behaviour in terms of occupants and lighting. For both days all of the available lighting was used in the same way. Of interest was the incremental increase of different types of lighting at the start of the day according to the needs of the users, showing the potential for users to engage in energy conscious behaviour. However, at other times of day this was not the case.

Organisers arrived before sunrise and turned on some artificial lighting. Between 11:00 and 15:00 levels of illuminance suggest that the amount of natural daylight could have compensated for some of the artificial lighting's use, however artificial lighting use during this period remained the same in order to present the lighting design that event organisers had chosen for this event. In observing the activity of the occupants, it is likely that higher levels of illuminance were also required to facilitate filming during this event. There were two main times where lighting use was wasteful, during the lunch hour when the hall was mostly unoccupied and at the end of the day when event organisers were tidying up. During both of these times, higher levels of lighting through the use of cove lighting, floodlights and stage spotlights continued despite occupancy being very low in the hall and there not being a degree ceremony taking place. Comparing the energy use at the start and end of the day, levels of illumination had been sufficient in the morning prior to sunrise for the event organisers to prepare for the event, and consequently should have been sufficient after sunset at 17:00. Hence, lighting energy use of cove lighting, floodlights, and stage spotlights during the lunch hour and at the end of each day was identified as waste. This amounts to 24kWh of lighting related energy waste for the Graduation day 1 and 24.8 kWh of lighting related energy waste for Graduation day 2, or 28.7% and 29% respectively of the total lighting energy use over those days.

4.4.1.9 Carol service 2

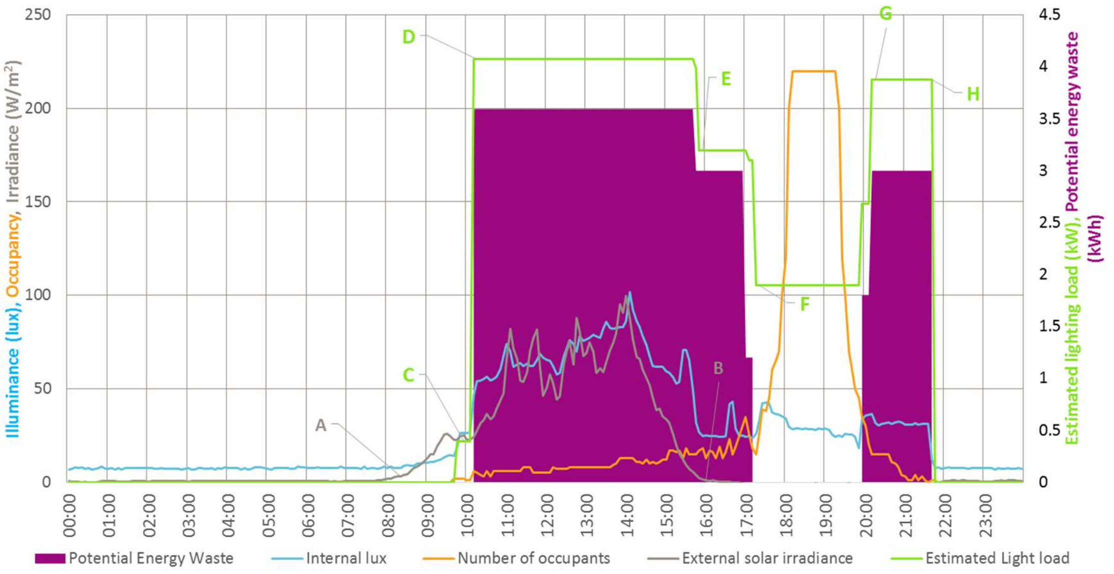

Figure 39: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Carol Service 2. Specific points of interest are as follows: A – Sunrise, B – Sunset, C – Four

chandeliers turned on, D – All ten chandeliers, cove lighting and stage spotlights turned on, E – Eight chandeliers turned off, F – Stage spotlights turned off for performance, G – Stage spotlights and eight chandeliers turned on after event ends, H – Porter turns all lights off.

During this carol service, event organiser behaviour was identified as the sole cause of the 29.3kWh of lighting related energy waste. This amounted to 74% of the lighting energy used that day. Interestingly, this was the only example of lighting use where the levels of artificial lighting during the performance were lower than the levels of artificial lighting at other times of day. During the evening carol service, additional lighting was brought in by the event organisers in the form of pre charged coloured LED boxes, reducing the reliance on fixed internal lighting. However, at other times of day there was a heavy reliance artificial lighting, despite it not always being necessary.

At point C of Figure 39, the porters had turned on four of the chandeliers. Once the event organisers arrived, further lighting in the form of the remaining chandeliers, the cove lighting and the stage spotlights were turned on at point D, as the porter showed the event organisers the lighting controls. These lights then remained on, despite increasing levels of natural light, as shown by the levels of external irradiance and the associated response from the internal illuminance levels. As the event organisers were setting up some equipment during the day, it is possible that they needed some task oriented artificial lighting and so the total lighting energy used during the daylight hours has not been considered as waste. At points E and F artificial lighting levels were reduced as some chandeliers and all of the stage spotlights were turned off. After the performance these were turned back on again and left on for the porter to turn them off almost an hour after the event had finished and the majority of the occupants had left the building. Consequently, the use of the stage spotlights and cove lighting during this time was superfluous to the needs of the occupants and therefore wasteful.

4.4.1.10 Exams 1, 2, and 3

Of the three exams monitored, Exam days one and two were very similar with two separate exams separated by a two-hour lunch break in each day. Exam day 3 consisted of only one afternoon exam. Despite levels of natural light being higher than for other events, blinds were used during all three days to reduce any potential glare problems for occupants. To ensure that all exam participants had adequate lighting, all sources of artificial lighting were used however, for all exam days the use of the stage spotlights was identified as waste as the stage area was not in use. For exam days one and two, the exam invigilators did not lower levels of lighting to their minimum requirements outside of the exam times and so there was additional waste identified during these times. In contrast, for exam day three, higher levels of lighting such as the floodlights were only turned on close to the time that exam participants arrived, despite the exam invigilators having been in the room for almost an hour. All of the lighting related waste for these three exam days is associated with the behaviour of the exam invigilators who were responsible for the building at these times. As expected, days one and two had a very similar waste profile amounting to 25.2kWh and 28.8kWh, or 37% and 43% of the lighting energy used over those days. For exam day three, due to the use of the stage spotlights, 5kWh of waste was identified, amounting to 18% of lighting energy used that day.

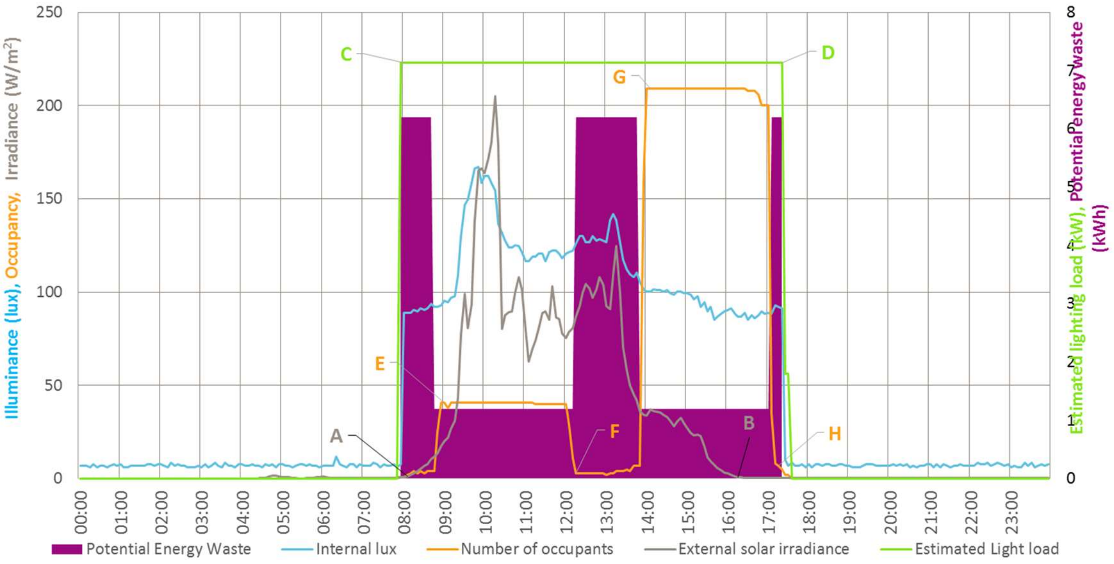

Figure 40: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Exam day 1. Specific points of interest are as follows: A – Sunrise, B – Sunset, C – All lighting turned on, D – All lighting turned off, E – Start of first exam, F – End of exam and lunch break, G – Start of second exam, H – End of exam.

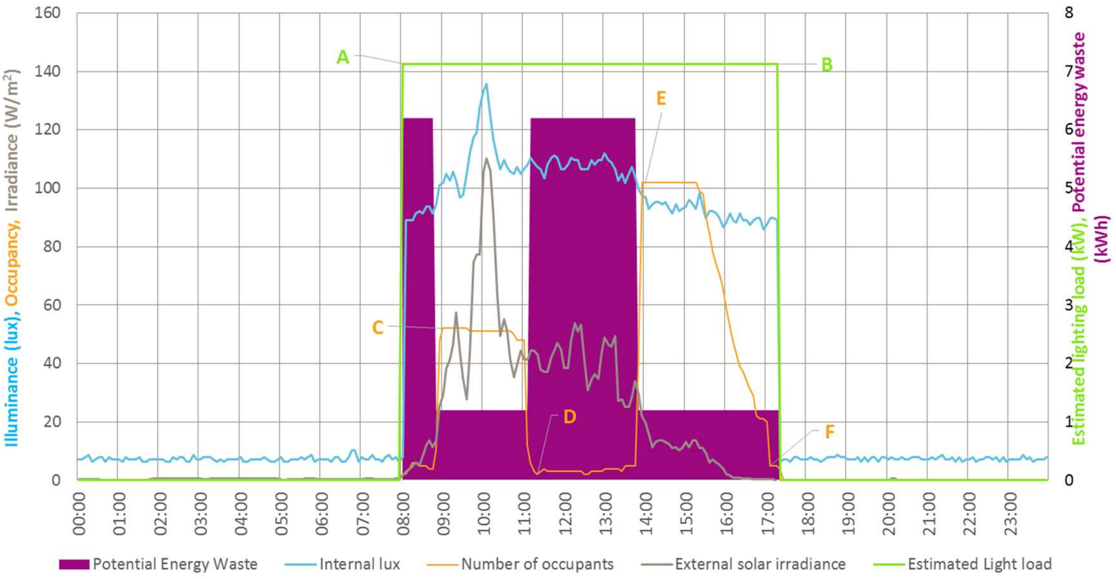

Figure 41: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Exam day 2. Specific points of interest are as follows: A – All lighting turned on, B – All lighting off, C – Start of first exam, D - End of exam and lunch break, E - Start of second exam, F – End of exam.

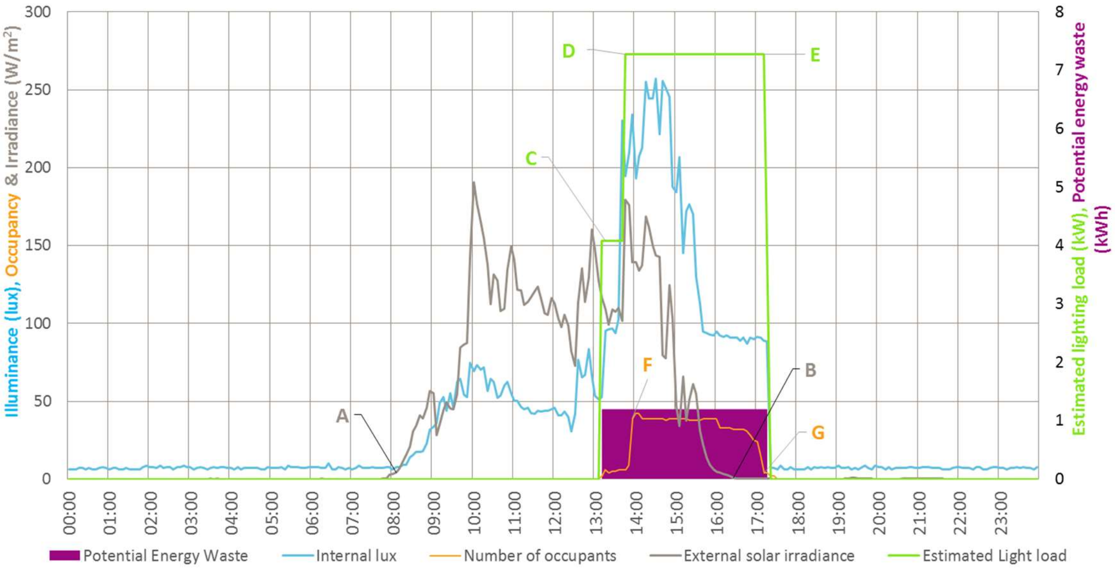

Figure 42: Estimated lighting use, lighting waste, measured illuminance and external irradiance for Exam day 3. Specific points of interest are as follows: A – Sunrise, B – sunset, C – Chandeliers, cove lighting and stage spotlights turned on, D – Floodlights turned on, E – All lighting turned off, F – Start of exam, G – End of exam

4.4.2 Heating energy use

This section discusses the heating energy used to heat each of the monitored events and identifies any potential heating energy waste based on occupant activity, and internal and external temperatures. Heating related energy waste was calculated as described in section 3.7.2. There were three main types of heating related energy waste identified;

- Poor BMS scheduling, where the times that the heating was on did not suit the needs of the occupants;
- Occupant behaviour, where occupants engaged with the building controls in a manner that resulted in heating energy being lost from the building;

- Inappropriate choice of set point temperature, where a lower set point temperature would have resulted in the BMS controlled heating system to turn off sooner once a lower set point temperature had been met.

4.4.2.1 Ball

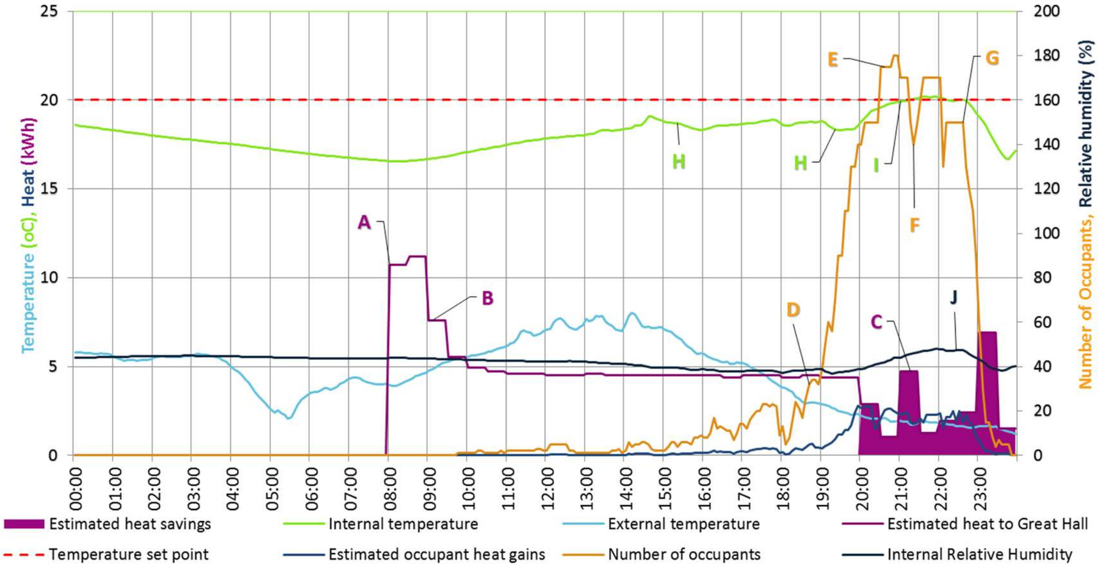

Figure 43: A – Heating on, B – Heating begins to plateau, C – Heating use fluctuates, D – Guests begin to arrive for the main event, E – Guests mostly dancing, F – Band have a break from performing, G – Guests leave, H – Temperature drop due to external door opening, I – Set point temperature achieved, J – Rise in humidity with increase in occupancy and activity levels

Figure 43 shows the variation of internal temperature throughout the ball with reference to external temperature, occupancy, occupant related heat gains and heat from the gas fired LTHW circuit. That the temperature set point was achieved only once occupant related internal heat gains increased during the main event in the evening is testament to the impact that these have on the internal environment. The temperature set point was achieved as occupancy levels rose and internal heat gains increased. Observations of the occupants themselves during the evening event showed behaviour that indicated they were too hot, for example the doors were opened to increase fresh air intake and people were visibly sweating, despite the set point temperature not being noticeably exceeded. This behaviour correlated with a 10% rise in humidity. With reference to Haigh (1982), this behaviour is possibly as a result of the rise in humidity rather than a rise in temperature.

The heating remained on during this time and gas consumption fluctuated throughout the evening event, correlating with the use of external doors for ventilation purposes. Had the set point temperature been lower, the heating system would not have continued to heat the room and it is possible that occupants would have been more comfortable with the room at a lower temperature. The purple shaded area identified in Figure 43 amounting to 136.2kWh of total heating related energy into the hall area, shows the potential saving if the building management system (BMS) had been scheduled to allow a lower temperature during the main evening event, thus avoiding the need for heating during this period. As the building's heating system is not zonally controlled, in order for this heating to be avoided the heating for the whole building would also need to be turned off. In this eventuality gas savings for the building as a whole would be higher, amounting to 197kWh or 15.3% of total gas used that day.

Prior to the evening event the temperature set point was not met and was only achieved once occupancy and occupant activity increased. This is potentially due to the event organisers' use of external doors causing increased heat losses, behaviour that demonstrated that they were less concerned with their thermal comfort. In terms of identifying energy waste, this event demonstrates how the current assumed occupancy schedule for the heating system could be considered inappropriate, as it was only continuously occupied from 14:00 onwards. However, without a better understanding of thermal losses through both open doors and the building fabric, an accurate quantification of this heating related waste and the impact that a delay in heating would have on evening internal temperatures is not possible. In terms of the scheduling of the BMS, the preheat time before continuous occupancy at 14:00 is in line with what should be expected for the month of December. Additionally, the heating comes on at 08:00 at with a falling internal temperature, and so it is likely that the BMS turned the heating on at this time to avoid any further temperature drop from which it would not be able to recover from in time for occupancy.

4.4.2.2 Concert 1

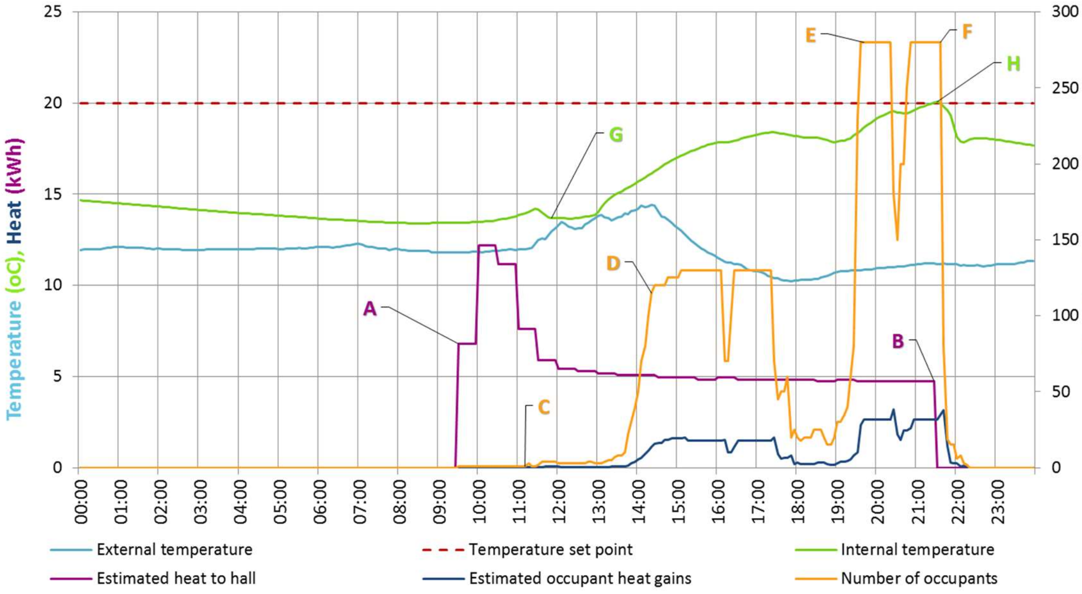

Figure 44: A – Heating turns on, B – Heating turns off, C – Event organisers arrive to set up for the event, D – Start of rehearsals, E – Start of evening concert with intermission, F – End of evening concert audience leaves, G – Dip in internal temperature with open external doors, H – Set point temperature achieved.

For Concert 1, the average internal temperature only exceeded the temperature set point by an average of 0.1°C. A maintenance issue with the BMS meant that the heating did not come on until after 09:30 when it was manually turned on after being off for the entirety of the previous day. This meant that the internal temperature in the morning dropped to below 14°C. Examining the heating related energy use and activity in the hall, the only identifiable heating related waste was the drop in internal temperature at point G, where the event organisers had left external doors open for 1.5 hours whilst the heating was on. At this time, the internal and external temperatures become equivalent with rising external temperatures and falling internal temperatures. Because of this behaviour, it was determined that the occupants were not concerned with their thermal comfort. It is therefore plausible to suggest a delay in the heating system coming on, especially as the internal temperature once the doors were closed was similar to the internal temperature prior to the heating coming on. This delay would see a saving of 216 kWh of heating related energy, or 26% of gas use that day.

As a whole, the temperature in the room struggled to meet the set point temperature and only did so towards the end of the concert, demonstrating the reliance on internal heat gains to reach this temperature. Although thermal losses through the building fabric have not been quantified, the internal temperature and heating use demonstrates that this building struggles to meet the set point temperature if the internal temperature drops below a threshold minimum without the additional heat from occupants. Compared to the day of the ball, where the external temperature dropped below 5°C in the morning, the internal temperature that day did not fall below 16.5°C because the building had retained some of the heat from the day before. This event had 100 more people in the room than the ball, and external doors were largely kept closed during the event itself. However, the level of activity of the occupants attending the concert was lower, meaning overall occupant related heat gains were very similar for the two events. This demonstrates the sensitivities of the building to variations in occupant activity, their subsequent internal heat gains, and the importance of maintaining a minimum internal temperature through the heating system.

4.4.2.3 Lecture 1

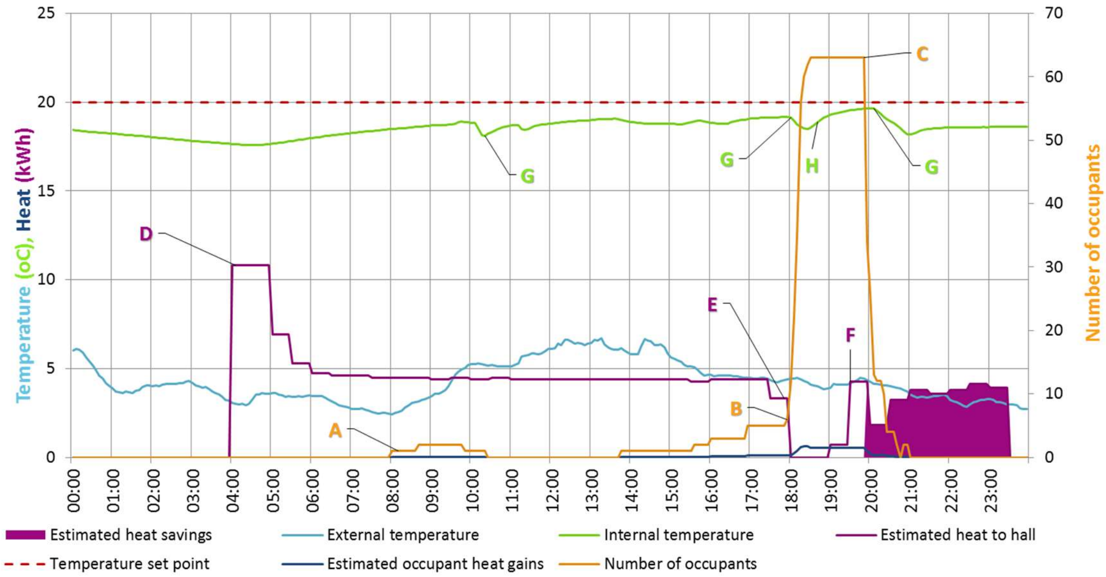

Figure 45: A – Porter setting up chairs, B - Guests arrive for evening event, C – Guests leave at end of event, D – Heating come on, E – Heating turns off, F – Heating comes back on and remains on after the event finishes, G – drop in internal temperature due to open external doors, H – Rise in internal temperature with closed doors and occupant heat gains

The most obvious heating waste for Lecture 1 is that the heating continued to stay on for almost four hours after the event had finished. The wasted energy in this period shown in Figure 45 amounts to 150kWh of heating energy or 15% of the heating energy used that day. The internal temperature during this event did not reach the set point temperature despite the additional heat gains from occupants as observed at point H. Examining the BMS logic, the minimum pre-heat time for the month of November, when this event was hosted is four hours. As the heating came on at 04:00, it is likely that the scheduling that day was set so that occupancy would be from 08:00. This is correct for when the porter arrived to arrange chairs in the hall, although his behaviour suggests that he was less concerned with his thermal comfort as he had left the external doors open to bring chairs in and out of the building. The internal temperature steadily rose from just after 04:00 until 10:00, at which point external doors being open led to a drop in average internal temperature by 1°C. Prior to this it had taken the heating system 6 hours to raise the temperature in the main hall by 1.2°C, and so almost all of this heating was lost. Consequently, the heating energy lost at this stage is a combination of poor BMS scheduling (as the porter did not require the room to be heated), and occupant behaviour (as the porter left the door open for over 20 minutes. This coupled with the identified energy savings due to poor scheduling at the end of the event day amounts to 513kWh of heating related energy, or 51% of gas used that day.

Examining the period between 12:00 and 15:00, the internal temperature plateaued despite a rising external temperature and the heating being on. This demonstrates the limitations of the heating system to achieve the set point temperature when the external temperature is below a minimum threshold temperature. However, the internal temperature regained the lost 1°C in only 3 hours, which could be explained by both the external temperature rising and also the building's thermal mass retaining more heat with the heating being on. At 18:00 the heating system turns off, shown at point E on Figure 45. It is possible that this is because the BMS temperature sensors had recorded that the internal set point temperature had been achieved. Based on the comparison between readings from the HOBO sensors used in this monitoring and the BMS loggers shown in section 3.6.3.3, the BMS loggers consistently recorded temperatures higher than those observed by the HOBO sensors, despite them being next to each other. This coupled with the location of the BMS sensors being higher than the standard 1.5m (which is where the HOBO sensors were positioned in the hall), could mean that the heating system had recorded that the temperature set point had been achieved and therefore responded by turning itself off. At point F, the heating came back on and stayed on, likely in response to a drop in temperature as recorded at point G at 18:00 on Figure 45.

4.4.2.4 Concert 2

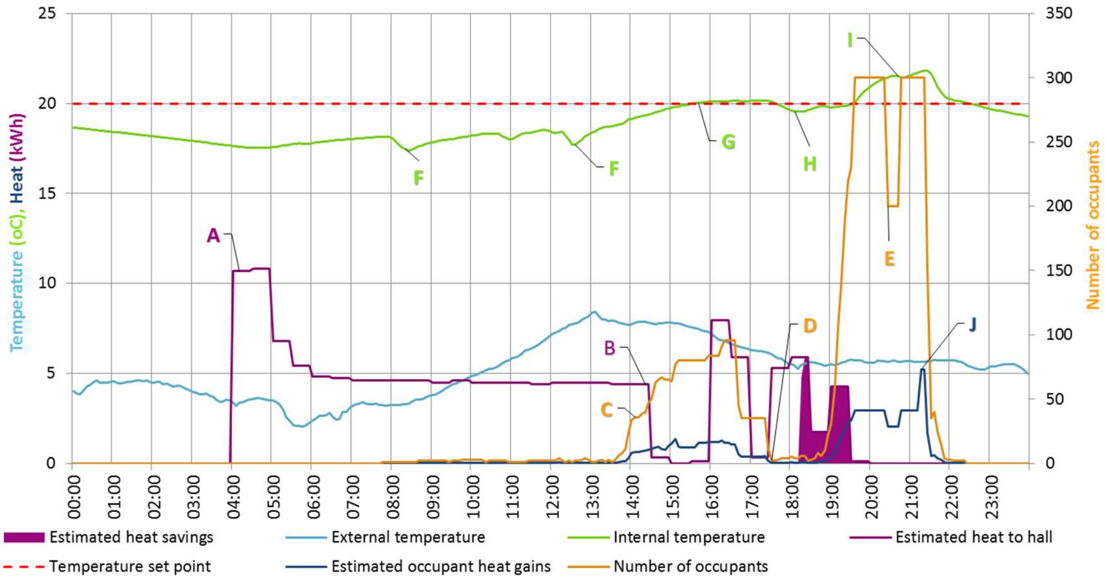

Figure 46: A – Heating comes on, B – Heating turns off, C – Performers arrive for rehearsals, D – Performers leave for break, E - Intermission during main evening event, F – Drop in internal temperature due to external doors opening, G – Set point temperature achieved, H – Internal temperature falls below set point following low occupancy, I – Temperature set point exceeded during evening performance, J – Occupant internal heat gains peak as whole audience is singing.

The event organisers for Concert 2 arrived at approximately 13:00 with performers arriving shortly afterwards for rehearsals. Prior to this the only building user had been the porter arranging chairs for the audience. The internal temperature in the hall began to steadily rise with the heating use from point A at 04:00, although this was affected by external door opening at points F. The set point temperature was only achieved once a greater number of occupants arrived and the doors were closed. Once the set point temperature was reached the heating system began cycling on and off. It is observed at this point that the set point temperature being achieved was slightly later than when the heating system first turned off and could be due to three reasons; firstly that the location of the BMS temperature sensors is higher than the standard 1.5m and so the air temperature could be slightly higher at that height, and secondly that there are only two BMS sensors compared to the ten temperature sensors used in this monitoring, so the average of temperature around the hall may have been lower than the temperature where the BMS sensors are positioned. Thirdly, as shown in section 3.6.3.3, the BMS temperature sensor consistently recorded the temperature to be higher than the temperature recorded by the additional sensors installed by the researcher.

The reliance on occupant related internal heat gains to achieve the set point temperature is demonstrated at point H, where despite the heating being on and external doors closed the internal temperature dropped below the set point. The potential heat savings identified in Figure 46 relate to the temperature rise at point I that correlates with an increase in estimated heat gains from occupants. The thermal energy from occupant related internal heat gains at this stage could have offset some of that from the heating system. This accounts for 53kWh of heating energy, or 6% of the heating energy used that day.

As with other events, e.g. Concert 1, the building users setting up for the event, in this case the porters, seemed less concerned with their thermal comfort, evidenced by them leaving external doors open for periods of time long enough to allow the average temperature of the room to noticeably fall. During this time, the heating system contributed to the internal air temperature and raised the temperature of the thermal mass, however, there is no net gain in internal temperature rise between the heating going on and the doors closing. This is shown at points F and suggests that the heating use could be delayed whilst building users are engaging in these activities. Delaying the heating coming on until 08:30 would see a potential heating related energy saving of 305kWh or 35.6% of gas used that day. Even though occupants leave doors open at around 12:30, delaying the heating further would mean that there is more risk that the heating would not be able to reach the internal temperature set point in time for the afternoon rehearsal period.

4.4.2.5 Concert 3

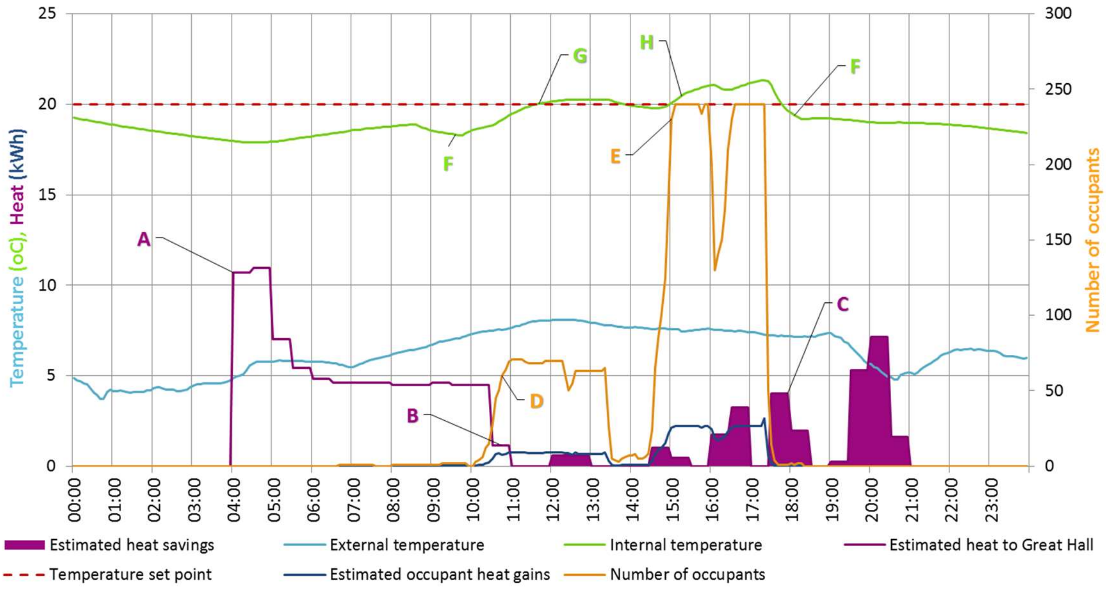

Figure 47: A – Heating on, B – Heating begins to cycle off and on, C - Heating turns on after event finishes, D – Performers arrive for rehearsals, E – Main performance with guests, F – Drop in internal temperature due to open external doors, G – Set point temperature achieved, H – Set point temperature exceeded.

As with Concert 1 and 2, Concert 3 consisted of a period of rehearsal for the performers shortly followed by a performance for guests with an interval period. The heating came on at 04:00 and by 10:30 was cycling on and off in response to the internal temperature which had reached its set point at point G. At point F at 09:00 on Figure 47 there is a decrease in the internal temperature as the external doors are left open. This is followed by a rise in temperature as the occupants begin their rehearsals and the external temperature rises. Analysing the heating consumption profile and the internal temperature profile together, shows that there is a lag in the response from the heating system to the observed temperatures. Multiple examples are visible during this event, for example a temperature drop between 09:00 and 10:00 sees the heating coming back on at 12:00, a drop in temperature at 14:00 sees the heating coming back on between 14:30 and 16:00, and a drop in temperature at 18:00 sees the heating coming back on at 19:00. As the gas consumption is only recorded half hourly, and the chart shows the data in 5 minutely intervals, the granularity of this data potentially distorts how the gas consumption appears over this time period. The averaged five minutely estimate for heating energy shows that when the heating is constantly on, the maximum consumption is on average 4.6kWh (this is approximately 6.67kWh of gas every 5 minutes, or 40kWh of gas half hourly, taking into account the boiler's estimated gross efficiency of 88%). During periods where consumption is lower than this, for example between 12:00 and 13:00, it is likely that the heating was not on for the full half hour period and that the recorded value is what was consumed within a shorter time period.

Additionally, the 6-hour time period that the hall was heated prior to occupancy 10:00 is reflective of the minimum pre-heat time set by the BMS for the month of December. As the BMS optimises the heating schedule based on the internal and external temperatures, it is possible that this minimum pre-heat period was calculated by the BMS optimiser because the internal temperature did not drop below a programmed threshold.

Therefore, even though it is suspect that the heating started at 4am (when concert 2 and lecture 1 seem to default to this time with similar internal and external temps) this scheduling seems to work well for this event. The heat loss at point F can be attributed as waste to any individual to the porter who opened the external doors at this point to bring equipment in and out. Overall, in terms of wasted heating energy, the bulk of the 206.5kWh of identified waste is due to the heating staying on after the event finished, with additional savings found through offsetting some of the heating with internal heat gains. In total, 33% of the heating related energy used that day is identified as wasteful.

4.4.2.6 Lecture 2

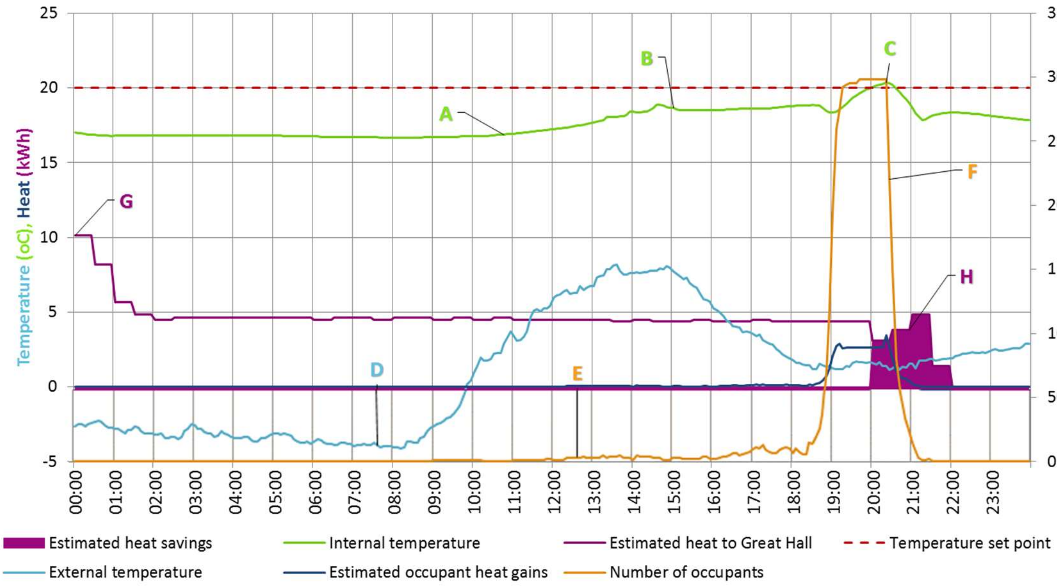

Figure 48: A – Internal temperature rise, B – Drop in internal temperature, C – Set point temperature achieved, D – Sunrise, E – Event organisers arrive to set up, F – Guests leave after lecture finishes, G – Heating comes on at midnight, H – heating stays on after event finishes

The overnight external temperature during Lecture 2 was below freezing. The space heating during this event was already operating at midnight but produced very little impact on the internal temperature which stabilised around 16.8°C. At point A on Figure 48, the internal temperature began to steadily rise and then drop slightly at point B. This temperature profile shows the sensitivities of the building to external temperatures and the limitations of the heating system. The dip in the estimated heat to the hall at 20:00 suggests that it is possible that the heating system turned off for a period once the set point temperature was achieved. However, due to the granularity of the gas data this is not shown in the chart and instead it appears that the heating continued to stay on. The estimated heating use then increases after the event finishes in response to the drop in internal temperature. This presents the only observable heat waste during this day, whereby the heating stayed on for 1.5 hours after the event had ended and potentially 2 hours after the set point temperature had been achieved. This amounts to 78.8Wh of heated related energy, or 6.4% of heating used that day.

4.4.2.7 Carol service 1

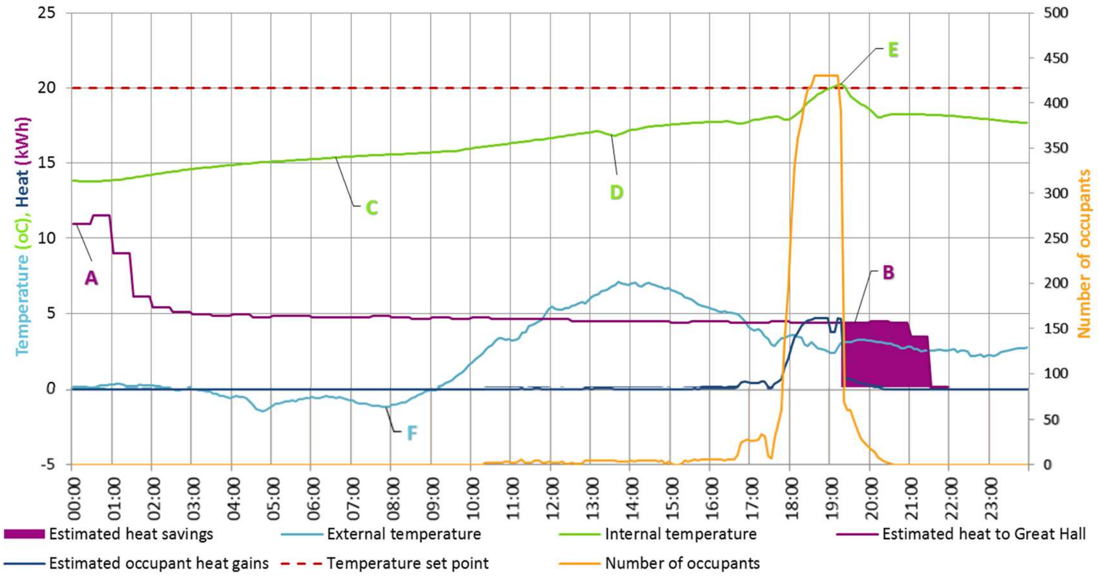

Figure 49: A – Heating turns on at midnight, B – Heating stays on after event finishes, C – Steady rise in internal temperature, D – Drop in internal temperature with open external doors, E – Set point temperature achieved, F – Sunrise.

The results of the energy data and observations for Carol Service 1 identified very little heating energy related waste. When observations began at midnight, the heating was already on at which point the internal temperature had dropped below 13.8°C. As was noted for Concert 1, the heating system struggled to meet the set point temperature with such a low initial temperature, doing so only with contribution from occupant related internal heat gains as shown by the sharp increase in temperature between 18:00 and 19:00. Interestingly, the rate of internal temperature rise throughout the day did not increase in response to the increasing external temperature during the day. This emphasises the effect that the building’s thermal mass can have on dampening the response of internal temperature to changes in external temperature. The drop in internal temperature after the event from 19:00 to 20:00 is in part due to a lack of occupant internal heat gains, and also because of open external doors that were in use intermittently throughout the evening event for guests to access the toilets. It is not possible to estimate here exactly what savings could have been achieved if these external doors that open directly into the hall were not in use. The only heating waste identified for this event is that the heating remained on after the event finished for over 2 hours. This amounted to 114kWh of heating related energy that could have been saved, or 8.8% of the heating energy used that day.

4.4.2.8 Graduation 1

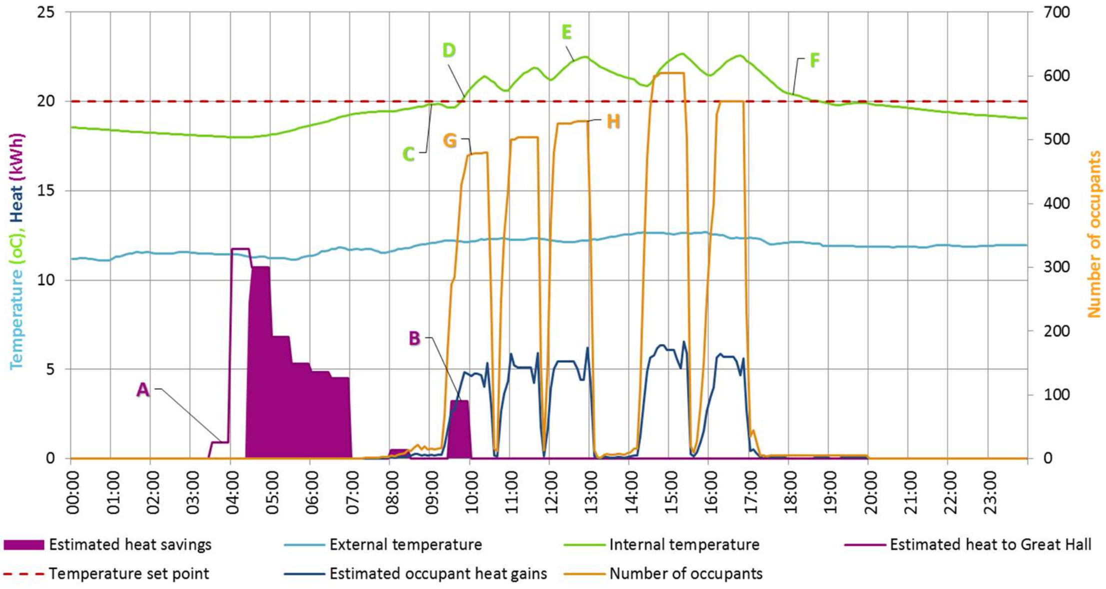

Figure 50: A – Heating turns on, B – Heating use fluctuates, C – Set point temperature achieved, D – Set point temperature exceeded, E – Internal temperature fluctuates with door opening and varying occupancy, F – Internal temperature drops with lower occupancy and open external doors, G – First degree ceremony, H – Lunch break.

Both graduation ceremonies show very similar heating and waste profiles. In both, the majority of the heating could have been offset by the internal heat gains generated by the occupants throughout the day. On both days, before the heating came on the internal temperature did not drop below 18°C. Interestingly, despite this and the very similar external air temperatures for the two days, the heating for graduation day 1 came on 2.5 hours earlier than for graduation day 2. Examining the temperature data for these two graduation ceremonies and the times heating comes on, Graduation 1 is colder by approximately 0.5ºC for both internal and external temperatures. This finding is interesting because a small difference in temperature of 0.5ºC has resulted in a significant increase in the pre-heat time for the same programmed occupancy schedule. Overall, this results in an increase in gas consumption of 110kWh. As Graduation day 2 managed to achieve the set point temperature before the occupants arrived with 2.5 hours less heating, arguably Graduation day 1 could also achieve the set point temperature in the same time, thus avoiding this extra energy consumption.

As the set point temperature is achieved 5 hours after the heating comes on, matching the BMS logic's coded pre-heat time for December, this seems to imply that the average design external temperature assumptions for December are around 11.5ºC. For both days there is a clear correlation with internal temperature and occupancy, indicating that occupant related heat gains, estimates of which are also shown on Figure 50 and Figure 51, contributed to a continued temperature rise above the set point in the absence of the heating being on. Drawing upon this evidence, the internal heat gains from occupants and lighting led to the building exceeding its heating set point temperature. The temperature fall at periods of low occupancy was exacerbated through the opening of external doors to allow people to enter and exit though it was not enough for the temperature to fall below the set point. During both Graduation days it was observed by the researcher that occupants were engaging in behaviour indicating that they were too warm, including taking off extra layers or fanning themselves to try and cool down. This behaviour was more common during events with higher occupancies, signifying that this was due to occupant related internal heat gains.

Graduation day 1 had less occupants than Graduation day 2. Despite the heating coming on earlier, there was less heating waste identified as this has been calculated based on the temperature rise above the set point for each 5 minutely period, the sum of which was lower than that for Graduation day 2. This heating energy from the occupants' internal heat gains is the energy that could offset the use of heating energy. For Graduation day 1, the calculated heating energy above the set point temperature equated to 224kWh of heating related energy, or 77% of the heating energy used that day. The majority of the remainder of the heating energy used could be attributed to that required at the start of the day to heat the water in the primary side of the LTHW system to temperature. Although the set point temperature being achieved is marked in Figure 50 and Figure 51 as when the average monitored temperature reaches 20°C, it is evident looking at this data that the heating turns off before this is observed. As mentioned previously, this could be due to three factors; the position of the BMS sensors being higher than the standard 1.5m; the location of the two BMS sensors not being representative of the room as recorded by the sensors used for this monitoring; and the BMS temperature sensor logging higher temperatures than the additional HOBO sensors.

4.4.2.9 Graduation 2

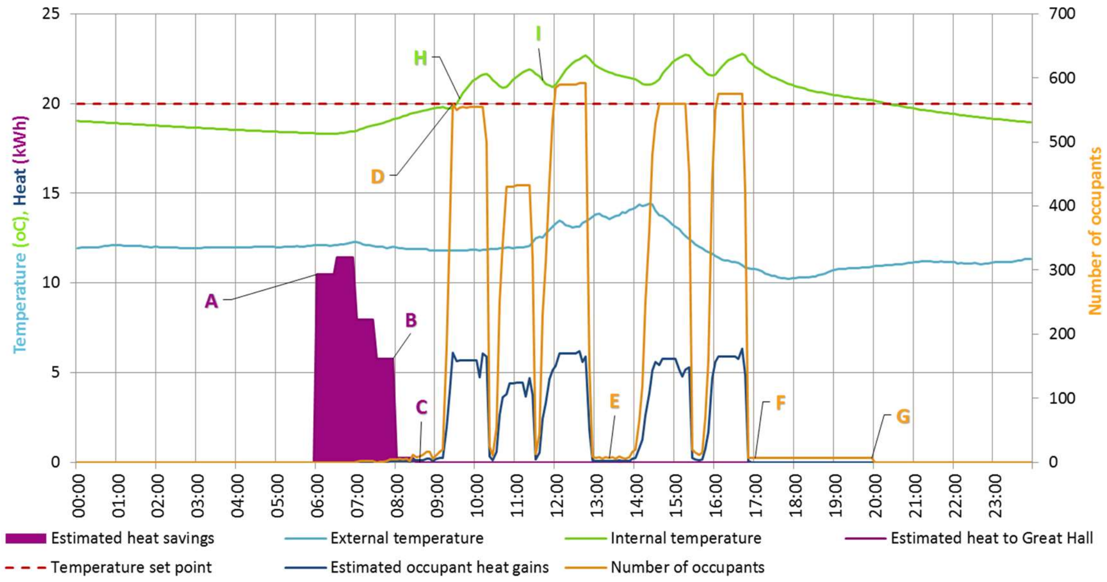

Figure 51: A – Heating turns on, B – Heating starts to turn off, C – Heating is off, D – first ceremony starts, E – Staff on lunch break, F – Last ceremony finishes, G – Staff finish packing up and exit

building, H – Set point temperature exceeded, I – Internal temperature fluctuates with occupancy and doors opening.

Figure 51 shows the variation of internal temperature throughout graduation day 2 with reference to external temperature, occupancy, and heat from the heating system. By 8:30am the heating system automatically switched off in response to the BMS temperature sensors recording that the set point had been achieved. As with graduation day 1, the internal temperature continued to rise in the absence of heating and the presence of occupants. Examining the period of time that the internal temperature exceeded the set point, the increase in temperature above the set point translates to 258.5kWh of energy. It has been estimated that the amount of heat used to heat the building in the morning was 215kWh. Therefore, 100% of this energy could be considered as waste. This amounts to 311kWh of gas that was combusted that day to heat the whole building. In examining a lower set point temperature for this event, the overnight internal temperature did not fall below 18°C, which as mentioned previously is adequate for other building types. In this circumstance the heating would not come on.

4.4.2.10 Carol Service 2

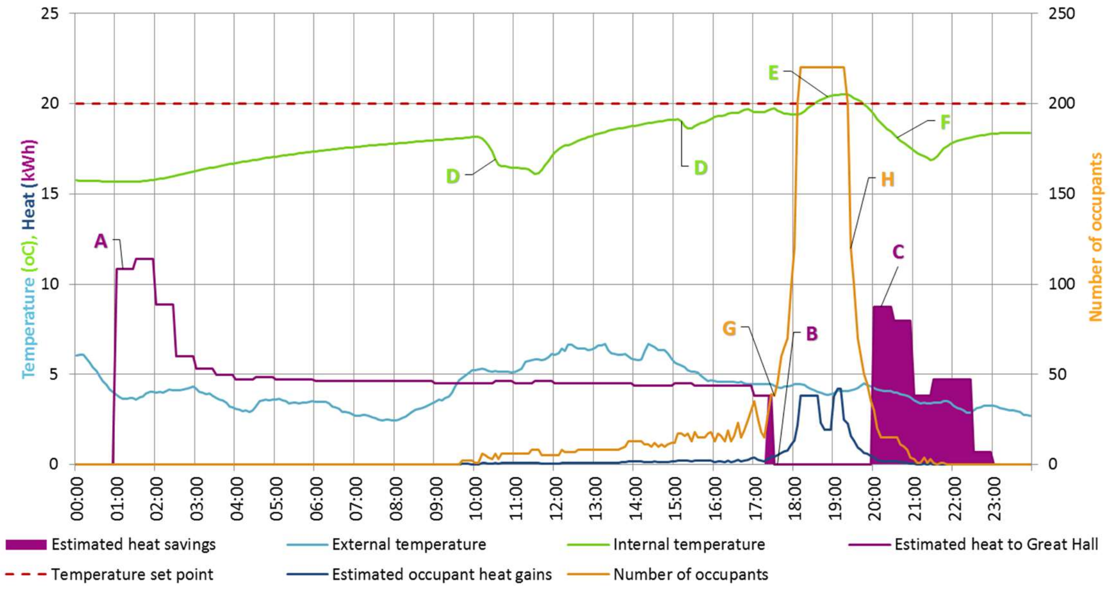

Figure 52: A – Heating turns on, B – Heating turns off, C – Heating comes back on after event ends, D – Internal temperature drop due to open external doors, E – Set point temperature exceeded, F - Internal temperature drop with open external doors

The heating for Carol Service 2 came on at 01:00 and remained on until after the event finished. The majority of the energy waste identified in Figure 52 was due to this scheduling overestimate at the end of the day, and an additional amount estimated from the temperature rise above the set point at point E. Once event organisers arrived at 09:40, their behaviour indicated that thermal comfort was not of great importance to them as external doors were left open. Although they had to bring equipment in from outside into the building that required the external doors to be open and took 25 minutes to do so, the external doors were left open for approximately 1.5 hours. The temperature drop caused by this behaviour is clearly shown at point D between 10:00 and 12:00, when the average temperature dropped by more than 2°C to 15.9°C. This amounts to approximately 174kWh of heating energy lost from the building. The BMS programming indicates that the heating system's minimum preheat time for December is 5 hours, with the BMS optimiser calculating additional pre-heat times based on the external temperature, the observed internal temperature, and the required set point temperature. For the day of Carol Service 2 this was 9 hours. The minimum temperature overnight was 15.5°C. Based on occupant behaviour it is possible to suggest a delay in heating, though with the overnight temperatures it is not possible to estimate how low the temperature would fall and the impact on internal temperatures for the rest of the day in the absence of heating without computer simulation that could take into account both thermal losses and the impact of the thermal mass. In total the energy waste for this event that includes the wasteful heating energy used at the end of the day, the contribution from internal gains and the open external doors, amounts to 365.3kWh of heating related energy waste, or 30.4% of the gas used that day.

4.4.2.11 Exams 1

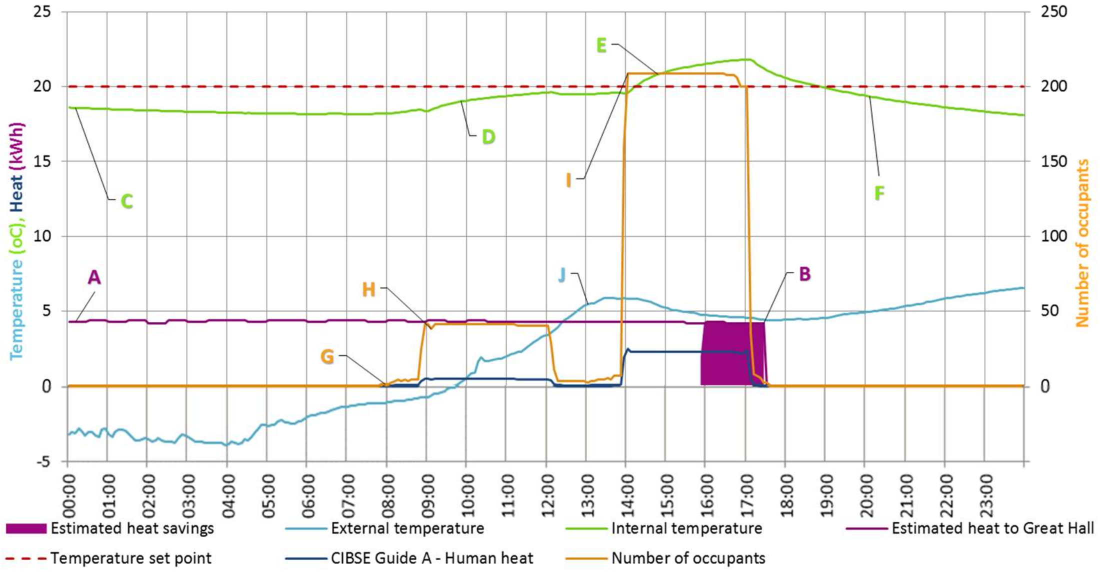

Figure 53: A – Heating continuously on from midnight 3 days prior to event, B – Heating turns off, C – Internal temperature has not dropped below 17.7°C for 3 days prior to event, D – rise in internal temperature, E – Set point temperature exceeded, F – Drop in internal temperature with heating off and no occupants, G – Exams team arrive to set up for exam, H – Start of first exam, I – Start of second

exam, J – Steady rise in external temperature

Exam 1 represented the first use of the hall since the Christmas break. All exam days show potential energy waste through inappropriate scheduling, whereby the heating came on either the day before or in the case of exam day 1, three days before. The reason for this is unknown, however the sub-zero external temperatures prior to Exam day 1 may have factored into this. However, as seen during other events, the BMS scheduling prompts the heating to turn off even when the internal set point has not been achieved if it is outside the scheduled hours of use. As the internal temperature did not drop below 17.7°C during these three days, it is likely that there was a fault with the heating system.

For both exam day 1 and 2, there were two exams, one in the morning and one in the afternoon. Exam day 3 had one exam in the afternoon. For all exam days the internal set point temperature was only reached once occupants arrived in significant numbers.

The temperature set point for Exam day 1 was achieved during the afternoon session by 14:15. Interestingly, this event shows a deviation from the normal activity of the BMS with the heating remained on after the set point temperature had been achieved. This indicates that there was either a problem with the heating system or the BMS sensor could be recording temperatures lower than the temporary HOBO loggers. This latter point is unlikely as for all previous events, and during the control monitoring period to examine the error between the two different sensors detailed in section 3.6.3.3, the BMS sensors on average recorded readings that were 2% higher than the HOBO loggers.

Additionally, the BMS manager could have increased the set point beyond 20°C or had manually changed the scheduling so that the heating stayed on irrespective of the internal temperature and stayed on until the exam was scheduled to finish. The latter of these options is considered to be the most likely, especially as the heating turning off aligns well with the time period that the hall was vacated at 17:30. This additional heating and the internal heat gains from the occupants resulted in the internal temperature exceeding the set point temperature during the afternoon exam. The energy waste identified in Figure 53, is due to the set point temperature being exceeded and amounts to 81.5kWh of heating related energy, or 9% of gas used that day.

4.4.2.12 Exams 2

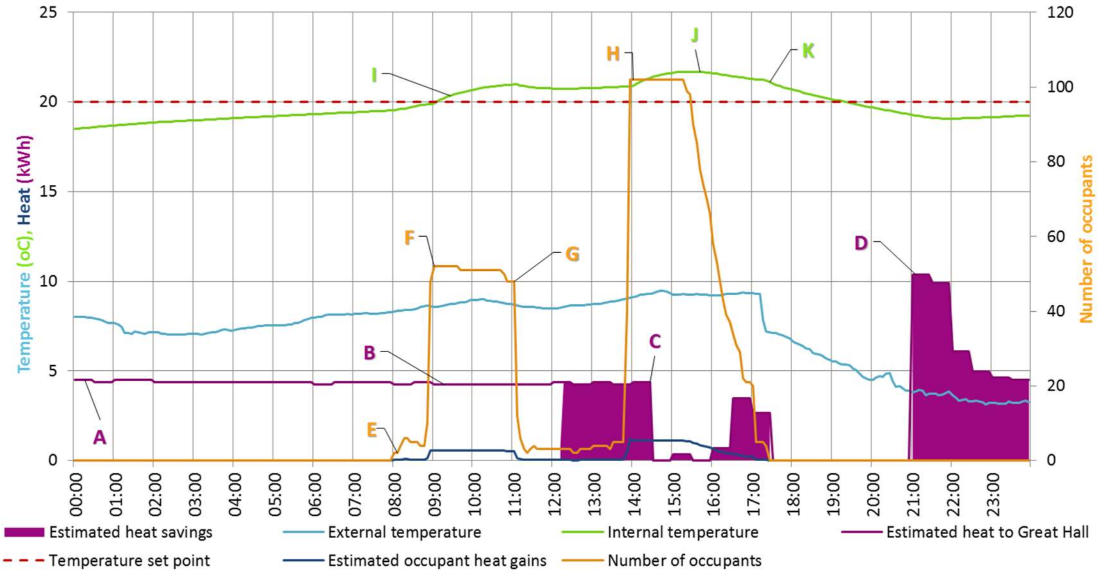

Figure 54: A – Heating on from 18:30 the day before, B – Heating stays on after set point temperature is met, C Heating use begins to fluctuate on and off before turning off at 17:30, D - Heating comes back on at 21:00, E – Exams team arrives to set up for exam, F – Occupants arrive for first exam, G – End of first exam, H – start of second exam, I – Set point temperature exceeded, J – Internal temperature peaks at 21.7°C, K – Internal temperature drops with no occupants or heating and falling external temperatures.

For this event, which was on a Monday, the heating came on at 18:30 the day before. In discussion with the BMS manager regarding both exam day 2 and 3, it is likely that this is because the scheduling had been manually set to come on at that time to ensure the hall was adequately heated for the students taking exams the next day. However, this heating schedule is based on the BMS manager's interpretation of what the occupants wanted with no direct engagement with building users. Additionally, this scheduling was not based on any direct data from the building in terms of the time that it takes to reach temperature and the contribution from internal heat gains. Looking at the data presented in Figure 54, this energy use is wasteful and the heating could have instead been delayed until at least 03:00 allowing for the programmed preheat time of 5 hours for December. This delay would see a saving of 451.4kwh of heating related energy.

Examining overnight temperatures, and the speed at which the set point temperature was achieved and then exceeded, this scheduling is overcautious. This observation can be further justified by comparing the event against another day with a similar external temperature and occupancy, for example Concert 3. Both events had an external temperature between 5°C and 10°C and an occupancy of around 50-60 people when the set point temperature was achieved. For Concert 3, the heating came on automatically at 04:00 to begin pre-heating. Therefore, it is highly likely that the set point temperature would be achieved with similar scheduling for this event. This is perhaps even more likely for this event as the external doors were not used as frequently, thereby reducing thermal losses through these means. The main difference between the two events is that the occupants for Concert 3 arrived in significant numbers (50-60 people) an hour later, and their level of activity was also slightly higher than the occupants during Exam day 2.

During Exam day 2, the internal temperature peaked at 21.7°C. Although this is not uncomfortable by CIBSE Guide A (CIBSE 2016) guidelines on temperature and comfort, it is still almost 2°C above the desired set point temperature. Had the heating been delayed it is likely that the desired set point temperature would still have been achieved through the heating system and internal heat gains but would perhaps not have been exceeded to this extent and provided energy savings. The use of the heating from 21:00 to midnight has been identified as waste, but as this is pre-heating for an exam the next day, this waste has been attributed to Exam day 3.

The temperature set point for Exam day 2 was achieved at 09:00 but as with Exam day 1, the heating stayed on despite this. The waste identified from 12:00 to 17:30 represents the heating energy that could be offset by the temperature rise above the set point. This temperature rise is due to both the heating and the internal heat gains from the occupants. Although the heating remained on once the set point temperature had been achieved, energy waste has not been outlined from 09:00. Instead, the thermal energy that accounts for the period of time that the set point temperature was exceeded was calculated, amounting to 160kWh. In reality, once the set point temperature has been achieved the heating system should cycle on and off in order to maintain the set point temperature and not exceed it for an extended period of time. This is only observed from point C on Figure 54 at approximately 14:30, which is 5.5 hours after the set point was achieved.

In a perfectly sealed environment with no additional internal heat gains, the temperature rise inside the space would equal the heat from the heating system i.e. from 09:00 to 17:30, and the temperature rise would therefore be much higher than is observed. As the building incurs thermal losses that are already taken into account through monitoring the internal temperature, and because there are additional heat gains from occupants and lighting, this calculated thermal energy is equal to the amount of energy from the heating system that could be offset if the set point temperature were to be maintained and not exceeded.

In total, the heating related energy waste identified for this event amounts to 612kWh of heating energy, or 58.7% of the gas used for this event. The heating use from 21:00 was to pre-heat the space in preparation for the exam the next day. As observed during that event (Exams 3), this was overly cautious and amounting to wasted energy. This energy waste is attributed to Exams day 3.

4.4.2.13 Exams 3

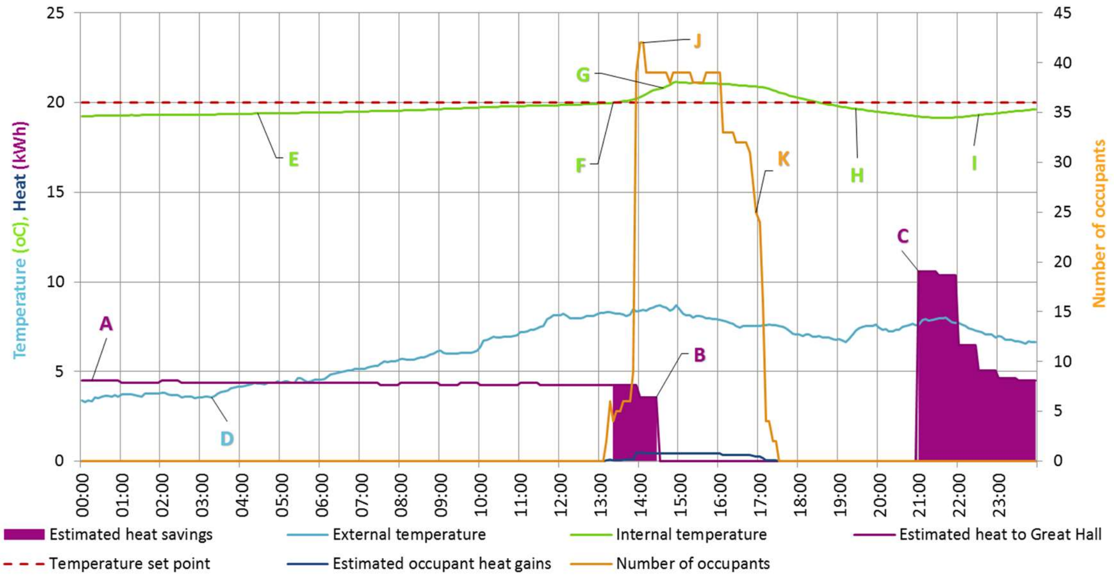

Figure 55: A – Heating on from 21:00 the day before, B – Heating turns off, C – Heating turns back on at 21:00 despite no occupancy in the hall the next day, D – External temperature begins to rise, E – Internal temperature stabilised at above 19°C overnight with increase in rate of increase from 07:00 (corresponding with a rise in external temperature), F –Set point temperature met, G – Set point temperature exceeded, H – Drop in internal temperature with no occupants or heating, I – Rise in internal temperature with heating use

For Exam day 3, the overnight temperature was maintained above 19°C and had not dropped below this since the previous morning. The set point temperature was exceeded with an occupancy of less than 50 people.

As with Exam day 2, the heating came on at 21:00 to preheat the space for the next day. This is an example of how clearer communication with building users and the BMS manager could lead directly to energy savings as the hall was not in use the next day and so it was not crucial that the set point temperature be achieved. Consequently, this heating energy use is identified as wasteful. As with Exam day 2 in addition to this, the heating energy that could be offset through internal heat gains is also identified as waste.

As this event only had one exam in the afternoon, based on previously monitored events with a similar external temperature, it is highly likely the set point could have been achieved if the heating had come on that morning instead of at 21:00 the night before. Overall, the heating related energy waste identified for this event amounts to 835.2kWh, or 83.3% of the gas used for this event.

The heating energy use for all three exams is also an example of a non-data driven energy management model employed by the BMS manager. In discussion with the BMS manager about these events, the researcher observed the BMS manager applying his own subjective judgement to the needs of the occupants without any objective data or dialogue with the occupants. This is because his rationale is that he did not want the students taking their exams to feel cold, but in doing so did not account for the discomfort caused to these students if they were too warm. Consequently, the heating system's scheduling is based entirely on the BMS manager's perception of what the occupants would need based on his knowledge of the building's construction, without understanding of the impact occupant related internal heat gains can have on internal temperatures.

4.5 Categorisation and quantification of energy waste

This section focuses on a high-level analysis of the data from the monitored events in order to identify potential energy savings opportunities and an insight into overall building energy performance for the heating season.

As with any complex events/buildings, the determination of waste will involve assumptions and experiences which could change from one assessor to another and any item of specific assessment could always be improved, though we believe the overall approach and the demonstration of the approach as presented are sound.

In order to provide an understanding of the impact of different activities on overall building energy use, it is of value to categorise the identified energy waste into its different sources.

Quantifying the different categories of waste and providing an insight into how it was generated from different sources can be useful in order for building managers and energy users to make informed and targeted decisions about a building's energy consumption.

The energy waste identified is separated into lighting related energy waste and heating related energy and is distilled from sections 4.4.1 and 4.4.2. For both types of energy use, the energy waste is also presented as a percentage of total lighting related energy of gas consumption. Total lighting related electricity, not total electricity to the building is used in this analysis because building level electricity also serves other end uses. In contrast, for heating the only purpose of the gas is to heat spaces that are not zonally controlled, and so heating related energy waste is presented as a percentage of total gas use.

4.5.1 Lighting energy waste

In examining the lighting energy use from each individual event, it was apparent that the energy waste was primarily due to two reasons; occupant behaviour or inflexible lighting controls, with behaviour being the larger and more consistent reason across the different events.

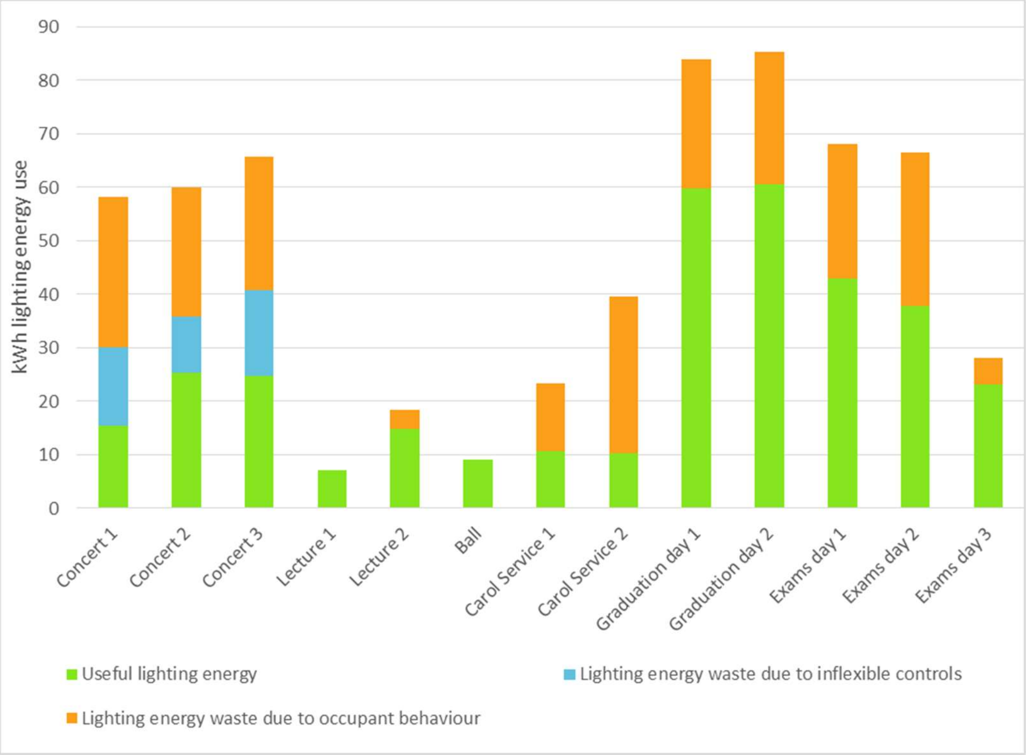

Figure 56: Kilowatt hours of lighting energy use per monitored event that was identified as useful, wasteful due to event organiser behaviour or wasteful due to inflexible controls

Figure 56 presents the overall lighting energy use from the monitored events and quantifies the energy that was identified as useful and wasteful for each. As expected from the monitoring not all events used the same amount of lighting energy, with some using comparatively very little to meet the event’s needs. Occupant behaviour was the most significant factor that contributed to lighting related energy waste. It is important to note that an occupant is defined as any member of the University’s staff, or any client hiring the space that had direct access to the building’s lighting controls for any duration of the day.

Only 2 events showed no lighting energy waste, lecture 1 and the ball. Both of these events had low levels of lighting with additional coloured, pre-charged LED boxes brought in for design purposes. In contrast to the other event that used these devices being Carol Service 2, minimal lighting waste was identified for these two events outside of the main activity in the evening. Events such as Graduation that are very repetitive and have a set format and design, with the same occupants interacting with controls, consistently showed a similar lighting energy and waste profile

Lighting waste due to inflexible controls was only observed for three events being the monitored concerts. However, it is possible that any dissatisfaction that the occupants for other events had with relation to the lighting flexibility was missed by the researcher, and that a lighting design was used that was not what the occupant would have preferred.

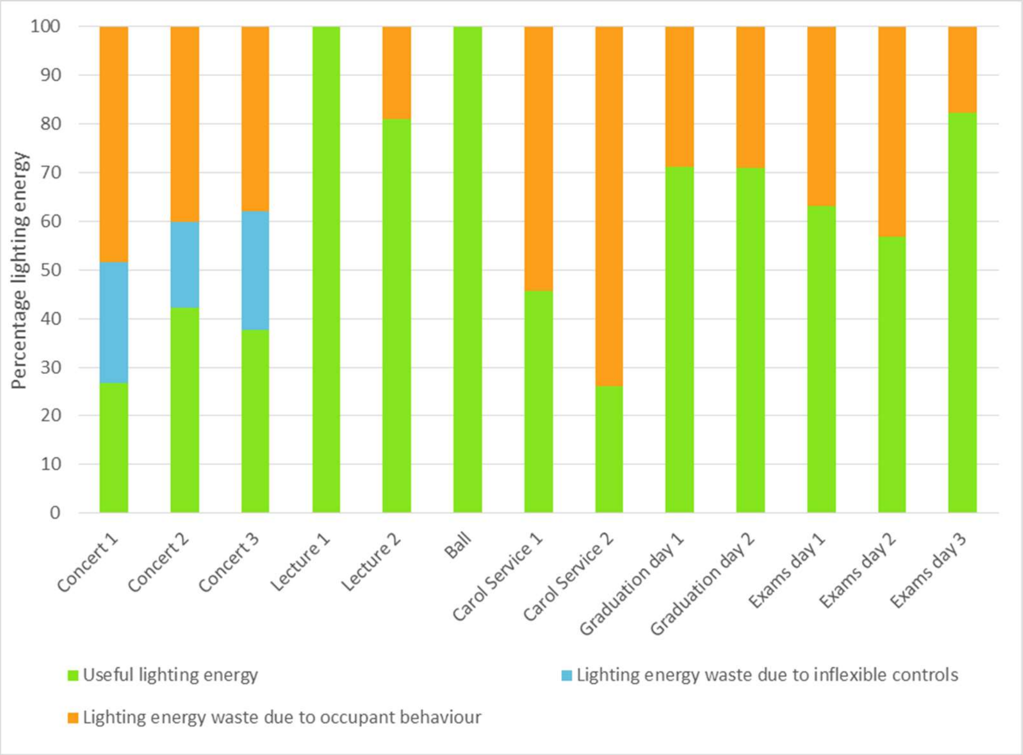

Figure 57: Percentage of total lighting energy use per event that was identified as useful, wasteful due to event organiser behaviour, or wasteful due to inflexible controls.

Presenting the identified waste as a percentage of the total lighting energy used per event, as in Figure 57, further highlights the events that had the best or worst lighting energy related performance. Concert 1 and Carol service 2 had the worst performance where over 70% of the lighting energy was wasteful. The majority of this was identified as being due to occupant behaviour.

Events such as the concerts and the carol services each individually had very different lighting use throughout the day in terms of the different lighting end uses they employed. Yet examining their energy use at this more macro level it appears as though they had similar overall lighting energy requirements and similar contributions to each identified category of lighting related energy waste. The exception to this was Carol Service 2 that had higher levels of occupant behaviour related energy waste. This reiterates the need to have more granular analysis in order to understand the drivers for energy use during the different event types in order to identify specific, but also demonstrates that the overarching concerns for energy waste are the same for all events. Because occupant behaviour is clearly the largest contributor to waste, it is important to further this analysis to understand why this behaviour is so wasteful and if there are any preventative measures that can be employed to encourage more energy efficient behaviours prior to occupants interacting with lighting controls.

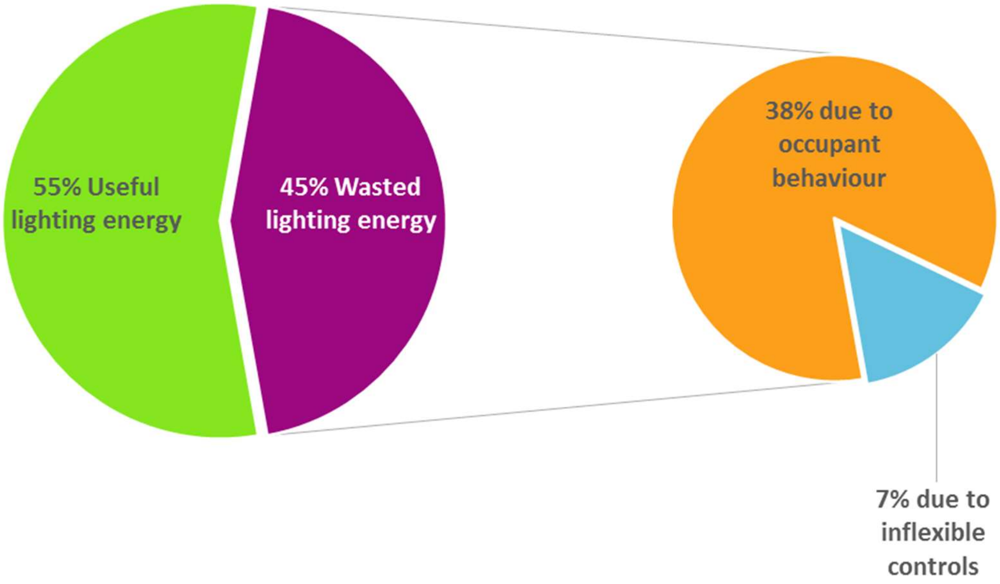

Figure 58: Breakdown of total lighting energy use across all monitored events in terms of useful and wasted energy.

Figure 58 shows that in total, 45% of the observed lighting energy use across all the monitored events was wasteful. Of this, changes to occupant behaviour present the greatest energy savings opportunity.

4.5.2 Heating energy waste

In examining the heating related energy waste, there were three main reasons for wasted energy; poor BMS scheduling, the choice of an inappropriate programmed set point temperature for the activity in the space, and occupant behaviour.

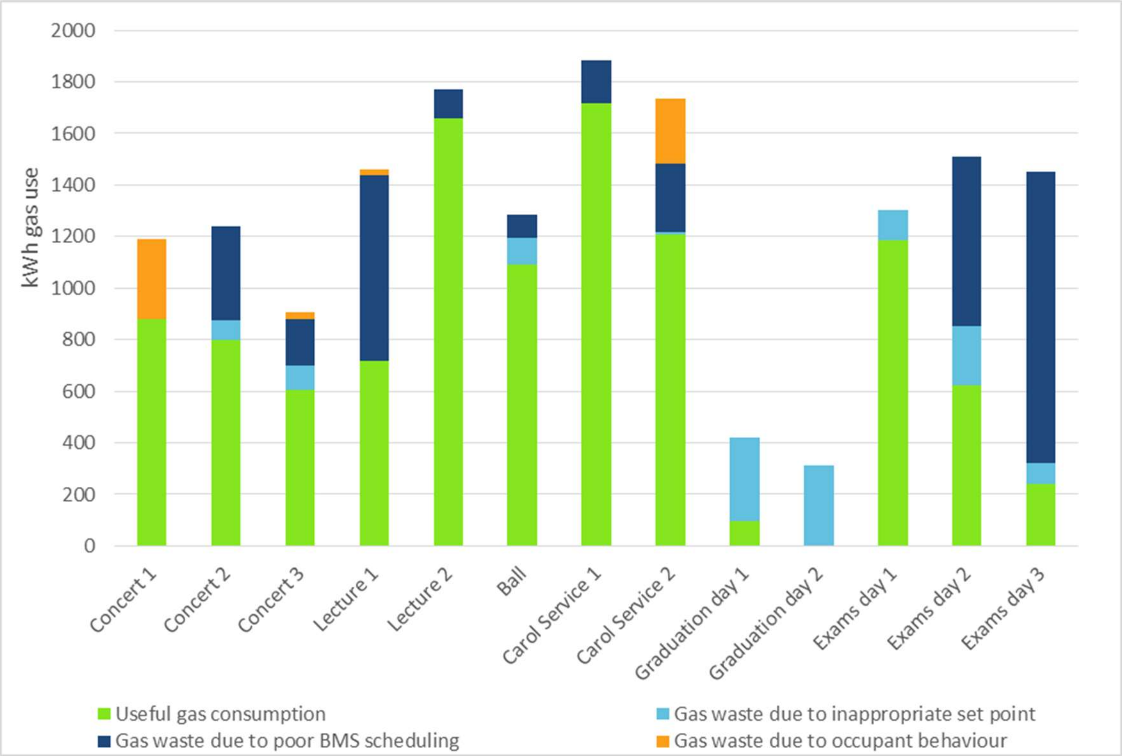

Figure 59: Kilowatt hours of heating energy use per monitored event that was identified as useful, wasteful due to an inappropriate set point being chosen or wasteful due to poor BMS scheduling.

Figure 59 shows the heating energy waste identified for each of the case study events. Each of the events had different heating energy requirements and as discussed for each of these events individually this was due to multiple drivers. These included external temperatures, varying internal heat gains depending on the occupancy and the activity levels of those occupants, and variations in heating use in the 24 hours prior to the monitored event as observed for Concert 1 and the three Exam days.

In terms of the different types of heating energy waste, occupant behaviour was primarily due to leaving external doors open when they were not needed for access. The inappropriate set point category refers to the potential for a lower set point to be programmed into the BMS in order to allow occupant heat gains to meet the true desired set point temperature, which in this case is 20°C. Poor BMS scheduling refers to the heating system not being scheduled appropriately for the true occupancy hours of the building and contributed the most to heating related energy waste. In order to identify this energy waste, it was important to identify the control system of the BMS, as through its analysis it appears that the BMS scheduling time is overridden if the external temp is below 0°C. In these situations, the heating appears to come on at midnight irrespective of occupancy times. This is reflected in the heating energy use profiles of the two events with the highest heating demand, which were Lecture 2 and Carol Service 1. On both of these days the external temperature was below freezing. The minimum heating requirements for the building have been inferred from the analysis of certain events e.g. Concert 1, Lecture 2, and Carol service 1. However, this has not been definitively identified through long-term analysis of the buildings heating use.

Another finding from the analysis based on the time that is taken for the hall to reach temperature, is that the heating system is potentially undersized. This was identified through temperature and gas consumption monitoring. The coding for the BMS control system states that that for December the heating system should be able to reach temperature within 5 hours when at the design temperature. The minimum design temperature would need to be identified to further this discussion, though from the analysis it appears that for the month of December this could be 12°C, which is not a realistic average for December. Further to this observation, it was observed on multiple occasions that the hall struggled to reach temperature in the absence of occupant heat gains, and that as the BMS control system is self-learning, this extended the pre-heat time of the building with very little changes in external temperature. This was observed for the two monitored graduation ceremonies, where a 0.5°C difference in internal temperature resulted in three extra hours of pre-heating.

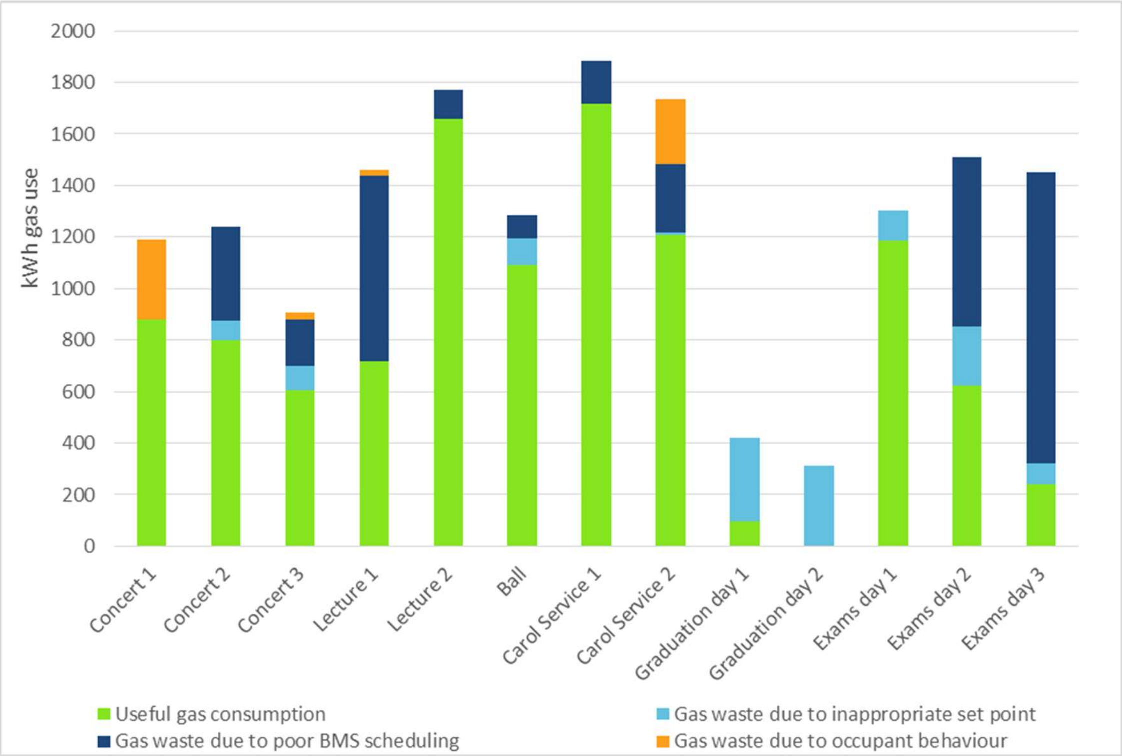

Figure 60: Percentage of total heating energy use per monitored event that was identified as useful, wasteful due to an inappropriate set point being chosen or wasteful due to poor BMS scheduling.

Examining Figure 60 and Figure 61, it is clear that the largest contributor to heating related energy waste was due to poor BMS scheduling followed by the choice of set point temperature. At present the programmed set point temperature is 20°C at all times during the heating season. As observed in the monitoring of these case study events, the heating system mostly behaves as expected and turns itself off once the set point temperature has been achieved. However, for certain events that have higher internal heat gains, for example the two graduation ceremonies where over 600 people were in the hall, even though the heating system turns off once the set point temperature is achieved, internal temperatures continue to rise due to the significant occupant related heat gains. The set point temperature was therefore exceeded in these circumstances, and although the monitored temperatures did not reach those classified as overheating (CIBSE 2016), the occupant behaviours indicated that people were having to find ways to cool themselves (e.g. through taking off layers of clothing or fanning themselves). The term “inappropriate set point” is chosen here as based on the control logic of the BMS, a lower programmed set point temperature would see the heating system turn off at a lower temperature in recognition that the internal heat gains from occupants would make up the remaining required degrees to achieve the true desired internal temperature. It is therefore important to have a detailed understanding of occupancy numbers and levels of occupant activity to factor occupant internal heat gains into the BMS programming.

Through the analysis of heating use it was observed that internal heat gains complicate long term analysis of the building’s heating use as their contribution can be significant enough to cause the heating system to turn off. Consequently, analysis of gas consumption with external temperatures can skew the analysis of the building’s thermal energy performance. This verifies the findings from section 4.2 of this chapter, where degree day analysis was applied to building gas consumption and gas consumption data was visualised over a year.

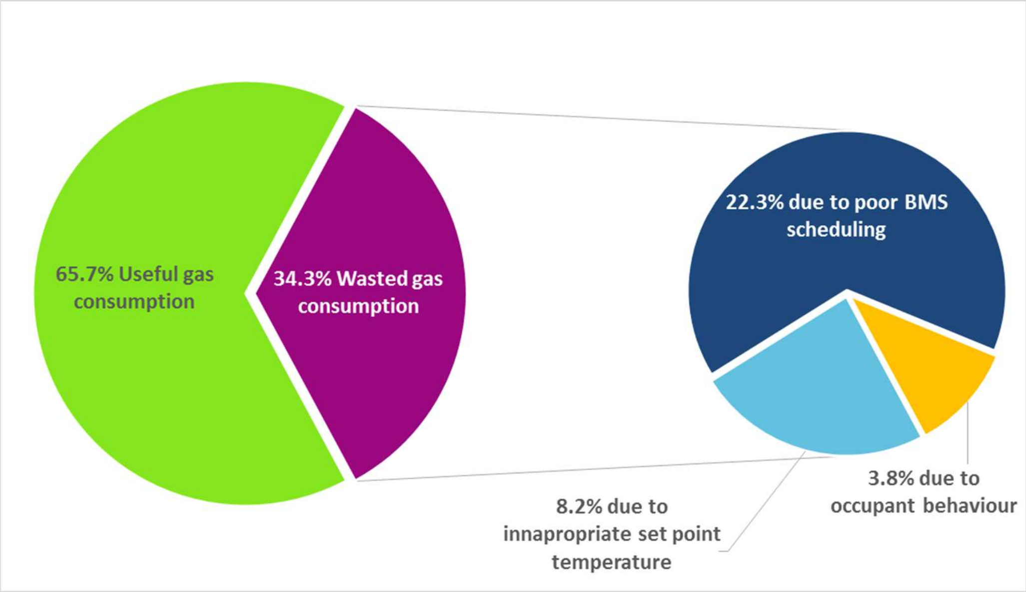

Figure 61: Breakdown of total heating energy use across all monitored events in terms of useful and wasted energy

It is important to note that the heating energy savings here are only for the monitored events and do not include the numerous times that the building was heated but unoccupied as observed by the researcher through observing the wider gas consumption data. It is likely that if this was factored into the overall analysis of heating energy use as presented in Figure 61, the contribution to heating related energy waste through poor BMS scheduling would be significantly higher than shown here.

More detailed reasons for how these different types of energy waste have arisen are discussed in the next section of this chapter where the individual actors that engage with the case study building's energy use are discussed in more detail with reference to the waste identified in this research.

4.5.3 Assigning actors to energy waste

This section focuses on attributing the identified energy wastes to different actors that engage or have engaged with the building in the past, in order to quantify the impact that their decisions and activities have had on energy efficiencies. For heating and lighting these actors were slightly different and are detailed below along with the energy waste that was attributed to them. The benefit of categorising the waste in this way is to then understand the context of the energy use and the behaviours and reasoning of each individual.

4.5.3.1 Lighting

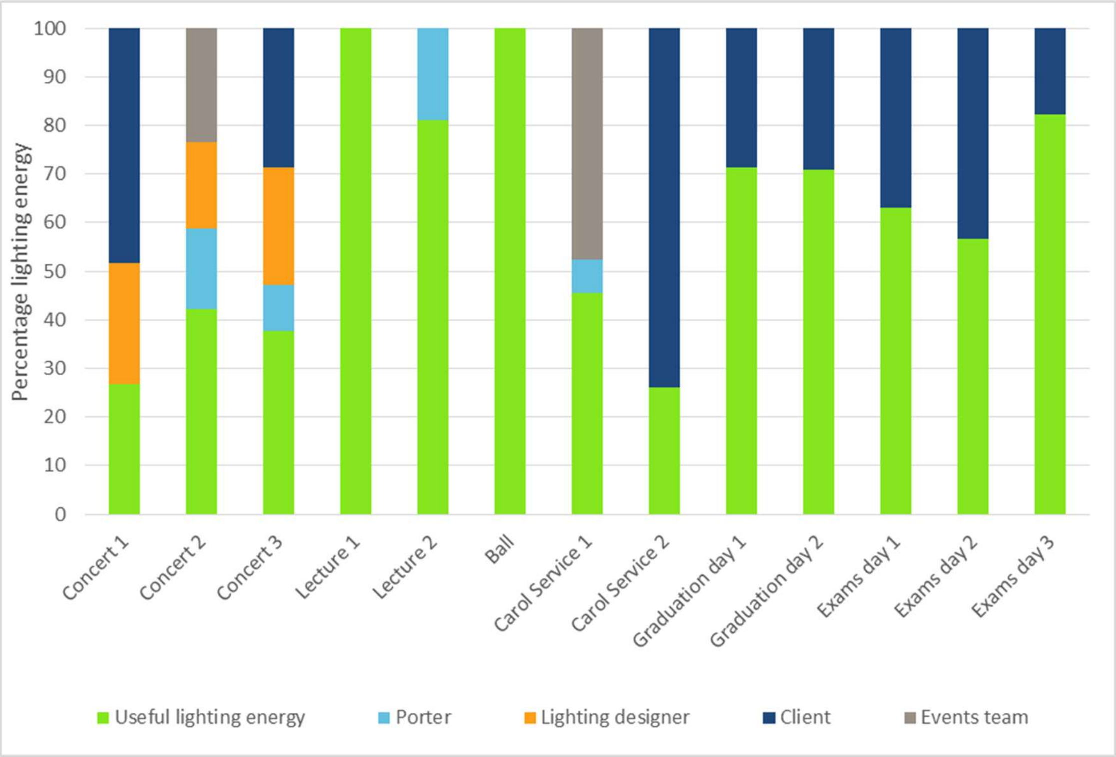

Figure 62: Percentages of identified lighting energy waste for each event attributed to building actors

Four actors were identified that contributed to lighting energy waste. These were the Porter, the Lighting designer, the Client, and the Events team. Each of these contributed to lighting energy waste in some way, and their contributions to the identified energy waste for the thirteen case study events is shown in Figure 62.

It was possible to attribute the energy waste from inflexible controls directly with the lighting designers. The lighting designer would have known the building design prior to designing the lighting system, and therefore would have known the proposed use of the building in terms of it being a venue, and would also have knowledge of the orientation of the building and the size of the windows etc. However, it is not clear how much the lighting designer would know about the design intent of the building and the needs for controls to be flexible so that the occupants using the venue could have a wider variety of lighting designs, which could potentially be more energy efficient. Nevertheless, as it is through the design of the current lighting system that the occupants were not able to employ their preferable lighting design. To link this with wider knowledge of venue lighting design, it is not unusual to have highly flexible controls in a venue building. Venue buildings often use this to their advantage through changing light levels as a signal to audience members e.g. to signal the end of the performance or intermission.

For the other actors, the occupant behaviour related waste that was identified earlier was further sub-divided in order to attribute the energy waste to the actor that had engaged in wasteful energy behaviour. As can be seen from Figure 63, the largest contributor to lighting related energy waste was the Client hiring the space to host their event.

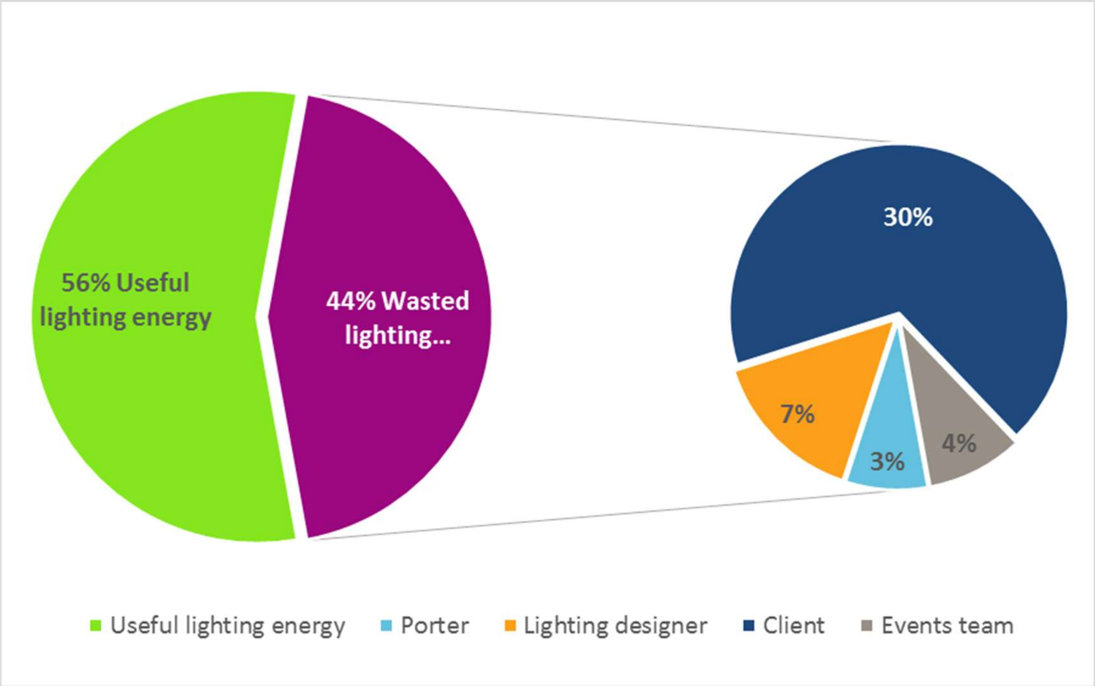

Figure 63: Percentages of identified lighting energy waste from all monitored events attributed to building actors

Through the semi-structured interviews with the Porter and the Events team, as well as through direct observations, it was identified that the Clients were introduced to the lighting controls, shown in Figure 64, on arrival to the building by either the Porter or the Events team. Following a short demonstration of which switches control which lighting end use, the clients were often left in charge of the controls to suit their lighting design as much as the lighting system allows. It was observed the clients often appeared confused when trying to use the controls and on occasion even asked the researcher for help in turning on the lights the wanted to use. As seen in Figure 64, the lighting controls are very dated and show evidence of a legacy of changes in the wiring infrastructure resulting in an interface that is not naturally intuitive to the user. Some controls such as the floodlights were not intuitive at all and operated with a small tool that was kept on top of the fuse cupboard adjacent to the switches, but often clients using the space did not know where this was, and sometimes it wasn’t where it was meant to be. In addition to this, the lighting chart on the wall was out of date with a confusing mixture of numbers and colouring.

However, for the two most lighting energy wasteful events, the Client either did not engage at all with the lighting controls (Concert 1), instead leaving them as the Porter had when demonstrating the different lights they could use; or engaged fully with the controls throughout the day but did not match this to the illuminance levels that they actually needed to fulfil their tasks (Carol Service 2).

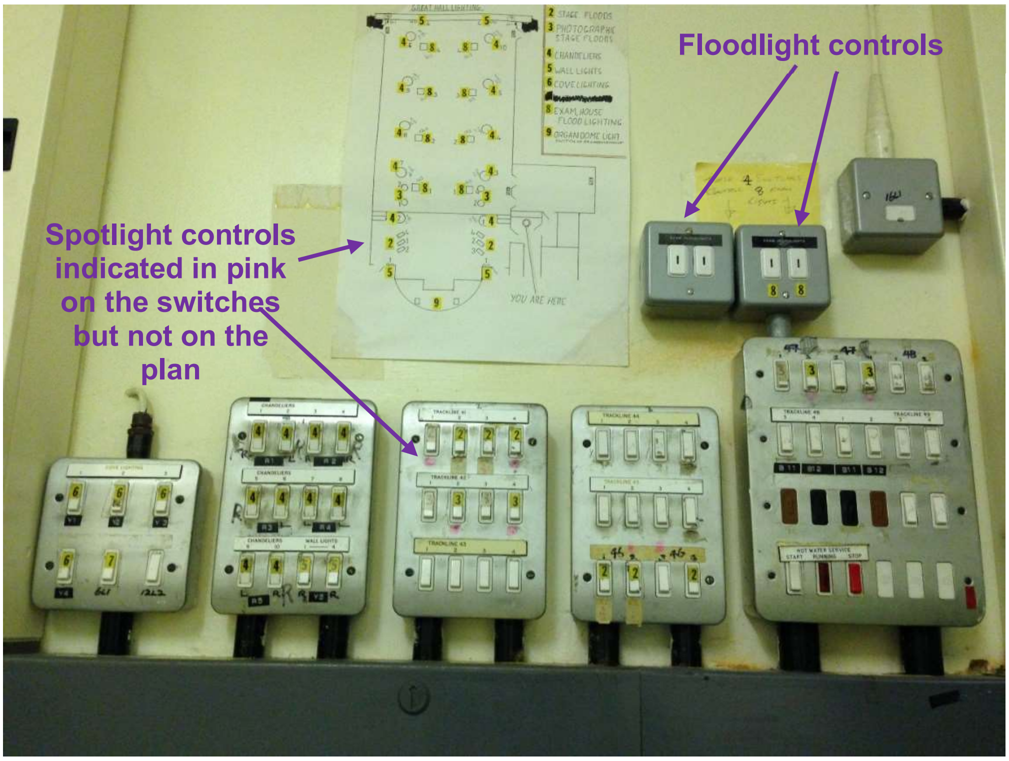

Figure 64: Lighting controls for the Great Hall

Aside from the problems with the controls, the behaviour of the clients did not always show that they were trying to engage in more energy efficient lighting designs that were being actively adjusted to suit their requirements. There are a number of potential reasons why clients may not be interested in engaging in energy efficient behaviour towards for lighting, listed below, some of have been observed by the researcher, others have been vocalised informally to the researcher:

- They do not care about the energy waste because they’re not being billed for energy use
- They do not feel as though they are permitted to interact with the controls because they don’t own the building, even though they have been shown that this is okay
- They do not want to bother the porter or events staff to change the lighting set up if they do not know how to. Instead they prioritise this interaction with these other actors for their main event. These Clients did not alter the lighting use from the original demonstration by the Porter or Events team member until it was necessary to do so for their event. This was despite any availability of natural light or the actual required illuminance levels for the tasks that they were engaging in.
- They are oblivious to the changing needs for higher or lower levels of illuminance

In addition to these factors, when observing all actors engaging in wasteful lighting energy behaviours, one of the main causes of the waste was that they did not adapt their lighting use to match their actual illuminance requirements.

4.5.3.2 Heating

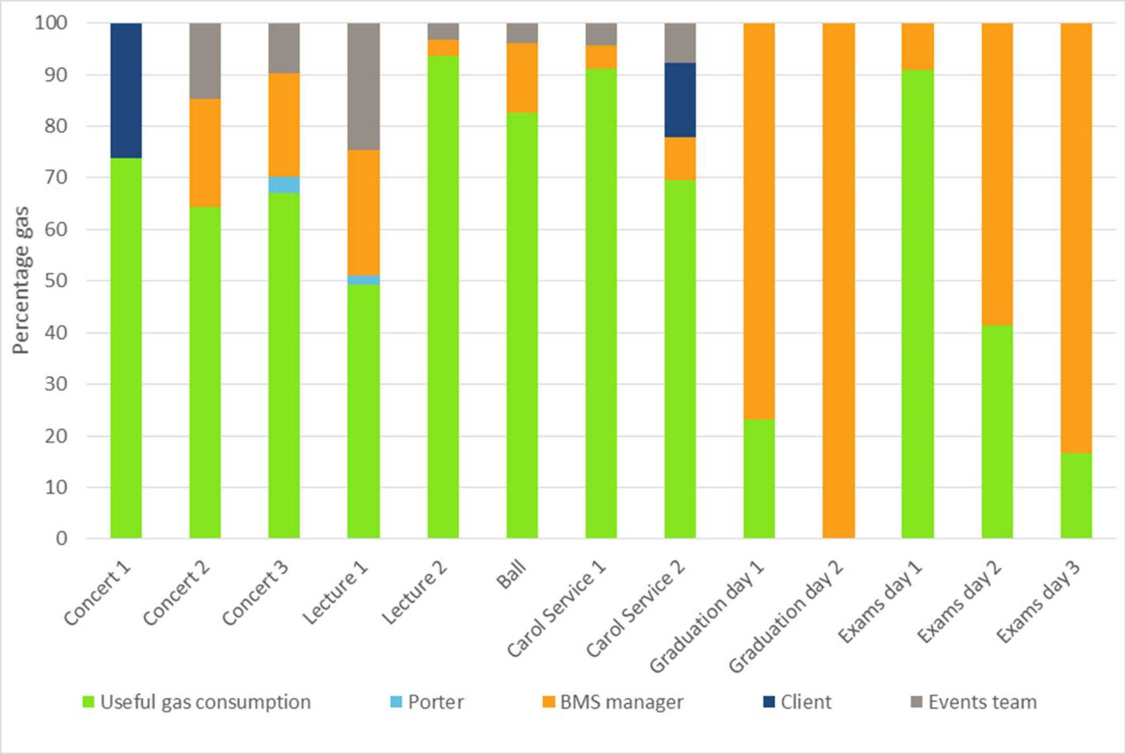

Figure 65: Percentages of identified gas waste for each event attributed to building actors

Four actors were also identified for heating related energy waste. There were the Porter, the BMS manager, the Client, and the Events team. General audience / guests to the building members are not outlined as actors as they do not actively interact with the building controls. In accessing some areas of the building e.g. the toilets that are located in a small building adjacent to The Great Hall, they may leave the external door open for a short period of time, but through the analysis the impact of this on internal temperature and / or humidity was shown to be minimal. The only example where this was not minimal was during the ball when building users who were guests, opened external doors for additional cooling in conflict with the heating system. The heating waste for this period was attributed to the building manager and the events team equally, as due to the type of activity and the internal heat gains from occupants the heating did not need to be on at this time, and this could have been communicated better between these actors. As shown in the detailed analysis of this event, better scheduling or a lower set point temperature would have avoided this conflict in heating and cooling requirements.

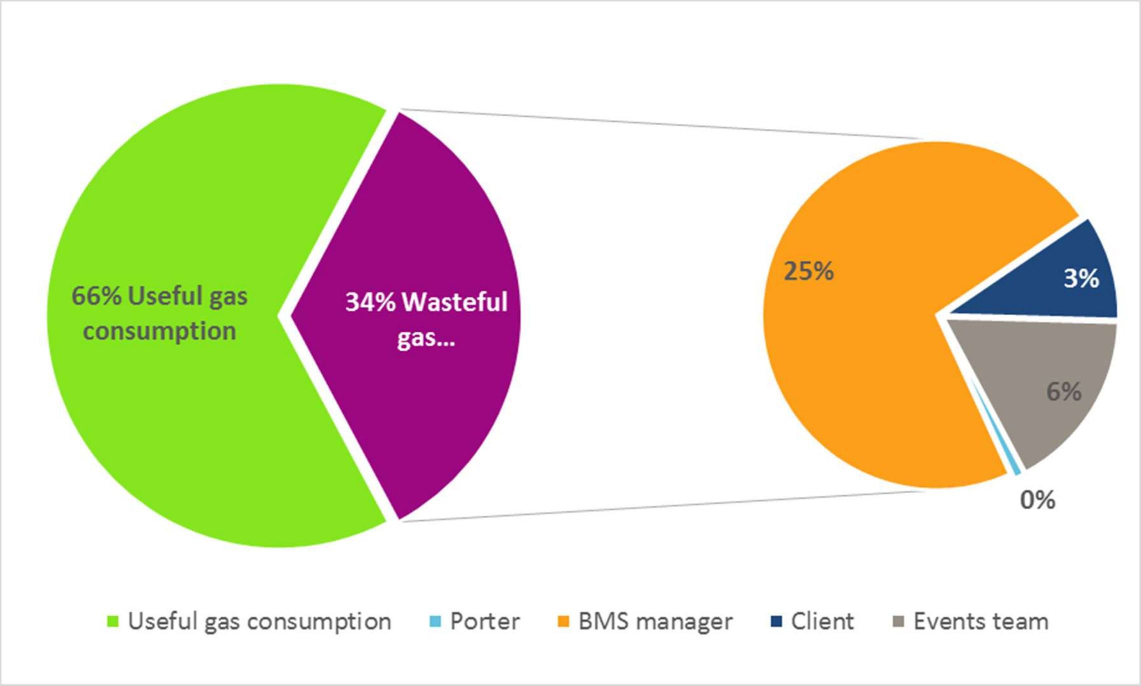

Figure 66: Percentages of identified gas waste for all monitored events attributed to building actors

As shown in Figure 65 and Figure 66, the majority of the identified heating energy waste was attributed to the BMS manager. This is primarily due to the decisions made around the choice of set point temperature, and also the scheduling of the heating around the different events. From the semi-structured interview with the BMS manager, the current strategy employed in managing the heating system is reliant on a central room bookings system populated by the events team and decisions made using the BMS managers own assumptions regarding the building occupants preferred levels of thermal comfort. The following is a quote from semi-structured interview with the BMS manager when asked the following question:

"…in terms of what's happening in that space, do you have any indication of what the activity is, how many people might be there?" (Researcher)

"Not really no there's on the booking list, there's no indication it might just say music practice, in which case I would imagine it's just a group of music people at the front of the stage probably practising, the rest of the hall's probably empty I would imagine. I don't know, if they use the hall to practice or if they've got a room at the back they practice. I don't know." (BMS manager)

In general, the BMS manager had a very limited awareness of activity in the hall and assumed scheduling was similar to other building times. Through the semi-structured interview, the BMS manager stated that he would rather have people come in and be at the right temperature and then overheat, than have people initially be cold and then reach the right temperature. Additionally, when addressing the basis on which he decided on the choice of set point temperature for all buildings on campus that have flexible spaces, the BMS manager stated that:

"On the basis that its lecture theatres are large spaces for people are sitting they can't move around so, and some of the lecture theatres are booked out so external organisation, so they're paying for the facility. The more you pay the more you can have basically, it gives them some, a little bit of comfort level so they can adjust it a little bit, but the set points will go back to the default settings after midnight and start from scratch." BMS manager.

It is important to note that this is not a data driven statement, nor is it based on any dialogue with occupants, and does not reflect the observations the researcher made of occupants at lower temperatures e.g. 18°C, when they did not behave in a manner that indicated they were cold. Additionally, this statement is heavily laden with the BMS managers own assumptions of what occupants preferred comfort levels are with no consideration of the impact of internal heat gains from occupants using these buildings towards maximum capacity or engaging in more metabolically active activities. There was also the assumption that people who were paying to hire spaces could have an extra degree of heat compared to other areas of the University such as office spaces that are set to 19°C, because Clients are paying to hire the space. This is not based on any monitoring of temperature during events, and so again does not consider the impact of occupant heat gains on temperature rise.

Further discussion revealed that the BMS manager justified the 20°C set point and the chance of overheating by explaining the BMS systems ability to turn off once the desired temperature is achieved. However, the heating turns off once this condition has been met, but the occupants continue to emit heat through their activities. Even though the occupants are continuing to emit heat, they cannot turn off their activity, in the same way the heating system turns off its gas combustion, and reduce their contribution to internal heat gains as they still have to fulfil their purpose in that space e.g. watch a performance or sit an exam.

Additionally, despite the heating system no longer burning gas to run the boilers, there is still hot water in the radiators that continues to emit heat into the room. The only way therefore for occupants to cool the room (and perhaps reduce the humidity) is to open external doors (in the absence of openable windows).

The following are quotes taken from the semi-structured interview when discussing the use of the heating system for events that are highly likely to cause the hall to overheat:

"…if you knew that it's graduation say, there's 600 people in there, all of the lights are on and if I were to present you with data that even in winter it gets to 25 degrees in there, would you start to change your set points?" (Researcher)

"At the moment there's nothing I can do is there? Because all we do is control the heating, we don't control the cooling and when they do the refurbishment job or improve the heating, at that point I would imagine the heating and cooling would be put onto the BMS system,

then we'd have some control over it, at the moment if the room is above set point it would just turn the heating off, if they get too hot then that obviously, they've got the local." (BMS manager)

"That's quite a reactive way to look at it, isn't it?" (Researcher)

"Well it turns the heating off, but there's no cooling available and there's no ventilation on the BMS system, so there's nothing we can automatically do. Obviously during the summer they've obviously got this cooling plant which they can, I gather they can switch on. So they, I know they use cooling during the summer" (BMS manager)

This dialogue revealed a very reactive energy management model whereby cooling was viewed as an answer to occupants overheating, despite a significant portion of temperature rise being due to pre-heating. The fact that the heating use earlier on was wasteful and unnecessary was not shared by the BMS manager, and indeed it was not viewed to be energy inefficient to cool after heating, when simply not conditioning the space at all may result in a more comfortable environment for the occupants.

The next actor with the largest contribution to heating energy waste was the events team. This was because the scheduling of the heating also relied on their communication with the BMS manager regarding the occupancy hours of the building and the time by which the desired set point temperature would need to be achieved. Through the semi-structured interviews, it was revealed that the events team seemed surprised that The Great Hall has a regular heating schedule on weekdays, even when the building is unoccupied. They said that the heating schedule for venue spaces has been designed by them as they have requested of the BMS manager that the heating requirement be scaled back for days when certain venue spaces on campus are not used. The events team expressed concern with relation to the heating scheduling in the Great Hall and said that they would consider contacting the BMS manager to change the scheduling and streamline it to the building's use. With reference to the preheating time for the Great Hall, the BMS manager responded as follows:

“It takes a long time to heat up…it's probably quite a challenging job to insulate the building and prove the heating in that space I would imagine, because it's a big space, an old building it's probably not, probably doesn't have cavity wall insulation or is well insulated… It takes ages to heat up that building, I've watched it, we have to put it on two or three hours before it's actually needed to make sure it gets up to temperature, it takes a long, long time to get up to temperature, even with the warm up period.” (BMS manager)

This statement mostly reflects what has been observed during the monitoring of the case study events. However, again it does not consider the impact of internal heat gains from occupants, and also does not consider any heat retained in the building overnight. An example where the BMS manager used this assumption to actively override the BMS controls was during the Exams period, where the heating was manually scheduled to come on the evening before the exam. This resulted in long periods where the heating was on but struggled to achieve the set point temperature, but as soon as occupants arrived the set point temperature was exceeded. This decision by the BMS manager had a direct result of generating heating related energy waste.

The remaining 3% of energy waste attributed to the Clients and <1% attributed to the Porter, was due to the use of door opening. In terms of assigning heating related energy from open external doors to individual actors, this could also be due to a design feature of the building (and thus could be attributed to the building designer), as it’s not the occupants fault that these doors open directly into the main hall area without any kind of double door system to reduce thermal losses. However, for this analysis this was attributed to the different occupants as they are aware of this design feature in using these doors and it is this conscious behaviour to leave the doors open that resulted in energy waste being identified.

4.6 Summary

This chapter analysed data from a case study multi-use venue building. Initially, longitudinal electricity and gas data were presented in order to demonstrate the variability of energy demand and consumption with reference to the varying demand from different events. Gas data was then used to demonstrate that macro level building performance tools such as degree day analysis are limited in their application to these kinds of buildings and risk providing a false narrative on building performance in the absence of wider contextual data concerning their use.

The next section of this chapter focused on thirteen different events that were monitored as individual case studies. These were analysed in terms of lighting and heating use. Each of the different events presented different waste profiles for both of these services to the building. This is despite some of the events initially appearing to be very similar e.g. exams. Reasons for these variations include changing occupancies and their associated internal heat gains depending on their activity levels, changing occupant lighting needs, changing behaviours with building controls, and different heating scheduling.

The identified energy waste was then categorised in terms of the type of energy waste and also the relevant actors that that waste could be attributed to. In categorising the energy waste in this way has meant that it has been possible to quantify the affect that each of the actors has on overall energy efficiencies for different uses of the case study building, and also identify potential reasons why these actors have engaged in wasteful energy behaviours. The benefit of categorising the waste in this way is to then understand the context of the energy use and the behaviours and reasoning of each individual. This will then inform Objective 3 which is to *provide recommendations for energy management and design of controls that are generalisable to buildings with a high diversity factor*, which will be discussed in the next chapter.

Chapter 5

Discussion

5.1 Introduction

This chapter discusses the results of this research and compares them to the findings from the literature review. It summarises how the aim of the research has been met by addressing each of the objectives stated in Chapter 1. Each objective is discussed in comparison to key literature discussed in the literature review.

5.2 Research findings

The overall aim of this research project was to investigate the relationship between occupant activity and energy performance of a multi-use venue building. This was approached by addressing the three objectives outlined in Chapter 1. Key findings from the research relating to each of these objectives and the literature reviewed in Chapter 2 are discussed below.

5.2.1 Objective 1: D*emonstrate the applicability of standard methods of identifying building energy performance when applied to buildings with a high diversity factor*.

5.2.1.1 The need to examine building performance beyond compliance modelling

As described in the literature review, typical energy models for compliance disregard the complexity of occupant use and control of buildings. Instead these models, through methods such as the National Calculation Methodology (NCM), use standard pre-set occupancy profiles and assumptions on internal heat gains which are selected by the building designer depending on assumptions about the how the space will likely be used in terms of time and activity.

There are no requirements for building designers to deviate away from these profiles and as a result there is no need for them to consider occupancy beyond these standard use profiles and the impact of occupant behaviour. Although arguably this is necessary, particularly for speculative developments where little will be known about the final use of the building, the inability to accurately model the impact of occupant behaviour on energy use has been heavily criticised in literature, as they present an idealised representation of building energy use (D’Oca et al. 2018; Hong et al. 2016; Menezes et al. 2012; Bourgeois et al. 2006). An example of this is where a building is naturally ventilated but the model does not take into account the effect of occupant behaviour and window opening on overall energy use (D’Oca et al. 2018). Whilst research has identified this as a major problem for understanding in use energy consumption for any building type it is emphasized here that it is even more problematic for buildings with a high occupant diversity factor and transient building uses, such as with venue buildings. Consequently, it is likely that there is a pronounced performance gap for venue buildings between anticipated and actual in-use energy consumption.

Concerns around the performance gap have led the construction sector to develop tools such as TM-54 (CIBSE 2013b). This is a step in the right direction in terms of incorporating more unregulated loads in predictive modelling and can potentially provide more accurate estimations of in-use energy consumption. Perhaps more importantly these types of tools can provide a method for the design team to understand the limitations of their modelling to predict in-use energy performance when only considering standard regulated loads. However while TM-54 does suggest the creation of more realistic and dynamic occupancy profiles for different spaces in the building, it does not consider how occupants interact with building services and controls or the different activities they may conduct in the space. To compensate for this deficiency TM-54 makes use of an overall ‘management factor’ (essentially a diversity factor) that is applied to appropriate end uses and accounts for how well the building is being controlled. Crucially, determining what this management factor should be is a subjective decision by the building designer undertaking the modelling and there is little guidance offered on how this should be determined. This is largely because in effect this is a diversity factor that can allow for variations in building energy management but as yet this has not been calibrated for different building types.

There is no diversity factor in TM-54 that can account for the variability of occupant interaction with buildings, and as identified through the review of literature and in this research, occupant's actions and the activities that they engage in can have a significant impact on the in-use energy performance of buildings. Therefore, assessments of buildings in-use, whether these are through monitoring or through simulation must also incorporate human factors to some extent in order to have a realistic estimate or representation of the overall energy performance of a building.

For venue buildings, these kinds of high-level models are very limited in their ability to provide realistic estimates of in-use energy performance. Without an understanding of the impact of variations in internal heat gains from different uses of the building affecting HVAC energy use, or the different lighting designs, or small power demands; assumptions made around these in efforts to try and model any kind of annual energy use is subject to significant inaccuracies and error. Therefore, aside from the ambiguous benchmarks found in CIBSE Guide F (CIBSE 2004) and TM-46 (CIBSE 2008) concerning public buildings and entertainment halls that were addressed in section 2.4.2, there is very little to guide venue building owners on what their buildings should perform like.

5.2.1.2 The problem of macro level building performance analysis

To overcome limitations in compliance energy modelling and to satisfy the growing needs of building owners to understand their energy use better, there is a growing appetite for research into in-use building energy performance. From the literature review in Chapter 2, it was identified that the majority of studies employ a macro approach to studying building energy performance (Wang et al. 2012; Wang & Shao 2017; Yan et al. 2012; Bordass, Cohen, et al. 2001; Noye et al. 2015). However, it is argued here that although this can validate models and can provide evidence to make generalisations across building at a high level, it does not allow an understanding of how occupants interact with the building, the occupants' satisfaction with the building, or incorporate the intricacies of occupant drivers for energy use that could be identified through a more micro-scale analysis (Haigh 1982).

Each of these could arguably provide more valuable feedback to design teams as it can allow them to focus on changes to the design that would benefit both occupants and energy efficiency. Examining the main methods used in identifying building energy performance such as benchmarking, degree day analysis of heating energy use, and more widely, Post Occupancy Evaluation (POE), it is evident that these approaches are severely limited in their ability to cope with the temporal complexity and variety of occupant activities that are inherent to the function of multi-use venue buildings.

As we have seen in the literature review, energy consumption does not necessarily equate to energy performance. This is because presenting consumption alone, as is often done through macro methods of energy performance analysis such as benchmarking that present consumption per m^2 to generate an energy use intensity (EUI) metric, does not provide any judgement on the energy efficiency of the building. That is to say that the useful energy consumption for a building has not been adequately distinguished from the wasteful energy consumption. This ability to identify energy waste is important because it would allow facilities/energy managers to identify appropriate and effective energy conservations measures in order to improve energy efficiencies.

The use of Display Energy Certificates (DEC) in recent years has seen a wealth of actual in-use energy data become available to the building energy performance researcher (Centre for Sustainable Energy 2018). To enable these to be usefully employed as comparative benchmarks to illustrate building performance it is essential that the buildings in each category have a defined purpose and activity where occupants have very similar needs of the building, and where the equipment that they use serves the same purpose, carrying out the same function. It is only in these examples where a judgement can be made on a building's energy performance based on building level consumption data alone.

Comparing some examples of these methods from literature with this research, Heathfield & Bottrill (2012) used building level energy consumption data from 157 different performing arts venues. The study developed new benchmarking metrics based on seated capacity to overcome the limitations of existing benchmarks not being able to fully account for changes in occupancy. However, as demonstrated by this research h the significant variation in building energy use and energy efficiencies, even between events that from the outset appear as though they could be very similar, this approach is severely limited. Through this approach Heathfield & Bottrill (2012) have neglected that the activities and events held within these buildings can all have a different impact on energy use and thus each event's individual energy efficiencies are not taken into account by solely relying on building level consumption data. Therefore, without an analysis of the energy requirements of the different events held in these performing arts venues, Heathfield & Bottrill (2012) have in effect presented nothing more than a list of energy consumption per seating capacity with no insight into the energy efficiencies of each of these different performing arts venues. Consequently, an analysis of building energy efficiency that considers the changing use and occupant requirements of the building is essential to understanding energy performance in multi-use venue buildings.

Recognising this limitation Heathfield & Bottrill (2012), do state that it is more useful for a building to develop its own building performance benchmark over time. This observation is key to this research, especially as through answering objective 2, event energy efficiencies were identified but no metric (EUI) was applied to provide an estimate of performance that could be compared against other multi-use venue buildings. This was deemed necessary as the occupants of multi-use buildings have been demonstrated to utilise the space for continually varying purpose and activities, where occupant have very different needs of the building, and where the equipment that they use serves different purposes, carrying out different functions. In contrast, this research has provided a richer picture of the impact of multiple event types on energy use and has identified the energy efficiency of multiple uses of the building. In doing it so has demonstrated the limitations of relying on benchmarked building level data when investigating building energy performance of buildings with a high occupant diversity factor.

Post Occupancy Evaluation (POE), was discussed at length in the literature review as it was identified as one of the primary methods used to determine building energy performance. Although there is no standardised method for POE, it is generally accepted that the approach should cover at least two main aspects of performance; energy consumption and occupant satisfaction. The review of the available literature identified that typically POEs will utilise a TM-22 bottom-up evaluation of the building's energy end uses to produce assessment of energy performance, and occupant surveys (typically the BUS survey and possibly additional semi-structured interviews) to determine occupant satisfaction. These approaches could be deemed macro-level. As discussed, the focus during POE's is generally on the former of these aspects and there will generally be limited consideration at the micro-level of how occupant's activities and their use of the building's controls and systems directly or indirectly impacts on performance. As shown in the results section, the mixed methods approach including direct observation at 5-minute intervals has shown that these micro-level behaviours (covering interaction with systems and activity levels) are important and substantial determinants of energy consumption. By looking at each event as an individual case study it was possible to identify how necessary energy use from individual end uses was to the needs of the activities that the occupants were engaging in.

5.2.1.3 The importance of a mixed methods approach

As emphasised, although a number of different methods are typically incorporated into POE, these tend to be focused at the macro-level. In Section 4.2, degree day analysis, which had been identified as an example of a typical macro level study used as a method to examine building energy consumption during POE's, was applied to annual gas consumption data for the Great Hall. Findings from this suggest that the building's heating system is operating exceptionally well, however the choice of base temperature of 15.5°C, which is typically used for wider building types (Bordass et al. 2001; Marshall et al. 2015; Galvin 2013), indicates that the building balances at a lower base temperature. The choice of a base temperature of 15.5°C in literature is essentially dependent on a target temperature of 18°C, with the assumption that the remaining 2.5°C is met through internal heat gains within the space.

This macro-level analysis belies the actual situation where direct observations revealed the variability in temperature rise produced as a result of the continually varying occupant activities. The direct observations and analysis also showed that the building regularly struggled to reach the desired set point temperature, programmed into the BMS by the building manager, of 20°C when the building was unoccupied. This demonstrates that analysis of energy consumption data without any contextual information ignores the nuances of energy consumption identified through direct observations. Consequently, in this situation a macro-level study of the energy consumption could be considered ineffectual as it would suggest that there is no need or scope for any energy conservation measures to improve performance, but in reality the data collected at the micro-level provides insights that can determine not only what the source of energy waste is but also what actor is responsible for it. This finding reinforces evidence from the literature which suggested that unless the context of the energy use is fully understood, energy conservation measures may struggle to meet their full potential (Haigh 1982, Lo et al 2012).

Although there has been some standardisation for the POE process (Leaman et al. 2010; Cohen et al. 1999; Bordass, Leaman, et al. 2001), no defined or prescriptive structure exists to enforce the regular use of the micro-scale analysis of energy performance, with direct observations of use that provide detailed enquiry into building energy use. Instead, very similar, engineering focused POE's are more common. It is possible that this is because POE's are carried out by engineers that have the same prejudices against the more social, occupant focused aspects of building use. Because of this they instead seek more material ECM's such as expensive upgrades in systems and building fabric before integrating the user's priorities with energy efficient control and use of buildings (Haigh 1982). Additionally, and very importantly, a micro-scale analysis is likely to be much more labour intensive and costly to implement, however the identified energy conservation measures may be centred on more sensitive management of the building services and occupant behaviour change. Therefore, although a macro level POE can be useful in terms of verifying models, when it comes to actually identifying potential problems in building design or understanding how the occupants use the space and identifying effective ECM's, the macro approach is too limited.

Of the POE's examined in the literature review, a study that examined a community centre was of particular relevance to this research (Technology Strategy Board 2015). The study of the Angmering Community presented sub-metered energy use per major energy end-use and compared this against other community centres. However, without analysis of exactly what kind of events these other community centres host, the frequency of them throughout the year, and their individual energy demands, there is a limited level of analysis that can be inferred from this level of data. Additionally, a benchmark of kWh/m^2/annum does not consider the height of the room. When compared to a building such as The Great Hall that has a maximum ceiling height 10.3m, this would present a flawed comparison, as the volume of this building would require much more heating than a room with a standard ceiling height of approximately 3m, even if they had the same floor area.

5.2.2 Objective 2: *Identify energy waste and potential energy saving opportunities for a multi-use venue building*.

This objective was achieved by carrying out an in-depth, high-resolution (5 minutely) case-study analysis combining the energy consumption, environmental conditions, and occupant activities, of multiple different events held at the case study building. In total thirteen separate events were monitored and analysed. Although some of the events initially appeared very similar to others, i.e. the three exams, it was demonstrated that each event had high levels of variability in factors which were determined to be key influences on energy consumption, such as different occupancy numbers, times or activity levels, or different levels of lighting and small power use. The analysis of this occupant focused micro-scale POE, identified the indirect and direct impact that the occupants can have on the internal environment and energy consumption and enabled the identification of energy waste which could be associated with different actors which would potentially be missed with more typical POE approaches.

5.2.2.1 The benefits of direct monitoring in identifying energy waste

Previous studies that investigated multi-use venue building energy use have not tended to additionally examine the energy efficiency of these buildings (Heathfield & Bottrill 2012; Grolinger et al. 2016). Instead, Grolinger et al. (2016) for example, monitored building level energy consumption in an attempt to forecast future energy use, primarily for the purposes of recharging clients. Although the study managed to predict the peaks in energy demand to within an acceptable level of accuracy, it was not able to predict an accurate overall daily consumption figure. This implies that there is not enough understanding or contextual information around the energy use during the events that the building hosts. However, despite the study managing to forecast energy use, there was no attempt during the analysis to identify any energy waste or make inferences on wider energy performance. This is because the data is primarily focused on energy consumption and not on any aspects of the building's energy efficiency and overall performance.

In order to identify energy waste for each of the case study events in this research, direct monitoring of occupants proved to be essential as it enabled the researcher to observe occupant behaviours and activities that led either directly (e.g. door opening, interaction with lighting controls) or indirectly (through internal heat gains depending on activity level) to instances of energy waste. It was identified during the literature review that there is a dearth of literature surrounding the impact that occupants can have on building level energy use for multi-use venue building. Instead the literature around occupant behaviour is generally focused almost entirely around buildings that have a very defined purpose e.g. offices (Masoso & Grobler 2010; Kontokosta 2016; Lam & Hui 1996; Nikolaou et al. 2012). Additionally, the aims of these research papers are often to inform macro-level building simulation models. Where studies do attempt to assess occupant behaviour and activities at a higher resolution (i.e. micro-scale), the majority of these involve detecting occupancy and their locations using technology, e.g. through Wi-Fi on mobile phones (Shao et al. 2017; Martani et al. 2012), or through remote sensing technologies above doorways (Erickson et al. 2009). As demonstrated through this research, detecting occupancy alone is not enough to understand the complexities of occupant behaviour and the context surrounding it that can lead to energy waste.

A significant segment of literature examining occupant behaviour in buildings is dedicated to trying to model their impacts on building energy use (Marshall et al. 2015; Haldi & Robinson 2011; Hong, Taylor-Lange, et al. 2015). This is challenging even for buildings with a defined use, where occupant behaviour has a repetitive interaction with the building and its controls. However, as mentioned previously, multi-use venue buildings have very high occupant diversity factors that change with different uses of the building. Venue buildings also have unpredictable calendars, with events that can sometimes be scheduled last minute depending on the availability of venue spaces. Therefore, developing a model that can forecast or simulate occupant interaction with multi-use venue buildings would be very onerous, with considerable error.

In developing the design of the monitoring for this research, a key text was identified as a study by Haigh (1982), where occupant behaviour and activities had been directly observed in different schools, in order to understand the impact that different building designs and their internal environments could have on occupant behaviour. Another key research paper that influenced the design of the monitoring programme was by Painter et al. (2016), where objective physical measurements, observational data and self-reported experience data were used to investigate the use of novel glazing technologies. Both of these studies heavily emphasize the need for a mixed methods approach that privileges the behaviour of the occupants in interacting with the building. This research mainly adopted Haigh's approach of directly monitoring the behaviour of occupants to observe their interactions with building controls and developed the monitoring approach further by directly aligning these observations with monitored energy use.

5.2.2.2 Findings from direct monitoring and analysis of The Great Hall

One of the main findings from the literature review that greatly shaped the design of the monitoring programme and research problem as a whole, was that occupant-building interaction had not been explored in detail for multi-use venue buildings. Multi-use venue buildings are distinguished from other buildings with a more defined purpose and use such as offices (Grolinger et al. 2016), and are an important area which is under represented in the literature. As the wider literature identifies that this occupant interaction has the potential to significantly contribute to building energy consumption, and because venue building energy use is so dependent on the different activities that they host, this became a key focal point for the monitoring and analysis of data.

The main findings from the monitoring and analysis of the thirteen case study buildings was that each of these events had different energy requirements despite high level similarities. An example of this would be the different concert case studies, where different occupancies, occupancy hours, and occupant activities, as well as different demands of small power led to very different heating and electricity consumption profiles. These variations along with differences in occupant behaviour or BMS scheduling led to different heating and lighting waste profiles being generated due to variations in the scheduling of the heating, the occupancy and occupant behaviour.

It therefore follows that building energy management should adapt to suit the needs of each of these events in order to reduce energy waste. Recommendations for more proactive energy management of this building and wider building types with high diversity factors are offered in section 5.2.3.

The analysis identified the energy efficiency of a number of individual uses of the building in terms of lighting and heating. It then categorised the identified energy waste in order to identify the contribution from each of the different waste sources as follows:

Lighting:

- *Inflexible controls* - This category was identified from direct qualitative observations of occupants trying to present different lighting designs to those available to them. This primarily centred on the use of the floodlights and chandeliers that stretch down the length of the hall on either side. The different light fittings are currently wired in pairs, however these are not adjacent to each other and so the occupants were not able only some of these lighting fixtures in the areas of the hall that they wanted the light and so resorted to keeping all of the lights on, leading to wasted energy with the use of the additional lighting for the rest of the space. This category is useful in terms of building performance as it demonstrates the importance of good lighting systems that have been designed with both the end user and energy efficiency in mind.

- *Occupant behaviour* - This category of energy waste was identified through direct observations of occupants interacting with building controls with a view to quantifying the energy waste from active occupant-building interaction. An example of this would be to observe the task that occupants were engaging in and provide a judgement of the levels of illuminance / number of different types of lighting fixtures in use that were required to perform that task. This judgement may be based on illuminance data from the environmental loggers before and after occupant interacted with the building controls, previous observations of the occupants engaging in the same or similar tasks, and changes in illuminance levels from just natural light to natural light and artificial lighting being used as well. In terms of proactive building performance, this category is useful because it identifies common occupant behaviours that can lead to energy waste and can help identify ECM to improve the energy efficiency of their behaviour.

Heating:

- *Poor BMS scheduling* - this category was identified from direct monitoring of occupancy hours, gas consumption and temperature data. By identifying the point in time from when the occupants required the heating to be at or close to the programmed set point temperature, and applying the known control logic from the BMS, along with analysis of internal and external temperatures, it was possible to identify more appropriate BMS scheduling. This type of analysis method was used to examine the period of time spent pre-heating the building for occupancy. A more obvious and instantly recognisable example of poor BMS scheduling was also when the heating remained on after occupants vacated the building. For proactive energy management, identifying this category is crucial to inform better scheduling of the heating system to ensure it aligns more closely with the needs of the occupants, and avoids heating the space for extended periods of time when this heating energy is not needed.

- *Inappropriate set point choice* – This category was identified primarily through the monitored temperature data with inference from the estimates of occupant related internal heat gains from calculations based on guidelines in CIBSE Guide A and observations of occupant activity levels. This is useful for proactive energy management as it could reduce the possibility of, and the period of time that the desired internal temperature is exceeded due to the contribution from occupant heat gains. It is important to note here that CIBSE Guide A guidelines on calculating occupant heat gains are only estimates and do not account for clothing type, and they assume an average body size. Therefore, these calculations can only realistically be used as a rough estimate of occupant related thermal energy to the environment. However, in plotting this data on the graph there is a clear correlation with temperature rise and occupancy related heat gains.
- *Occupant behaviour* – As with lighting, this category of energy waste was identified through direct observations of occupants interacting with building controls with a view to quantifying the energy waste from active occupant-building interaction. Examples of this included leaving doors open when the heating was on, and then overlaying this observation with the monitored temperature drop in the room to attribute that heating energy loss to the occupant(s) that kept the door open after their need to open it was satisfied. This is useful for proactive energy management as can inform better scheduling of the heating system and can also identify ECM, for example, engagement with building users to improve their behaviours, or improving the design of the doors to reduce thermal losses.

Each of these categories have been identified through the monitoring and analysis in order to target the areas of building energy management that were the worst performing. It is worth mentioning here that the thirteen events that were monitored in order to present the diversity of different waste streams that could be identified from the different types of events hosted in the building. As such these quantifications of waste cannot be directly compared with those found in literature, especially as those are primarily presented on an annual basis. Where percentage savings are presented, these have only been found for buildings with a more predictable use pattern, where that percentage can be extrapolated within an acceptable level of error across the year. Comparing findings from the analysis on the different categories of waste to the findings on the same or similar categories of waste in the wider literature on wider building types, would potentially be an unfair comparison. This is because the analysis of any number of events held in a multi-use venue building would only represent the unique situation of the building's energy use during those events. Therefore, an annual presentation of energy performance analysis would only be representative of the events held in that year, and the interaction of those specific actors with the building during those specific events under those specific conditions.

However, despite not being able to directly compare quantifications of energy waste identified through analysis of multi-use venue buildings, it is still possible to relate the drivers for energy use and waste from these buildings to those found in the literature and to further investigate the application of ECM identified in literature to these building types.

An example of this relates to improper scheduling of HVAC systems. The literature review presented studies for office buildings that showed the impact proper scheduling of HVAC and also small power and lighting use when aligned more accurately with occupancy. A study by Masoso & Grobler (2010), showed that over half of an office building's annual energy consumption occurred during non-working hours and identified air conditioning systems being left on during these times as the largest contributor to energy waste, followed by occupant control over lighting and small power equipment left on after occupancy has ended as the next main contributing factor. This research therefore has direct application to the category identified in this research of *Poor BMS scheduling*.

The literature review presented findings from a POE conducted as part of the BPE programme which was considered highly relevant to this research. The POE focussed on a community centre that catered for a host of different activities ranging from painting classes to dance and indoor sport. As the only in-depth POE of a multi-use venue building found by the researcher, this presented a key study from which to compare the findings of this research. Responses from the BUS occupant satisfaction surveys found that occupants were generally very satisfied with the thermal performance of the building. However, the more qualitative data gathering through semi-structured interviews reported that the occupants engaging in more sedentary activities were satisfied with the air quality in the building, whereas those engaging in more intensive activities (such as dancing) found the spaces too warm and thus resorted to opening windows and using portable fans to improve their thermal comfort even in winter, resulting in conflict cooling and heating. The POE therefore found that these occupant behaviours had a detrimental effect on energy performance particularly through wasting heat, however this waste was not quantified. Although the community centre did not do any direct internal environmental monitoring and relied on the building user survey and semi-structured interviews to generate this finding, this has direct parallels with the impact that different activities held in The Great Hall were shown to have on the internal environment. This research showed that internal heat gains varied according to occupancy and occupant activities of the different monitored events. The impact of these internal heat gains on the internal temperatures and humidity thus varied according to the different types of activities being held, resulting in different responses from the occupants. For some events, e.g. the ball and graduation, it was observed that occupants appeared to be feeling too warm, with behaviour relating to door opening for ventilation, taking layers of clothing off or fanning themselves to try and cool down. Therefore, this POE in the literature has direct application to the identified category of "*Inappropriate set point choice"*.

In general, the most important data that was collected during this monitoring programme was the qualitative, contextual data around how the energy in the building was being used. This involved observations of occupant-building interaction, decisions on which the heating systems were controlled, and observations of occupant satisfaction with the building. Each of these provided essential information used to identify the usefulness of energy use and consequently the energy efficiencies of the different events.

5.2.2.3 Findings through attributing energy waste to actors

From the literature review, studies reported the importance of feedback to different building actors to inform them better regarding their energy behaviours and invoke more energy efficient behaviours (Lo et al. 2012; Haigh 1982; Shao et al. 2017). Based on these findings, this research attributed the identified energy wastes to different actors that engage or have engaged with the building in the past, in order to quantify the impact that their decisions and activities have had on energy efficiencies.

In terms of the lighting energy use, there were two main findings that emerged from the analysis presented. Firstly, it was identified through assigning lighting energy waste to different actors in the building, that the clients (30% of total lighting related energy) contributed the most to lighting related energy waste, compared to the Porter (3%), the Events Team (4%), and the lighting designer (7%) of whom the energy waste due to inflexible controls was attributed.

Secondly, that the controls had a confusing labelling system and the controls were generally not flexible enough to present a lighting design that clients wanted. During the monitoring of certain events, it was observed that the Clients that were trying to use the building controls were confused, and on occasion asked the researcher directly for help in trying to use them. The majority of this confusion centred around the labelling for lighting controls for the Great Hall, that was difficult for the occupants to understand, and also around the inflexibility of the controls. This second reason, although not the largest contributor to energy waste presented some frustration for Clients, whereby one light switch would turn on a pair of floodlights or chandeliers, that would not necessarily be in the same area of the hall, thus leading to frustration where clients could not design the lighting as they wished. This led to worse lighting related energy efficiencies due to more lights being used than was often required to produce the conditions that the occupants wanted.

Most of the literature that details occupant behaviour in buildings or human factors that impact on total energy use tend to group all building occupants together as one (Masoso & Grobler 2010; Hong et al. 2017b; D'Oca et al. 2018). Where the human element of building performance has been separated into actors that affect building energy use, there has generally been no attempt to directly assign energy waste to these different actors. Haigh (1982) for example, categorised occupants into "Teachers" and "Pupils" to show that it was primarily the teachers that interacted with building controls whereas pupils only affected the internal environment passively through their different activities. However, as mentioned previously, although Haigh identifies the behaviours from the occupants that are in response to the changing building environment, there is no energy monitoring in this study, and so these behaviours are not attributed directly to instances of energy waste. In another example, D'Oca et al. (2018), attempted to identify the different various human agents that affect energy performance over a building's entire life cycle. In terms of the agents identified by D'Oca (2018), "Designers", "Occupants" and "Operators and Managers" have direct parallels with "Lighting designer", "BMS Manager", "Porter", "Events team", and "Clients" that have been identified in this research. Unlike D'Oca (2018), this research splits up the category of "Occupants" further into individual actors, and as can be seen from the analysis, this yields further insights into energy use, warranting more investigation as to why those actors, or agents as referred to by D’Oca, engaged in such energy wasteful behaviour.

Categorising the energy waste into the different actors enabled the identified energy waste to be given an ownership, so that any energy conservation measures that are identified are targeted at the actors that have been identified as being responsible for that waste. This could potentially make energy conservation measures more effective and negate some of the problems identified by Lo et al (2012).

5.2.3 Objective 3: *Provide recommendations for energy management and design of controls that are generalisable to buildings with a high diversity factor*.

Achievement of Objective 3 of this research was based on both the findings from the monitoring and analysis of the thirteen case study events, and also analysis of relevant literature. The key recommendations that have been identified for lighting and heating energy management in the Great Hall are:

Lighting:

- Install a more flexible lighting system that allows for greater control of individual lighting fixtures
- Install dimmable lighting – Manually dimmable lights would enable clients to have even more flexibility of the lighting design. Daylight dimming would be advantageous when natural daylight levels are sufficient as seen with some of the events e.g. Concert 2, where artificial lighting continued to be used even when natural daylight levels were sufficient. Daylight dimmable lights in conjunction with a more flexible lighting design as described above would be highly beneficial in avoiding bright lights being on close to windows where natural daylight is sufficient. It would also be more energy efficient for when natural light levels increase and meet the needs of the occupant so that there are no longer requirements for higher levels of artificial

lighting. An example of this is also found in Concert 2 where the Porter was setting up the hall in the early hours of the morning but during this task natural light levels rose sufficiently to meet his lighting needs.

- Improve dialogue or even require a formality with clients using the space and interacting with the controls to better advise them on how the controls work, what the impact not using them correctly is, and encourage them to seek more help from events team or porters when interacting with controls if they are unsure how to operate them.
- Install more intuitive controls with clearer instructions – as seen from the discussion in section 4.5.3.1 and Figure 64, the current lighting controls are very confusing for someone who is not familiar with the building. This led to energy waste when clients were left in charge of the lighting use as they were often unsure how to change the lighting design using the existing infrastructure.

Heating:

- It was repeatedly observed through the monitoring and analysis of the thirteen case study events that the internal temperature struggle to meet the desired set point temperature in the absence of additional internal heat gains from occupant activity. A significant portion of the discussion around heating energy savings concerned the pre-heat time of the space prior to occupancy and the potential to reduce this time with a view to improving energy efficiencies, thus aligning the heating use better with occupant needs. The concern with this strategy of delaying the heating is that the set point temperature in the room may not be achieved in time for occupancy with a falling internal temperature in the absence of heating. However, as demonstrated by Budaiwi & Abdou (2013), when applied to intermittent cooling, an oversized system could ensure that the programmed set point temperature is achieved by the desired time. Therefore, to avoid extended pre-heat times, an oversized heating system could be an avenue of interest for the building managers and University estates team.

- Data driven alteration of the BMS governing principles (logic) to account for variability in internal heat gains. This would require estimates of occupancy and occupant activity and the associated internal heat gains, as well as clearer anticipated occupancy hours in order to estimate the temperature rise in the hall under different conditions. By factoring this into BMS logic, the scheduling for the heating system would change to proactively anticipate the additional internal heat gains from these sources as a positive contribution to achieving the programmed set point temperature.
- Alter the programmed set point temperature for different activities according to occupant levels of metabolic activity in order to avoid any conflict between heating and cooling.
- More data driven, evidence-based assumptions for BMS coding – e.g. pre-heat times of 6 hours for Dec and Jan may not be necessary for all events. This needs to be carefully considered alongside the chosen set point temperature
- Better communication between the events team and the BMS manager so that more accurate occupancy schedules are put through to the scheduling system that informs the BMS optimiser
- Better feedback from clients, and building users on their thermal comfort to inform the choice of set point temperature for different types of events
- Use backstage doors to bring in equipment when possible to avoid external doors to the hall being open for extended periods of time
- Install a mechanism or design feature to minimise thermal losses through doors being left open that open directly to the hall. This could be a double door to door system, or it could be as simple as a spring mechanism that pulls the door shut after

it has been opened. This could be especially useful when bringing in / taking out equipment.

- Have accessible controls on the radiators in the hall. With local controls on the radiators in the form of TRV’s, occupants could stop the hot water from entering certain radiators in the hall and thus reduce the further heating of the air in the hall.

In terms of recommendations for energy management in buildings that have a high diversity factor beyond the case study building, it is possible to apply the factors that Baker & Steemers (2000) stated impacted building energy performance, and provide recommendations for building design, building systems and occupants:

Design: The most important feature of the design is the performance of the building fabric is organised to avoid problems that can lead to a crisis of discomfort e.g. a good design feature of the hall is the use of blinds that are easy to use, intuitive and effective. Openable windows and doors for building ventilation. Additionally, the use of zoning could also be beneficial though this was not directly investigated in this research but has been identified in the wider literature as a potential solution to improve energy efficiencies in venue buildings (Budaiwi & Abdou 2013).

Systems: The most obvious recommendation for systems is to have more flexible controls flexible lighting systems that can allow dimming or more effective zoning of the different lighting fixtures than was observed in The Great Hall. For heating there is the potential to install oversized heating systems in order to increase the rate at which spaces heat up. This could potentially alleviate some of the issues surrounding venue buildings often only being used intermittently, though there would need to be an analysis of the potential energy savings of this system versus the current status quo in a building. It was also identified that more local controls e.g. TRV’s on radiators could be a simple solution to reduce the risk of spaces overheating.

Occupants: For occupants, the key to improving energy efficiencies is not in the attainment of one or two physical parameters, but in making them fit better with their uses and the building occupants' needs. This research identified the potential to exploit ambient energy in the form of occupant related internal heat gains. This is something that could be applied to all buildings with a high occupant diversity profile. This could be done by factoring in anticipated internal heat gains from occupants (or machinery if this is where the building has a high diversity factor), to the control logic for BMS's. Additionally, a closer examination of heating set points is also valuable to ensure that this is tailored to the occupants needs if their activity levels (and consequently their metabolic rates) are highly variable. This is to ensure that at higher or lower levels of activity, their thermal comfort needs are met. Another recommendation is that lighting needs should be used more sensitively to the actual needs of the occupants.

5.3 Research methods

Micro-scale analysis of building energy performance is potentially a labour intensive and therefore expensive undertaking, and it is important to determine whether this extra effort is worthwhile in terms of identifying energy waste, improving energy efficiencies and feeding back design problems to design teams. In terms of the process of carrying out these micro-scale studies, as has been done in this research, the use of certain technologies, for example effective sub-metering or people counting equipment could significantly alleviate the burden on the researcher. However, direct observation are imperative in identifying the nuances of occupant behaviour and energy use and management that can enable the detection of energy waste. These observations can be useful to all building types regardless of how variable their use is in order to better understand occupant-building interaction. However, for venue buildings, where there is such diversity in the use of the building, and where there are often external clients who are less familiar with the building controls, direct observations are vital in providing the contextual data of why energy was used and how useful it was to the needs of the occupants and the activities they were engaging in.

In terms of the overall monitoring approach, it was found that not all the data that was collected was useful for all of the events. In particular, relative humidity (both internal and external) was only useful for some events such as the Ball. External humidity was only useful to provide context for rises in internal humidity that were weather related.

External solar radiation was mainly useful as a measure of how overcast the day was, but as the units (W/m^2) are different to those for illuminance (lux) that was recorded by the internal environmental sensors, they could not provide a direct measure of natural light levels inside the hall at different times of day. This was compounded by the orientation of the building and location of the windows as well as the use of blinds.

Finally, with reference to the semi-structured interviews, it was found that the most useful interview was with the BMS manager, which provided much needed background knowledge of the BMS control system and the decision making process behind the building's heating scheduling. The remaining interviews provided good background knowledge regarding the management processes surrounding the energy use at the Great Hall, however this could possibly have been attained through more informal means.

In general, however, this level of very occupant focussed POE, provided very rich contextual data that was invaluable in identifying the energy efficiencies of different uses of the building and the different drivers behind energy use and waste. It has already been said that the direct monitoring of the occupants was key to providing this rich context. However, in order to alleviate the onerous nature of the monitoring programme and to improve accuracy in the data, effective submetering, potentially down to individual end uses would be advantageous. Overall, this research offered a more holistic approach to the more engineering focused macro level POE's that are innumerable in the literature.

Chapter 6

Conclusions

6.1 Introduction

The Discussion chapter detailed how each of the research objectives were answered through this research and how they contributed to the current body of knowledge focusing on the post occupancy evaluation of multi-use venue buildings. This chapter begins by defining the overall contribution to knowledge. It goes on to present a critique of the methods used, the implications for wider research and the identified limitations of the research. Finally, it proposes recommendations for future research.

6.2 Key conclusions and contributions to knowledge

The aim of this research was to investigate the relationship between occupant activity and energy performance of a multi-use venue building. The overall conclusions and contributions to knowledge are listed below:

- A micro-scale occupancy focused POE approach has been developed and implemented. This approach incorporates quantitative and qualitative data to provide a detailed assessment of the energy efficiencies of different uses of multi-use venue buildings
- A characterisation profile for the multi-use venue building has been created for the first time detailing the main causes of energy waste specific to this building type. This is achieved through categorising energy waste to identify the cause of the waste and attributing energy waste directly to different actors.
- This new insight can lead to more targeted recommendations for energy management, with wider impact and implications outlined in the following section.

6.3 Research implications

This research presented an in-depth occupancy focused POE to identify the energy efficiencies of individual uses of a multi-use venue building. Concerning the wider literature and the field of building performance and POE, this research provided a mixed methods approach to micro-scale occupancy focused POE. Through this approach these methods can assess the impact occupants have either actively or passively on the energy performance of these types of buildings. This research design can potentially be applied to all buildings or building areas that have a high diversity factors, in order to provide more context and texture to the quantitative data that is often used for more macro-scale POE’s.

This new method of analysing multi-use venue buildings and the new insights created pave the way for wider implementation of the approach to other building types by other researchers and research groups. The wider future impact enabled by this research, will lead to the creation of an important new knowledge base, identifying the causes of energy waste specific to every major building type in the UK and beyond. This in turn will greatly facilitate targeted and effective energy efficiency interventions for all main building types by energy managers with diverse levels of expertise and experiences.

In terms of the direct benefits to the proactive management of the Great Hall, this research has provided a greater understanding of the energy performance of individual events and the impact of changing occupant activity has on energy use. This could potentially lead to a more energy efficient building. For the users of the building, more proactive energy management of the internal environment could also provide a more comfortable internal environment. Through conversation with the BMS manager it was revealed that the Great Hall is to undergo a refurbishment project involving improvements to the heating system, the finding from this research could feed into the decisions made for this proposed refurbishment.

6.4 Research limitations

One clear limitation of this research is that the in-depth cross sectional studies only covered the heating season, whereas a more comprehensive analysis of building performance would also analyse the impact of hosting different events in other seasons in order to develop a better understanding of the impact of seasonality on building energy performance.

Effective sub-metering would enable analysis of electrical end uses without the need for a continuous audit process and would reduce the associated error of this analysis by having accurate measurements of electricity use instead of estimates based on observations. However, through direct observations it was also possible to analyse the context around why the certain end-uses were employed at different times and to make a judgement of whether that energy use was necessary to the occupant’s tasks.

Another limitation of the research is that estimates of heating savings due to a delay in the pre-heat time do not fully take into account the continuing temperature drop in the space without the heating on, nor do they take into account any potential benefits from solar gains. In order to interrogate this limitation further dynamic thermal simulation models could be applied to individual uses of the building to view how different pre-heating strategies could provide more accurate estimates of savings.

The analysis of small power use was limited as plug in equipment was often brought into the building by clients for each event and event organisers often set up small power equipment well in advance of when it was needed to ensure that the equipment is running and that there will be time to deal with any technical issues in advance of the event. Due to the limitations in sub-metering (either at the distribution board or at plug level) it was not possible to separately monitor these. Instead an estimate of small power use based on the observed power ratings and estimated load diversities was used to provide insight into building level electricity consumption for small power consumption. Based on this analysis it was possible to estimate the internal heat gains from small power use, and this was found to be minimal compared to the occupant related heat gains. This method of monitoring and observation is however inaccurate and better sub-metering would enable a more reliable analysis. Better submetering of small power would also enable energy efficiencies related to small power use to be identified based on the energy consumption and observations of occupant behaviour.

For the gas consumption data, the highest resolution available was half hourly. Whereas all other data was at least 5 minutely in resolution. Therefore, the representation of gas consumption over the same 5 minutely resolution is not fully representative of how the true gas use in those 5-minute periods.

For the analysis of the heating system, it was not possible to quantify the impact of thermal mass on the internal temperature. This was indirectly observed through the monitoring of the internal temperatures when the heating was not on, however this temperature change would also include any thermal losses or gains through exfiltration, and during the day this would also include solar gains.

6.5 Recommendations for future research

Further analysis of the impact of different activities on energy use during other seasons in the year would be of great interest to examine the energy performance of the building with different climatic drivers for energy use. With specific reference to the Great Hall, through the audit process it was identified that the two cooling units employed in summer have the largest any demand of any other electrical end use in the building. An analysis of the building during the cooling season could potentially yield significant further energy savings opportunities depending on observations of how this equipment is used. Through the semi-structured interviews, the building's ability to overheat in the summer months, especially with large occupancy numbers was brought forward as a concern by multiple interviewees.

A potentially major source of energy savings could be to investigate the intermittency of building use and the minimum heating requirements during unoccupied days, in order to scale back heating during these days as much as possible. It would also be of interest as part of this to assess the value of installing an oversized heating system in order to speed up heating on days when it is required for occupants.

Another area that could be investigated further would be the energy waste related to small power use in venue buildings. It was not possible to monitor this consumption using plug monitors, but this level of analysis could also yield potentially sizeable energy savings. This is especially true when factoring in occupant behaviour and the variety of different small power equipment with wide ranging energy demands that have been observed in use in multi-use venue buildings.

Finally, the last recommendation for future research is to perform an in-use analysis of the impact of energy conservation measures on actual energy use. This is something that is still very much lacking in the current body of knowledge surrounding the energy performance of buildings as a whole. Although some studies have aimed to examine some energy conservations measures such as the impact of feedback on occupant behaviour (Bordass & Leaman 2005; Carrico & Riemer 2011; Shao et al. 2017; Chiang et al. 2014), long term studies examining the impact of energy conservation measures are rare in the literature. In terms of multi-use venue buildings, no published examples of this have been found by the researcher.

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Appendix A - Key aspects of building design affecting building energy efficiency

Key aspects of a building's design such as its form, orientation, and the materials used to construct its fabric can have a significant impact on the actual in-use energy consumption. These aspects are discussed in detail in the following sections including suggested potential energy conservation measures that could be taken by designers and/ or operators to reduce energy waste.

Building form

The shape and overall size of a building (also known as the building's form) will have a bearing on the spatial layout and volume of the internal spaces which will require space conditioning (i.e. heating, cooling and ventilating) and has implications for energy flows through the building fabric (i.e. heat gains and losses). As such, the building form will have a significant impact on in-use building energy performance.

Designers can take steps to minimise in-use energy consumption associated with the building form through the use of passive design techniques. For instance, in order to reduce heat losses and gains through the fabric, the exterior surface area of a building can be minimised in relation to its volume, this favours a more compact building form, as opposed to long and narrow (Tymkow et al. 2013; Oughton & Hodkinson 2014).

Additionally, shallower floor plans (or the use of internal courtyards or atriums) can enable greater daylighting and improve the potential for natural crossflow ventilation relative to deeper plan buildings which generally require more artificial lighting and mechanical ventilation (Tymkow et al. 2013; Oughton & Hodkinson 2014)..

Building orientation

The building’s orientation will dictate solar gain into the building which can have consequences for energy consumption, for example it may result in additionally cooling demand. Variations in the sun’s path during the different seasons affects solar radiation penetration patterns and therefore heat gains and losses. In the UK, during winter the sun path is at a low angle and solar radiation generally enters south facing facades at a lower angle. During summer, the sun path is at a higher angle, and consequently glare free daylight is more easily available on the north façade as minimal solar radiation will fall at a high angle. The south side of a building in summer will generally be subject to high levels of glare with the sun path at a higher angle. Strong solar radiation at a low angle is continually received by the east and west facades of the building all year round.

By considering this designers may be able to adjust the orientation of the building early in the design process to make use of solar gains in winter and minimise solar gains in summer whilst simultaneously minimising glare which can lead to occupant discomfort.

Building envelope

The building envelope comprises of elements such as walls, floors, roof, windows, and doors. The envelope acts as a barrier between the variable external environmental conditions and the internal conditions of the building, with the intention of providing a stable comfortable environment for the occupants. The material properties of the building envelope will have a significant impact on the energy required to maintain a suitable internal environment due to heat gains and losses.

For example, the thermal conductivity of a material is the measure of how easily heat can flow through it. Lower thermal conductivity indicates a longer time for heat to transfer through the material hence better thermal performance (Oughton & Hodkinson 2014).

The R-value is a measure of the thermal resistance of a material and considers thermal conductivity and thickness. The higher the R-value, the greater its thermal resistance. The R-value has the units m^2K/W and is calculated by using the formula:

$$R = l/\lambda$$

Where:

- l = the thickness of the material (m)
- λ = thermal conductivity of the material (W/mK)

The U-value (or thermal transmittance) identifies the ability of a building element (which will generally consist of a combination of materials) to conduct thermal energy. It is equal to the inverse of the element's total thermal resistance.

$$U = \frac{1}{[Rsi + R1 + R2 + \cdots + Rso]}$$

Where:

- Rsi = internal surface resistance (m^2 K/W)
- Rso = external surface resistance (m^2 K/W)
- R1, R2 etc. = the thermal resistance of the materials making up the element (m2 K/W)

Steady state heat transfer

Heat transfer through the building envelope occurs through conduction, convection, and/ or radiation. The transmission of heat energy through the solid components of the building envelope through these types of external load is primarily driven by the temperature difference between the interior and exterior environments. Steady state heat transfer calculations can provide an estimation of the heat loads in the building and are generally considered adequate to size building heating systems for conventional forms of building construction (Oughton & Hodkinson 2014). However, they assume that the heat exchange is a function of the difference in the internal and external temperature at a specific point in time and do not take account of the thermal mass of a building (Oughton & Hodkinson

2014). The impact of thermal mass on heat losses and gains is discussed in later in this appendix.

There are two types of external load that are significant when considering heat gains and losses of the building envelope: direct transmission through the fabric, and infiltration/ ventilation loads.

Fabric

Heat loss through the building envelope during winter months occurs by direct heat transmission through the building fabric. Heating energy is generally required to compensate for this loss to provide a comfortable internal environment for the occupants. Buildings heating systems will be sized to compensate for steady state heat losses (Oughton & Hodkinson 2014). Other heat sources are often present which can serve to reduce the overall heating energy required in operation. For example, heat gains from people, lighting and equipment can often make a significant contribution.

Energy for cooling is required to offset heat gains from internal and external sources. Significant gain occurs from the transmission of energy through the building envelope and from internal building processes (e.g. equipment, lighting, and body heat loss). These gains, which can occur throughout the year, are discussed in following sections of this appendix. A key objective of energy management is generally to save energy cost by reducing the energy required for cooling, while maintaining an environment suitable for both processes and occupants.

The heat loss or gain through a building element is calculated by the equation:

$$Q = U \times A \times (T_2 - T_1)$$

Where:

- Q = heat loss rate (W)
- U = 1 / R-value = Thermal Transmittance (W/m2.°C)
- A = surface area (m^2)
- T2 = external temperature (°C), T1 = internal temperature (°C)

Infiltration and ventilation

Infiltration is the uncontrolled flow of air through the building fabric and occurs when air outside the building leaks into the building through cracks and other openings in the envelope, such as around windows, doors, dampers, skylights, etc., as well as door or windows left open by occupants (for purposes other than natural ventilation).

Ventilation is the intentional displacement of indoor air through mechanical ventilation systems or through intentional use of windows and doors for natural ventilation. Designers will size ventilation systems to provide adequate fresh air to satisfy the activities within the building. Energy is required to increase the temperature of the infiltrated air from the outside temperature to the space temperature inside the building. The amount of energy required at any given time will depend upon the amount of air being introduced into the building, and the difference between the outdoor and indoor temperatures.

The rate of infiltration or ventilation is a result of the pressure difference across the building envelope. This pressure differential can be due to wind, the chimney or stack effect (i.e. the difference in density between the indoor and outdoor air), or the pressure created by mechanical ventilation systems. A simplified approximation of instantaneous heat gain due to ventilation and infiltration can be given by the equation:

$$Q_V = C_V(T_{2-}T_1)$$

Where:

- Qv = heat gain due to air infiltration/ventilation
- T1 = internal temperature (°C), T2 = external temperature (°C)
- Cv = is the infiltration/ventilation conductance (W/K) and is itself given by the equation:

$$C_V = \rho C_p N V$$

Where:

- N = number of room air changes for air entering the space at the outside air temperature (per hr)
- V = volume of the space (m3)

Thermal mass

In general building elements have both mass and thermal resistance which will produce a time lag in heat transfer as they will absorb heat energy. The thermal mass (or thermal admittance) of a material quantifies its capacity to absorb, store and release heat energy. It is calculated with the equation:

$$h = \Delta Q / A \times \Delta T$$

Where:

- h = heat transfer coefficient ($W/(m^2K)$)
- ΔQ = heat input or heat lost (W)
- A = heat transfer surface (m^2)
- ΔT = difference in temperature between the solid surface and the adjacent air space.

Thermal mass can be useful as it can serve to smooth out extremes in temperature and therefore improve occupant comfort. Materials with a high thermal mass can effectively be used as a ‘thermal buffer’ which serves to reduce the rate of temperature any change. Typically, thermal mass within buildings is concentrated in walls and floor slabs which tend to be constructed of heavy weight materials with high specific heat capacity.

The buffer effect of thermal mass can be utilised by designers such that heat or coolth can be stored when not required and released when it is. For instance, well-insulated floor slabs and walls can be positioned such that they are exposed to solar radiation during the day when they will store heat which can then be released during the night as the external air temperature reduces. Alternatively, where daytime cooling is required this can be provided through the use of a night-time cooling strategy where high level soffits can be exposed to the air during the night to cool them down.

In general computer simulation modelling is used to analyse the dynamic response of a building structure as this is an onerous task to undertake by manual methods (Oughton & Hodkinson 2014). Dynamic simulation models are required to be undertaken for new buildings and retrofits to demonstrate compliance with Part L of the Building Regulations. Dynamic simulation calculations also evaluate other key properties of the building materials including the Admittance (Y) which is the ability of a surface to smooth out temperature variations in a space, the Decrement factor (f) which represents the ability of a building element to reduce the magnitude of a temperature change at one face before this penetrates to the other, and the Surface factor (F) which is the admission and absorption of energy to the thermal capacity of a structural element.

Solar gain

Although solar radiation can be transmitted into a building through the external fabric the majority (depending on the material of the structure) is generally through windows and can have significant impacts on the heat flow within a building. Solar radiation entering through windows is absorbed by the internal surfaces of the room and then readmitted back into the internal environment. Calculating the impact of solar gains is a requirement of Part L Building Regulations and, due to its complexity, is generally undertaken by computer simulation. The mean solar heat gain to the internal environmental is given by:

$$\bar{Q}_{se} = \bar{S}_e \, \bar{I}_t \, A_g$$

Where:

- $\bar{Q}_{se} = the$ mean solar gain to the internal environment
- $\bar{S}_e =$the mean solar gain factor environmental node

- $\bar{I}_t$ = the mean solar irradiance (W/m^2)
- A_g = the area of glazing (m^2)

Steps can be taken to minimise the impact of solar gain by introducing internal or external solar shading, or by using tinted glass.

Building use

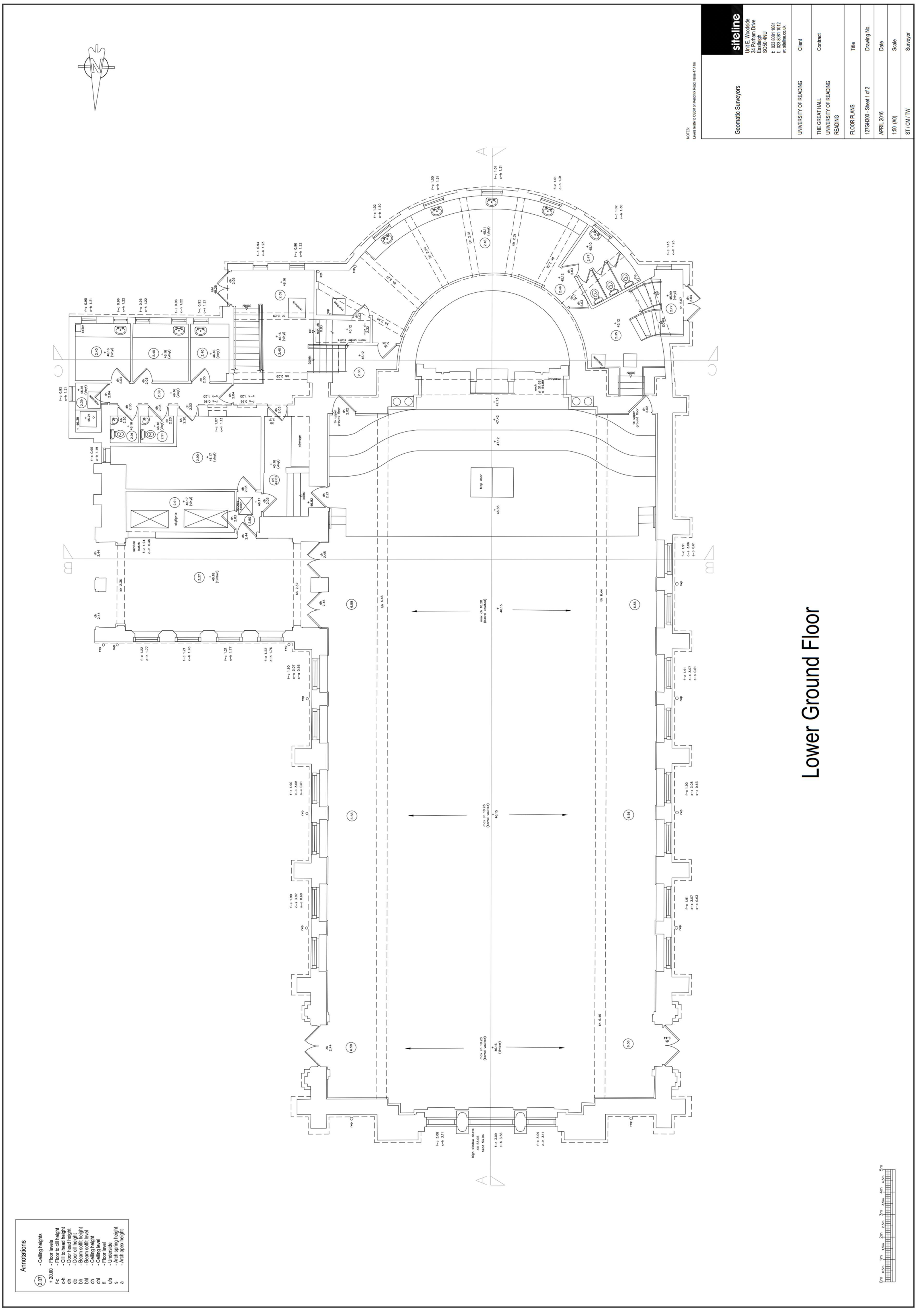
Internal heat gains occur due to the heat released by activities or equipment within the building. In general there are three main causes of internal heat gain within a building: occupants, lighting, and equipment (Tymkow et al. 2013).

Lighting heat gains are due to both convection and radiation the proportions of which will depend on the type of lighting used. The radiative part of the heat gain will initially be absorbed building fabric and internal furnishings before being reemitted back into the conditioned space. Due to the thermal mass of the building fabric and furnishings this will create a time lag with the absorbed energy be radiated back into the internal space after lights have been switched off.

Internal heat gains from equipment will obviously vary depending on what equipment is brought into the building. Due to this they can be difficult to accurately anticipate during the design stages, designers generally use values for typical equipment and consider the heat gains in the form of W/m^2 (Tymkow et al. 2013).

Occupants can also interact with buildings passively through their internal heat gains, which refers the increase in heat into a space from equipment, building services, and occupant activity. Occupants emit heat and moisture in the space. The rates at which the heat and moisture are released depend on the different states of activity of the people in the conditioned space. People give off energy to the building space in the form of dry heat (sensible) and moisture (latent heat). This energy release can either have a positive or a negative effect on the building’s energy usage; during heating periods it will reduce the overall heating requirement for the building but when cooling is required, the energy released by people will place an additional load on the cooling system. The quantity of energy released varies for different people, and also depends on their body mass, their level of activity and their mode of dress. This is of relevance to this research as occupants in venue spaces can undertake a variety of activities which can affect the rate of internal gains – e.g. dancing or sitting still.

Appendix B – Elevations & floorplans


Lower Ground Floor
NOTES:
Levels relate to OSBM on Kendrick Road, value 47.41m
Geomatic Surveyors
siteline
Unit E, Woodside
34 Parham Drive
Eastleigh
SO50 4NU
t: 023 8081 1081
f: 023 8081 1012
w: siteline.co.uk
Client
UNIVERSITY OF READING
Contract
THE GREAT HALL
UNIVERSITY OF READING
READING
Title
FLOOR PLANS
Drawing No.
127GH300 - Sheet 1 of 2
Date
APRIL 2016
Scale
1:50 (A0)
Surveyor
ST / CM / TW
Annotations
2.07 - Ceiling heights
+ 20.00 - Floor levels
f-c - Floor to cill height
c-h - Cill to head height
dh - Door head height
dc - Door cill height
bh - Beam soffit height
bhl - Beam soffit level
ch - Ceiling height
chl - Ceiling level
fl - Floor level
u/s - Underside
s - Arch spring height
a - Arch apex height
N
A
B
C
trap door
storage
skylights
service hatch
DOWN
UP
0m
1m
2m
3m
4m
5m

Appendix C - End-use breakdown of fixed loads in the Great Hall.

Table 9: End use breakdown of fixed loads in the Great Hall. The table shows the location of energy consuming piece of equipment of device, the model if available, its end use, the number of individual units and the installed load in kilowatts

End use	Level	Area	Room code	Item	Model	Energy	No.	Installed load per unit (kW)	Total installed load (kW)
Space heating	Basement	Boiler plant room	B02	Main boilers	Remeha Quinta pro	Gas	2	129.55	259.09
Space heating	Basement	Boiler plant room	B02	Main boilers	Remeha Quinta pro	Heat	2	114.00	228.00
Pumps	Basement	Boiler plant room	B02	Primary pumps		Electricity	2	0.90	1.80
Pumps	Basement	Boiler plant room	B02	Secondary pumps		Electricity	2	2.20	4.40
Space cooling	Basement	Store	B03	AC units	Denco	Electricity	2	5.00	10.00
ITC	Basement	Rehearsal room		Switch unit		Electricity	1	0.20	0.20
Hot water	GF	Changing room (banana)	UG01	Water heater	Sadia	Electricity	1	3.00	3.00
Hot water	UGF	Changing room (banana)	UG01	Water heater	Sadia	Electricity	1	3.00	3.00
Hot water	GF	Changing room	G03	Water heater	Sadia	Electricity	1	3.00	3.00
Hot water	Outside GF	Toilets outside	TBCD1	Water heater	Sadia	Electricity	1	3.00	3.00
Lighting	GF	Hall	G01	Chandeliers	CFL 11W	Electricity	90	0.01	0.99
Lighting	GF	Hall	G01	Hall Front & Back	CFL 18W	Electricity	8	0.01	0.09
Lighting	GF	Hall	G01	Cove lighting	LED 8W	Electricity	18	0.01	0.14
Lighting	GF	Hall	G01	Floodlights	MH 250W	Electricity	8	0.40	3.20
Lighting	GF	Hall	G01	Stage spotlights	Hal 150W	Electricity	8	0.15	1.20
Lighting	GF	Lobby	CRG01	-	CFL 26W	Electricity	4	0.03	0.11
Lighting	GF	Properties store	CDG01	-	T12 40W	Electricity	1	0.04	0.04
Lighting	GF	Changing room	G06	-	T8 36W	Electricity	5	0.04	0.20
Lighting	GF	Changing room	G06	-	T8 18W	Electricity	1	0.04	0.04
Lighting	GF	Changing room corridor	CRG04	-	T8 36W	Electricity	1	0.04	0.04
Lighting	UGF	Changing room	UG01	-	T8 36W	Electricity	5	0.04	0.20
Lighting	UGF	Changing room	UG01	-	T8 18W	Electricity	1	0.04	0.04
Lighting	UGF	Changing room corridor	UGST2	-	T8 36W	Electricity	1	0.04	0.04
Lighting	GF	Entrance hall corridor	CRG02	-	T8 36W	Electricity	2	0.04	0.08
Lighting	GF	Dressing room	G03	-	T12 40W	Electricity	1	0.04	0.04
Lighting	GF	Dressing room	G04	-	T12 40W	Electricity	1	0.04	0.04
Lighting	GF	Dressing room	G05	-	T12 40W	Electricity	1	0.04	0.04
Lighting	GF	Dressing room corridor	CRG03	-	T12 40W	Electricity	1	0.04	0.04
Lighting	GF	Green room	G02	-	T12 40W	Electricity	3	0.04	0.13
Lighting	GF	Green room lobby	CRG01	-	T8 18W	Electricity	1	0.04	0.04
Lighting	GF	Green room lobby	CRG01(SC)	-	T8 18W	Electricity	1	0.04	0.04
Lighting	Basement	Store	B03	-	T12 40W	Electricity	6	0.04	0.26
Lighting	UGF	Toilets near Green room	WCG01 01	-	fan and lights	Electricity	1	0.07	0.07
Lighting	UGF	Toilets near Green room	WCG01 02	-	fan and lights	Electricity	1	0.07	0.07
Lighting	UGF	Corridor outside left UG01	UGST1	-	T8 36W	Electricity	2	0.04	0.07
Lighting	UGF	Corridor outside right UG01	UGST2	-	T8 36W	Electricity	2	0.04	0.07
Lighting	UGF	Toilet in UG01	WCUG1	-	T8 36W	Electricity	1	0.04	0.04
Lighting	GF	Toilet in G01	WCUG03	-	T8 36W	Electricity	1	0.04	0.04

Appendix D – Example semi-structured interview questions

UoR Energy Analyst

- Can you tell me a little bit about your role in the estates team?
- What kind of strategies have you explored to manage the buildings in a more energy efficient way?
- How do you decide which buildings you want to improve?
- Thinking about the Great Hall, what kind of reasoning do you have for managing the building better? What kind of strategies immediately spring to mind in terms of how you might improve its energy management?
- What kind of use would you find out of a project like mine / how might you use the output from this research?

Events assistant + events manager

- How many events are typically held each year?
- What kind of events are held in The Great Hall and are there any that you could describe as "typical, repetitive or even a standard type" or are they all different?

Questions about how events and guests are organised*:*

- Is there a typical process from start to finish from a client picking up the phone and saying they'd like to have an event hosted at The Great Hall to you delivering an event and then closing it down after the guests have left? If so, what is it?

- How do you charge clients for events? What might be a typical breakdown of what they are charged for?
- Questions about how the Hall is set up to host the event:
- Once a client describes what they want out of the space how do you go about delivering that to them? Maybe you can use an example of an event?
- Do you attend the events yourself? If so, in what capacity? What kind of responsibilities do you have during an event?
- When running events do you keep a track of people entering and leaving the hall or building?
- Questions about the Hall's ability to meet expectations:
- What kind of experiences do people attending events have of the space, do they offer feedback to you?

Questions about future events (focussed at manager?):

- In terms of future events how do you go about learning from past experiences and ensuring that you have a bank of knowledge to call on for the design and set up of events?

Porter

Questions about day to day management of the building

- Can you talk me through a typical calendar year for the Great Hall and how you are involved with it on a day to day basis?

- There are a few different university users of the building e.g. catering / cleaners, what kind of arrangement do you have with these different people?

Questions about how the room can be set up + occupancy

- The hall can be set up differently for different events, can you describe some of the more common arrangements and also some of the more unusual ways that the space is used.

- What is the range of different equipment used for different types of events? Is there any typical or common equipment? If clients booking the hall bring additional equipment, do you have any involvement in its set up? Do you provide any guidance on what can and can't be used?

Questions about interaction with clients / events team

- When the events team book an event in, what kind of information do you get about it to help you prepare and to understand what is needed out of the space?

- What kind of involvement do you have on events days?

- During an event, how do you ensure that the client that has booked the hall have everything they need and are comfortable?

Questions about interaction with BMS team / managing building services

- How conscious are you of how comfortable audiences / people are during an event and do you try and actively monitor events?

- What kind of interaction do you have with the BMS team?

- Aside from heating and cooling, how do you manage other energy consumption in the building?

<u>BMS manager</u>

Questions about events:

- How aware are you of the different types of events in the hall? What kind of relationship do you have with the events team and the porters managing the building?

Questions about the heating / cooling systems

- Can you describe the heating and cooling systems in the hall and how they are managed on a day to day basis?

Do you have any kind of alert system related to the comfort in the hall, if so, are there any occasions that it has been triggered / you would expect it to trigger?