University of Reading

Technologies for Sustainable Built Environments

User behaviour and perception as drivers for lighting energy efficiency and performance gap reduction in higher education

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Submitted in partial fulfilment of the requirements for the degree of Doctor of Engineering,

October 2017

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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October 2017

ABSTRACT

User behaviour and perception are key drivers for lighting energy efficiency and performance gap reduction in higher education. Changing the way we conduct post occupancy evaluation to include retrofits and understanding users' needs more thoroughly will ultimately lead to a greater reduction in CO_2 emissions. A pilot interview study was carried out with University of Reading Whiteknights campus with a total of 6 staff and students in 2014 and developed into a main interview study with 9 academic staff in 2015. During 2014 to 2016 data loggers were deployed for six months to 10 single occupancy offices, 13 classrooms and 14 corridor areas in 3 buildings on campus that were used for both teaching and office space. The data from the loggers was used to calculate hours of lighting use and occupancy, time of day analysis and a prompt study.

The findings from interviews revealed that lighting control design in classrooms lacked consistency across the real estate portfolio; office occupants felt their spaces were neglected and; the piecemeal upgrades contributed to their frustrations of being unable to control their lighting effectively. Post occupancy evaluation in single occupancy offices, classrooms and corridors was carried out using environmental loggers to quantify the levels of hours of wasted lighting use for performance gap analysis relating this to external factors and CO_2 emission savings. Significant hours of wasted lighting were found in all three task areas in the three study buildings. Interesting findings in the office study found that lighting use and occupancy patterns varied by both building and size of office. To combat this prevalent lighting waste continuous commissioning and verification were suggested as practical measures to reduce the CO_2 emissions and energy consumption and improve user satisfaction. Finally the prompt study exploring office occupant's habits was found to link light switching behaviours on exit to the time of day and suggested the corridor lights being off influenced the action of switching off lights in the office. This thesis contributes to knowledge by providing new significant findings in both post occupancy evaluation and human behaviour in light switching.

ACKNOWLEDGEMENTS

My EngD could not have been possible without the support, care, love and time people have generously given me.

Dan Fernbank, thank you so much for your excitement and drive to help my project become embedded into the Sustainability Team and E&F practices. Without your support, funding and time our goals would not have been achieved.

Professor Phil Beaman, whose enthusiastic attention to detail drove me to finally learn to write in an academic voice. Phil, you provided me with a sense of humour when I had lost mine, you were sympathetic and kind.

Professor Li Shao, whose selfless time and care kept me going, you encouraged me, gave me positive and challenging feedback and always kept an eye on the bigger picture.

The best bit was you all allowed me the space, time and ability to become an independent researcher quite early on, so thank you sincerely for granting me academic freedom.

Dr Steve Davies, you were the first person to open my eyes to research in my undergraduate degree at Bath. If I had not chosen the waveguide project supervised by you I doubt I would have the desire and thirst for research, your supervision and guidance were fundamental to me enjoying my project and go on to tackle a doctorate.

Jenny Berger, Emma Hawkins, Dr Stacey Waring, Dr Dan Williams, Georgie Watson and David Miller, thank you for being the support team at TSBE organising, finding time and money, committing to conferences and making things run in a professional way, it has been a pleasure to work with you all.

Jo Burton, Kim Wan, James Thorpe, Tom Yearley, Anna Glue, Karen Stanbridge, Ruth Harris, Steve Boon, Janis Pinch, you have all given me so much support over the years encouraging me with smiles and laughter, the E&F department is a great place to work and feels like a family because of you.

Dr Sam Mudie, Saadia Ansari, Dr Rich Tetlow and all other TSBE research engineer students and graduates, we have all shared support in times of difficulty and celebrated when good events happen too. Sam you taught me how to be a parent and get through the tough times with a small person whilst completing thesis milestones.

My family and friends, thank you for giving me the space I have needed to complete this work. Your words of encouragement and support were crucial to me in times of need, your love, patience and kindness were generous.

Paul, my husband, my best friend and father of our son. There is no way I could have completed this without you. We have shared so many good and difficult moments, losing our first baby was one of the most heart breaking moments for us, but together we grieved and found a way to carry on each day. Our son Izaak is a delight because he has so many of your qualities.

PUBLICATIONS & PRESENTATIONS

PEER REVIEWED PUBLICATIONS

I. Users' experiences of lighting controls: A case-study
van Someren, KL, Beaman, P., Shao, L. May 2017 (0), p.1-16 in Lighting Research & Technology doi.org/10.1177/1477153517709063

II. Calculating the lighting performance gap in higher education classrooms
van Someren, KL, Beaman, P., Shao, L. in International Journal of Low-Carbon Technologies, doi.org/10.1093/ijlct/ctx015. Presented at 16th International Conference on Sustainable Energy Technologies, University of Bologna, Italy, July 2017.

III. Determining the difference between predicted vs. actual lighting use in higher education corridors
van Someren, KL, Beaman, P., Shao, L. in Frontiers in Mechanical Engineering special edition research topic: Energy & Built Environment. doi:10.3389/fmech.2017.00011

IV. Prompting light switching behaviours in corridors and offices in a UK university campus
van Someren, KL, Beaman, P., Tetlow, R., Shao, L. in Proceedings of 28th CIE Session 2015, Paper OP55 presented in Manchester 2015.

INDUSTRY PANEL

V. Panel Discussion: Why aren't controls easier to use? Lux Magazine Lighting for Large Estates. 21st May 2015, Cavendish Centre, London, UK.

COLLBORATION

VI. Penn State University and University of Reading collaboration trip. I presented my qualitative user experience interview findings to Penn State academics alongside my TSBE colleagues in September 2015.

ACRONYMS

BUS	Building Use Studies
CIBSE	Chartered Institution of Building Service Engineers
CO_2e	Carbon dioxide equivalent emissions
DEC	Display Energy Certificate
EngD	Engineering Doctorate
EPBD	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
F-gases	Fluorinated Gases
FM	Facilities Management
GIA	Gross Internal Area
GHG	Greenhouse Gas
GPRS	General Packet Radio Service
HCI	Human-Computer Interaction
HEFCE	Higher Education Funding Council for England
IAQ	Indoor Air Quality
ICT	Information and Computer Technologies
LAN	Local Area Network
M&E	Mechanical and Electrical
O&M	Operation and Maintenance
PIR	Passive Infra-Red
POE	Post Occupancy Evaluation
PROBE	Post-Occupancy Review of Buildings and their Engineering
RIBA	Royal Institute of British Architects

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Chapter 1 Introduction

The Engineering Doctorate (EngD) programme is a professional doctorate. This four-year research degree incorporates 120 MSc credits and is based in industry. The EngD is part-funded by the Engineering and Physical Sciences Research Council (EPSRC) and is specifically for applied original research in industry. The work included in this thesis was managed by the Technologies for Sustainable Built Environments at the University of Reading and was sponsored by the Estates & Facilities Department at the University of Reading, the industry sponsor.

1.1 Global perspective of energy efficiency

The Intergovernmental Panel on Climate Change (IPCC) Working Group III Report "Climate Change 2014: Mitigation of Climate Change", details the impact of buildings on global emissions (Lucon *et al.*, 2014). Total global final energy use in buildings was 32% of total global final energy use in 2010 (Lucon *et al.*, 2014). Building emissions were calculated at 19% of global emissions related greenhouse gases (GHG), 33% of global black carbon emissions and between 13-33% of F-gases globally (Lucon *et al.*, 2014). Policy instruments intended to assist building owners and occupiers to become more energy efficient have been short lived in the UK. The UK Government's 'Green Deal' was introduced in 2013 and scrapped in 2015 (Holder, 2017), limited uptake from the residential market left the policy unviable as the financial interest rates were overinflated and no agreement was reached relating to the commercial sector. The UK Government's zero-carbon homes policy was also scrapped in 2015 (Mark, 2016). The UK government dramatically cut feed-in-tariffs for solar electricity generation by 65% which had the knock on effect of property occupiers stalling or retracting their intended solar installations (Vaughan, 2016). The IPCC report does however recognise that buildings and retrofits have very long lifespans and highlights a very significant 'lock-in' risk where carbon intensive options are used for several decades (Lucon *et al.*, 2014). The impact of behaviour, lifestyle and culture having a major effect on buildings' energy use is also explicitly stated by the IPCC authors (Lucon *et al.*, 2014). The latest UK Government report 'Meeting Carbon Budgets: Closing the policy gap on climate change' recognises that UK emissions from buildings have risen for the past two years and recommends major overhaul with new policies for reducing emissions (Committee on Climate Change, 2017). It is clear that robust policy is essential to preventing locking in old technologies to both new and existing buildings through retrofit.

1.2 Estates & Facilities Carbon Management & Strategy

In 2009 the University of Reading Estates & Facilities Team formed a specific team to target energy use and sustainability, the Energy Team was created and since its inception has grown in size and scope. During the academic years 2010 – 2011 the University of Reading's Senior Management Board committed to a Carbon Management Plan, a specific requirement of the Higher Education Funding Council for England (HEFCE). The target for reducing carbon dioxide emissions was set at a 35% reduction in carbon dioxide equivalent emissions by the academic year 2015/2016) against a baseline year of 2008/2009. In early 2017 the University of Reading achieved the 35% emissions reduction target (Sustainability Team University of Reading, 2017). The Carbon Management Plan was ambitious and targeted future emissions to be an additional 10% to total a 45% reduction by 2020 against a 2008/2009 baseline.

Based on the University of Reading's Whiteknights Campus this research was focussed on existing buildings on campus, the majority of which were constructed at least 10 years ago with some dating from the 1950s in their construction. This existing building stock provided significant potential for implementing suitable refurbishment and retrofit strategies by informing future energy efficient installations on campus as the cost of total building replacement was unlikely both financially and operationally. Analysis of the energy saving potential of the existing buildings was limited by the availability of building level metering on site. Industry work was completed during 2013 analysed the metering data on site and the need for future metering. This allowed for better reporting as part of the EU Directives 2002/91/EC and 2010/31/EU on the energy performance of buildings Display Energy Certificates (DECs) in publically accessible campus buildings over 500m^2. Both the metering strategy and energy efficiency projects were crucial to the Carbon Management Plan's success.

The ability to sub-meter buildings to develop a better understanding of specific areas of consumption was also explored during 2013 with the installation of NoWatt metering in the chemistry building. This work started in June 2013 and finalised in December 2013 due to complications arising within this complex building and a lack of prioritising the installation internally. To rely on metering data requires an understanding of the circuits within the existing building. As the majority of buildings on campus have been continuously adapted, retrofitted and refurbished over the lifespan of the property obtaining accurate information in the form of M&E drawings, schedules of installations and O&M manuals was highly unlikely. Even when these drawings were obtained from maintenance and project staff in the Estates & Facilities department it would be perhaps naïve to assume that every contractor had the rigorous endeavour to update these drawings accurately and then make these available. Some of the meters within campus buildings were directly (manually) read infrequently, others had profiled data that records changes every minute, therefore the range of data, its quantity and quality was vast. The installation of the NoWatt sub-metering in the chemistry building allowed for a granular level of detailed information that was not previously available for any of the science buildings on campus. The

NoWatt sub-metering was a pilot project managed by the researcher and carried out in 2013 developed the ethos with the industry sponsor of collecting data before, during and after an energy efficiency upgrade. The chemistry building had new variable air volume drives fitted to the fume cupboard air handling units and the NoWatt metering assisted in providing robust evidence to further support other fume cupboard project upgrades as it demonstrated the savings initially calculated prior to deployment. The measurement and verification process of this project was vital for providing robust evidence to the Sustainability Team to gain greater support from senior management for further projects. This pilot demonstrated the use of metering data and as a result the other fume cupboards on campus were upgraded based on this proof of concept and evidence. The Sustainability Team won a Green Gown award in 2016 for Facilities and Services based on these science laboratory upgrade projects (EAUC, 2016). It is this process of checking the system, measuring the outputs and analysing the data before, during and after an energy efficiency upgrade that followed through to the lighting and occupancy studies that formed the collection of final EngD projects reported in this thesis. In the first six years of our University's carbon management programme, lighting retrofit projects made up 12% of the total carbon energy efficiency projects and the nine lighting upgrades cost a total of £810,532 and achieved savings of £164,951 per annum (p.a.) and 800 tCO_2e (p.a.) (Fernbank, 2013). The scope of the doctorate focussed on the lighting energy efficiency projects as they contributed towards the industry sponsor's goal of reducing carbon and energy use.

1.3 EngD research scope

The EngD research scope was designed to identify where carbon emissions could be reduced to contribute towards the industry sponsor's Carbon Management Plan and the academic requirements for producing original, significant, challenging, synergistic, publishable and defendable work. Lighting and occupancy provided gaps in industry and academia by collecting in field data from existing buildings in relation to people and their habits. For the industry sponsor better specification, operation and maintenance of lighting could be developed by understanding patterns across different tasks and buildings.

1.4 Aims & Objectives

The focus of this thesis is how habit and design are interlinked in lighting use. The thesis proposes that by understanding users' needs and patterns of behaviour better lighting design will follow that could lead to energy savings. The conceptual framework of this thesis is illustrated in Figure 1.

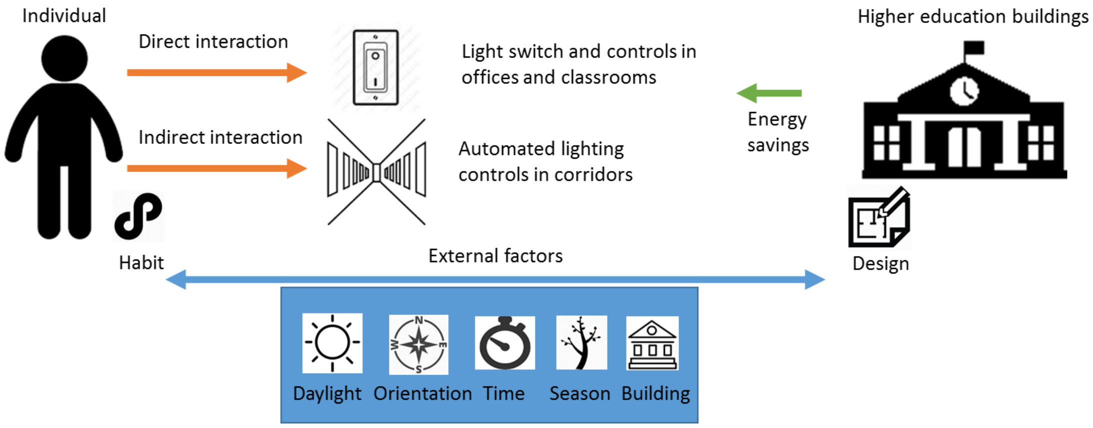
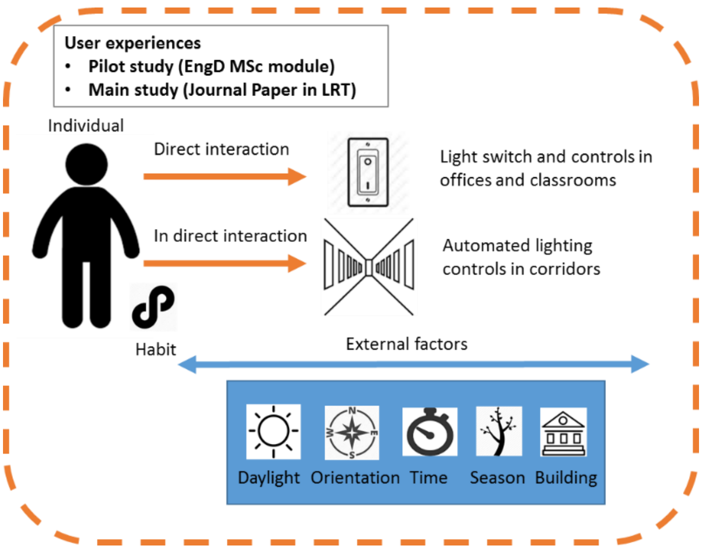


Figure 1 Conceptual framework of thesis

The main aim of the work described in this thesis was to gain insights from end users and their experiences, measure lighting use and occupancy in field and to explore the habitual patterns of light switching. The literature review of previous work found gaps for contributing to knowledge in the field of post occupancy evaluation (POE) of lighting. Two main methods of empirical post occupancy evaluation were followed – learning from experience; and using the energy assessment and reporting method.

1.4.1 Users' experiences

Learning from experience as a POE method a pilot study using semi-structured interviews was carried out in 2014 as part of the EngD Masters module. This pilot posed broad energy related questions to 4 post graduate students and 2 staff members, the ethics approval outline questions are included in Appendix A. From this pilot objective 1 was formed to: Explore end users experiences by applying qualitative methods of semi-structured interviews, Figure 2. Questions, included in Appendix B, were openly explored relating to:



(1) Automation in corridor areas;

(2) Corridor dimming, sensitivity and timing;

(3) Orientation of building;

(4) Office daylight, blinds and artificial lighting;

(5) Office lighting habits and patterns of behaviour;

(6) Seasons/weather;

(7) Classroom lighting controls – examples of excellent and poor designs;

(8) Views and blind use

Figure 2 User experiences

These questions were addressed in the main study and built upon the wider pilot study questions to focus on user behaviours and perceptions in lighting. Building upon the user experiences findings the topic of human factors in lighting was reviewed in the context of light switch design. The second method of POE measured run hours of lighting, illuminance and hours of occupancy using environmental loggers to conduct the energy assessment and reporting method of POE as shown in

Figure 3.

1.4.2 Waste avoidance objectives

The objectives of this group of studies were to:

Objective 2: discover any interesting patterns of lighting on use and occupancy in offices

Objective 3: measure the performance gap of lighting in classroom and corridor environments

Objective 4: look at external factors to see if they influenced lighting, occupancy and wasted lighting;

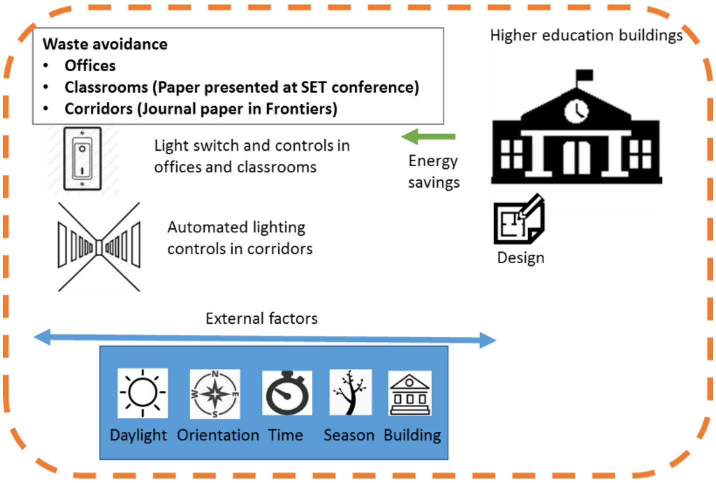


Figure 3 Waste avoidance

Objectives 2, 3 and 4 were chosen as they covered three of the key space types by task area on campus: offices, classrooms and corridors. In offices light switching patterns and time of day occupancy would provide a greater understanding of how and when the offices were used. The classrooms and corridors were areas that had been upgraded as part of the carbon management energy efficiency plans and therefore performance gap analysis could be carried out. External factors could reveal interesting influences on user behaviour and therefore reveal more about lighting use and occupancy practices.

1.4.3 Prompt study objective

Objective 5: determine if there was a relationship between office lights being left on and the corridor lights being on.

The combination of interdisciplinary subjects from psychology, engineering and design then identified a further gap which completed the research design. This third and final study crossed both habit and design, in Figure 1, using cues or prompts as a concept to encourage energy saving behaviours. It proposed that wasted lighting in offices could be occurring due to a lack of contrast between the office and corridor on exit.

1.5 Thesis structure

This thesis is organised into six further chapters. An overview of each chapter is provided and a table of applied methods is shown in Table 1.

Chapter Two - Literature Review

Chapter two summarises the finding of the literature review. Topics covered include current practices for energy efficiency on a large scale, concluding that design and post occupancy evaluation provide a gap in knowledge. End users in the built environment are identified as a forgotten group in lighting and lighting controls. Lighting and occupancy patterns are explored for waste and the performance gap between design intent and practice offers an area for new empirical findings. Finally human factors in lighting is briefly examined in relation to habits and prompting people to avoid wasted lighting use, another area for a significant contribution to knowledge.

Chapter Three – Users' experiences

Chapter three analyses two end users' experience studies by applying qualitative methods of semi-structured interviews. Qualitative methodological considerations are discussed and the lack of end user engagement in built environment energy efficiency and lighting projects in post occupancy evaluation methods is described. This chapter addresses Objective 1 and is divided into three sub-sections. Firstly it presents a pilot study that looked at the broad views of post-graduates and staff in relation to energy efficiency on campus. The main study refers to the journal paper publication (I). My specific contribution to paper I was in design, data collection, data analysis and writing the article, 85% of the final version, the remaining 15% contribution was from my supervisors, my co-authors, in the form of editing the draft and final manuscripts. The main study developed the pilot study findings and focussed on lighting, lighting controls and occupancy in offices, classrooms and corridors. The chapter concludes with future research opportunities to study lighting control use for people with disabilities.

Chapter Four – Waste avoidance

Chapter four describes the research undertaken to meet the quantitative intentions of the project and addresses objectives 2, 3 and 4. It is divided into three distinctive sub-sections relating to offices, classrooms and corridors. The waste avoidance data focussed on three buildings – Humanities, Maths and Urban buildings as these were identified as part of the long term real estate strategy and core estate. The Faculty of Arts, Humanities and Social Sciences represents 40% and Faculty of Science 19% of student population (University of Reading, 2014). The first study investigates the lighting and occupancy patterns in ten single occupancy offices. The second study focuses on lighting and occupancy in classrooms reporting the design vs. actual data from lighting upgrade projects. The classroom study refers to journal paper publication (II). My specific contribution to paper II was in design, data collection, data analysis and writing the article, 85% of the final version, the remaining 15% contribution was from my supervisors, my co-authors, in the form of editing the draft and final manuscripts. The third study looks at corridors again reporting the design vs. actual data from lighting upgrade projects. The corridor study refers to journal paper publication (III). My specific contribution to paper III was in design, data collection, data analysis and writing the article, 85% of the final version, the remaining 15% contribution was from my supervisors, my co-authors, in the form of editing the draft and final manuscripts.

Chapter Five – Prompt study

Chapter five builds on the novel prompt study piloted in another EngD thesis carried out by Dr Tetlow (2014). The prompt study refers to the conference paper publication (IV) where the concept of the prompt was outlined. My specific contribution to paper IV was in designing Study 2, data collection, data analysis, writing and presenting the paper 65% of the final version, the remaining 35% contribution was from Dr Tetlow and my supervisors, my co-authors, in the form of editing the draft and final manuscripts. The prompt study sought to determine if there was a relationship between office lights being left on, or switched off, as a direct consequence of the corridor light state and difference (or lack of) in illuminance levels in the office and corridor spaces.

Chapter Six – Findings and conclusions

Chapter six collectively discusses the results from chapters three, four and five. The findings are discussed in relation to publications and contributions to original knowledge relating these back to the literature. The research is critiqued in relation to the original research problem, aims and objectives to reach conclusions. The main findings from the research are summarised to include the impact of this research to the industry sponsor and the implications for the wider industry. Limitations of the research are discussed alongside recommendations and future work.

1.5.1 Table of applied methods

Chapter	3 Users' Experiences		4 Waste avoidance			5 Prompt
Publication		Paper I		Paper II	Paper III	Paper IV
Focus	Pilot study	Main study	Offices	Classrooms	Corridors	Offices/ Corridors
Questions asked	What can postgraduates and staff working in campus buildings teach us about energy saving devices and controls?	What are the experiences of teaching staff interacting with lighting, controls in offices, classrooms and corridors?	How long and when is the office lit and occupied? Do office patterns differ between buildings?	How long and when is the classroom lit and occupied? How does this compare to the design expectations?	How long and when is the corridor lit and occupied? How does this compare to the design expectations?	Does the corridor light state influence an office user to switch off their office lights on exit or leave them on?
Location	University of Reading Whiteknights campus		Urban, Maths and Humanities buildings			
Date	March 2014	March/April 2015	Pilot: 3 Urban offices Dec 2014-June 2015 & 1 Urban (3rd floor) corridor Dec 2014 – Jan 2015 awaiting further loggers Feb 2015-June 2015: 3 Urban (3rd floor) corridors in total to match offices Continuation: April –Sept 2015 Urban (2nd floor) 6 classrooms, 4 corridors Dec 2015 – June 2016 Humanities (1st floor) 5 offices, 4 classrooms, 4 corridors; Dec 2015 – June 2016 Maths (1st floor) 2 offices, 3 classrooms, 3 corridors			
Participants	6 in total: 4 post graduates, 2 staff members	9 teaching staff in total	10 single occupancy offices	13 centrally bookable classrooms	14 corridor locations	The same 10 single occupancy offices in Ch4
Interaction studied	Individual experiences, views and opinions	Individual experiences, views and opinions	Individual office patterns of lighting and occupancy	Individual classroom patterns of lighting and occupancy	Corridor patterns of lighting and occupancy	Difference between office and corridor illuminance, light state and time of day patterns
EngD Industry relevance	Understanding different views and opinions from a variety of backgrounds	Learn from design mistakes to change future specifications and POE methods	Time of day Waste patterns	CO2e, electrical consumption and yearly hours of use for performance gap analysis		Design criteria Time of day
Data collection methods	Semi-structured one to one interviews		In field studies using HOBO U12-012 Lux data logger & HOBO UX90-005 (or UX90-006) Occupancy/lights on logger			
Analysis / Statistical test	Thematic analysis		Time of day analysis Lighting and occupancy monthly & annual hours of use	Annual hours of use CO2e electrical consumption		Binomial regression using mixed models with random effects Chi Square Regression
Expected outcome	Energy reduction through post occupancy evaluation and designing for habits					

Table 1 Applied Methods for all studies

Chapter 2 Literature Review

2.1 Introduction

The literature review chapter starts with the much wider context of trying to achieve energy efficiency on a large scale. The initial section explores the topics that were considered in the research scope and concludes that post occupancy evaluation and design offer the most feasible long term solutions of reducing carbon emissions and electricity consumption on a large scale such as a campus. This leads to the review narrowing to specifically focus on the aim of this research – to explore the habitual patterns of light switching, to gain insights from end users and their experiences, and to measure lighting use and occupancy in field. The literature review sections address the main purpose of the work in identifying where user behaviour and performance gap analysis can impact energy savings.

2.2 Energy efficiency on a large scale

2.2.1 User behaviour change

Behaviour change offers one of the biggest barriers and yet provides some of the greatest opportunities for mitigating the impacts of climate change (IPCC *et al.*, 2001). In energy use behaviour change often covers a wide range of interventions that focus on altering people's existing patterns of behaviour to choose more sustainable or energy efficient options. The behavioural insights team in central government identified three main options for behaviour change in energy use through discounting the future, social norms and finally defaults (Cabinet Office Behavioural Insights Team, 2011).

Many of the behaviour change ideas applied to sustainability in the built environment have been adapted from social cognition theory based models. Behaviour change studies have routinely focussed the majority of their attention on theoretical models (theory of reasoned action, theory of planned behaviour, trans-theoretical model, social practice theory and value belief norm theory are all common) which will not be explored here as they are *pure* research problems and outside the scope of this applied industry research. Although behaviour change work has value the direct application of theory models to practice in field has problems, as people's habits are unlikely to present themselves in a laboratory experiment. For example, suppose that "habit" accounted for much of the variation in electrical consumption at an office workstation (Tetlow *et al.*, 2013) this result is not only specific to this office or set of offices (other workplaces with other factors intervening might give different results) but it is also far from clear what behavioural interventions would serve to change habits positively, even within this single environment. The solutions sought to an industry sponsored engineering doctorate are based on *practical* outcomes a distinction noted by Booth, Colomb and Williams (2003), there is limited evidence of actioned outcomes of sustained change from these theories (Menezes, 2013; Maleetipwan-Matsson, 2014; Tetlow, 2014). Exploring the use of randomised control trials in energy related behaviour change campaigns Frederiks et al. (2016) identified that pursuing the ideals of a highly artificial testing environment could limit the external validity and relevance of randomised control trials findings. They explicitly acknowledge that minute-by-minute energy related behaviours cannot be captured through traditional metering or direct observation (Frederiks *et al.*, 2016). One of the behaviour models that is most relevant to actionable outcomes and sustainability in the built environment is the Fogg Behavioural Model, this has been adapted and is illustrated in Figure 4.

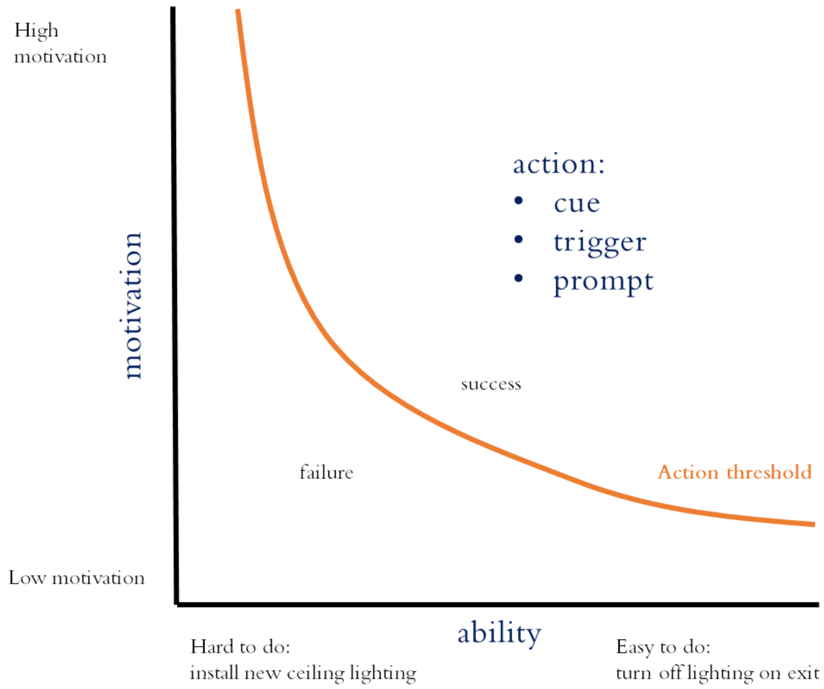


Figure 4 Adapted from Fogg Behaviour Model with lighting examples

Based on the 'tiny habit' philosophy (Fogg, 2012) this model combines three elements of motivation, ability and trigger. These elements and others will be explored in greater detail in the nudge section later, but essentially the occupant must have all three in order to complete the action of turning on the light to the required settings. As we will later explore some light switch designs do not lend themselves to occupants discovering what is possible with the settings. The Fogg model is based on the idea of an activation threshold being reached whereby the action is easy to do, there is low motivation required and crucially this new action has a trigger. The reward for carrying out this new action Fogg describes must be a positive acknowledgement of the new action, a mini celebration (Fogg, 2012). The Fogg model implicitly assumes an element of self-regulation which will be discussed further. Taking a complementary approach to environmental behaviour change Nielsen (2017) argues that four main self-regulation strategies support goal striving in the context of environmental behaviour change: planning, automatization, cognitive change and lastly effortful inhibition. In this review paper automatization is supported by two sub-areas of habitualisation and counteractive control. Habitualisation is described as being an establishment of beneficial habits that become automatic processes to support the goal(s), thus freeing up cognitive resources to do other activities. The mental associations of the frequently performed behaviours which are based on a recurring situational cue are identified and Nielsen (2017) acknowledges that some habits may be seasonal, for example riding a bike in summertime. The same could apply to preconceived ideas relating to summertime behaviours and users lighting patterns. Counteractive control is defined by the author as a disconnect between having the higher order intent to do something (e.g. save energy) and the proximal temptation to not carry this out (e.g. leave the lights on when vacating a space) (Nielsen, 2017). The study concludes by clarifying an important lesson from self-regulation research where people sometimes fail to act or conform to their own standards or goals (Nielsen, 2017).

The need for habits to be repetitive is asserted by Neal et al. (2006), in which the authors conclude that further understanding is required for the mechanisms of habit context, motivation, response, intention and minimal conscious control to be understood and their contribution to behaviour evaluated. A climate change study exploring individuals' perceptions of their environmental activities differentiated one time actions from repetitive "habit-webs", which can form where patterns of habitual behaviour are linked to one another (Neal, Wood and Quinn, 2006; Page, Page and Berman, 2014). The environmental context can trigger routinely repeated habit-webs automatically. A core part of behaviour change philosophy within the built environment is that tiny habits are repeated within the context of the environment's design. The recurring situational cue in this research is the environment the occupier resides within. Behaviour change programmes which target habits and habit networks have the ability to facilitate the energy reduction on a large scale with lasting results without necessarily engaging the occupier's goals or motivations - certain behaviours can be encouraged by making them easier to perform by default without directly influencing goals or motivations (e.g., Thaler & Sunstein, 2008). Increasing environmental motivation and encouraging behaviour change through interactive engagement, via feedback and gamification, has however become a major theme of energy efficiency programmes in its own right. These two themes were explored in greater detail to ascertain if they could provide the energy savings required by the industry sponsor.

2.2.2 Energy consumption feedback

Feedback in energy efficiency relates to users being informed of their energy use. Intervention studies have developed from extensive earlier work examining home energy display information using energy data through feedback (Darby, 2006, Wood & Newborough, 2007, Froehlich et al., 2010). Energy feedback is explored further with an emphasis on energy display interface design. The design components to be included in energy feedback are fundamental to communicating information to users. An outline of the design components used in a recent study of university dormitory residents in California provides a framework that builds on previously defined design components (Jain et al. 2012), these include:

> Historical comparisons, normative comparisons, incentives (financial & non-financial), disaggregation, rewards & penalties.

Examples of each of these would be: historical comparison compared to a week ago, normative comparison to another dorm resident, financial incentive of being paid to take part, non-financial incentive use of a game, disaggregation of data to separate uses such as kitchen small power, small power in room, lighting, heating and cooling, and rewards and penalties would be a real time incentive to repeat behaviours or not repeat certain behaviours. Jain et al. (2012) used a Welch two sample t-test to analyse the data which sought to compare user logins, through web analytics with specific design components. The mean user login data by component revealed statistically significant differences (p values of $< .001$) between the mean number of logins on sites containing historical comparisons and incentives versus sites without those design components: users visited the site with those features almost 3 times more frequently. There were no significant differences between sites with normative comparison and disaggregation components and the control site without such features (Jain, Taylor and Peschiera, 2012). This supports the idea that using both historical comparisons and incentives will improve feedback design and engagement. Incentives for building users to reduce their energy consumption is a topic which is reviewed in further detail. There is contradictory evidence of financial and non-financial incentives producing energy savings from building occupiers. In the Wood and Newborough study (2007) the authors conclude that displaying energy in monetary units might not be helpful due to the small financial savings linked to tiny changes. The authors do however suggest that longer term expenditure displayed on a screen might aid energy conservation (Wood and Newborough, 2007), again an element of historical comparison strengthens this feedback tool.

Recent energy saving intervention studies at a UK University identified that building users had an absence of motivation and intention to save energy and it was recognised that monetary savings are not sufficient to motivate a change in behaviour in this context, suggesting that more innovative approaches are required (Murtagh *et al.*, 2013). These studies emphasise the need to examine incentives and motivations used in energy feedback studies with particular care to context and culture. An example of a non-financial incentive can include a game-based approach as a design feature of energy feedback interfaces. An energy feedback interface is either a computer website where users log in or a screen which displays energy consumption in a communal area. Competitions are also a feature of energy feedback studies at universities. Petersen et al. (2007) incentivised dormitory residents with an ice-cream party for the winning dormitory of an energy competition, only a few of the winning students actually attended the reward event. Energy reduction studies in university environments have not explained the links between competitions and games as the non-financial incentivising factor in intervention design. The context of these interventions is also a determining characteristic in assessing their uptake by building users (Petersen et al. 2007, Podleschny & Grove 2009, Murtagh et al. 2013). Gamification was another area of user behaviour interaction considered as part of this research.

2.2.3 Gamification

Serious games, persuasive and pervasive games and gamification are terms derived from Information and Computer Technologies (ICT) and Human-Computer Interactive (HCI) technologies. ICT and HCI technologies can employ educational theory and have been used to teach, persuade and inform building users of their energy use through feedback. The motivating elements of games combine: fun, play, rules, and goals; they are interactive and adaptive; have outcomes and feedback that involve competition and challenge; and tell a story (Prensky, 2001). This is developed further with serious games as these also include the element of *purpose* (Marsh, 2011). The process involved in a persuasive interface feedback model was demonstrated by Chen et al. (2012) using a virtual aquarium to interact with the user's environment. The prototype virtual aquarium was applied in two graduate student offices in a Taiwanese University to simulate energy conservation behaviour and found the energy conservation ratio percentage rose by 9.93% & 13.57% for each office respectively in comparison with a floating baseline over an 8 week period (Chen *et al.*, 2012). Chen et al. (2012) suggested that users of the energy game interface became fatigued by the displays and this led to a lack of motivation and persuasion to continue energy saving behaviour. Survey questionnaires used in this study highlighted the context of the student's working schedules to meet deadlines, lack of motivation and climate as barriers to reduction in energy saving during the study as the students declined in motivation.

In order to include the participants in their pervasive game Simon et al. (2012) ran user centred design workshops. Their pilot-study 'Climate Race', was a pervasive prototype game addressing office workers. The Climate Race results suggest that energy wastage was reduced during the evaluation period and this method demonstrates the potential of the game-based approach (Simon *et al.*, 2012). However this was a pilot study and the authors acknowledge that the participants were environmentally aware and motivated, another group may not be so personally invested; the authors are intending a follow up study with a control group to validate their findings.

Other applications of ICT energy saving games have involved 'Energy Chickens' a virtual simulation display in a commercial office in Penn State USA (Orland *et al.*, 2014), the Department of Energy and Climate Change (UK Government body now Department for Business, Energy & Industrial Strategy) implemented gamification into their energy engagement with 'CarbonCulture' during 2010 and 2011 (Department of Energy and Climate Change, 2012); and the serious game 'Green My Place' aimed to transform behaviour and energy awareness in five public buildings in five European cities – Helsinki, Leiden, Lisbon, Luleå and Manchester (Cowley et al., 2011).

The relationship between self-regulation, engagement, feedback and reducing energy waste is a research gap that could be a future area of research. The lack of consistency in both the game-based design and results in reducing energy consumption underlines the variances this approach claims to make about being a potentially viable tool for energy engagement. However, the complexity involved in creating, designing and implementing these serious games is significant and the context of the application environment and culture is critical to participant's perceptions of these non-financial incentives to engage in energy saving. A more robust and repeatable research design, method and analysis could allow for a direct comparison of these energy efficiency methods but further research needs to be conducted in the game-based approach if it is to provide the necessary results for energy saving. Non-financial intervention design, such as those using games, also needs to allow for quantifiable data collection. In summary, the game-based approach is perhaps overly complex and a simpler method for engagement and energy feedback design could be adopted through different forms of incentive. Although game-based studies and competitions can be useful in raising awareness they might not actually achieve long-lasting energy reduction especially on a large scale, a point acknowledged by the Carbon Trust (2016).

2.2.4 Design

Design for sustainable behaviour (DfSB) is a relatively new topic that has received attention in the sectors of technology for applications in gamification (section 2.2.1), mobile phone use (Lilley, 2009) and products such as refrigerators (Tang and Bhamra, 2012). The built environment's design of control switches for manual operation and automation has received recent attention for how these support and enhance sustainable behaviour through design. One study that does analyse the different design elements of manual lighting control switches is the work by Dugar and Donn (2011). This study systematically assessed the cognitive skills and perceptual-motor skills required for each of the control's features and found that clear simple actions for operation were key with better textual or iconic representation (Dugar and Donn, 2011). Another manual lighting control researcher who's thesis is dedicated to the subject, supported the findings of Dugar and Donn (2011) by concluding that oversized switch plates that were simple and permitted affordances, affected the individual's optimal use of lighting (Maleetipwan-Matsson, 2014). Finally the The Society of Light and Lighting's (2016) guidance on the subject corroborates the other authors point and builds on this to detail the response time of system, ease of discoverability and feedback are all part of good switch panel design.

Light and lighting is designed for the user to interact and control their surroundings unlike some large scale heating and ventilation systems. In the built environment researchers have developed the concept of design in practical contexts of facilities management on a large scale – small power consumption in commercial office buildings (Menezes, 2013), the impact of occupant behaviour on the energy performance of non-domestic buildings (Tetlow, 2014), assessing the operational performance of educational buildings against design expectations (Burman, 2015), non-visual lighting requirements and choice of glazing (Paradise, 2014) and finally, occupant behaviour relating to lighting controls and user interface designs in commercial buildings (Maleetipwan-Matsson, 2014). Reviewing this selection of theses collectively they have all used mixed methods to integrate empirical studies.

The common themes that emerged as main conclusions and relevant significant findings from the theses are displayed in Figure 5, these were:

1. Benchmarks:

"*An overarching finding was that designers, in their endeavours to meet the ever stringent regulatory targets, specified various measures that had not been subject to thorough risk assessment from operational point of view.*" (Burman, 2015).

"*current practices revealed that designers rely heavily on published benchmarks to account for small power consumption and loads at the design stage*" (Menezes, 2013),

The benchmarks were not robust, defined or verified for small power or other services and Menezes went on to co-author CIBSE TM54 (CIBSE, 2013) as a result of these findings.

2. Procurement:

"*An important finding is that, as these factors are not discrete entities, the capacity of the occupants to influence in-use energy performance is determined during the design and construction process. Essentially the boundaries within which they can act are determined at this stage.*" (Tetlow, 2014)

"*…the effect of the glazing is strongly interconnected with other design parameters of the room, such as the colour of the surfaces. Overall though, the glazing specification had the most significant impact on the light that reaches a person's eye within the Case Study room*" (Paradise, 2014)

3. Attitudes

"*When combining affective- and outcome-related beliefs as attitudes, there was no significant association identified between this variable and the*

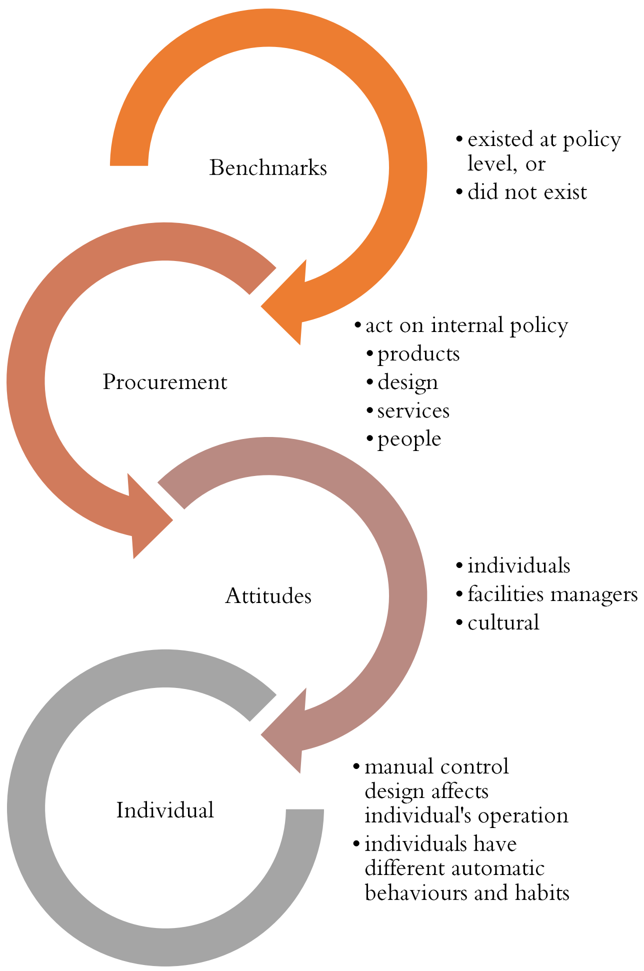


Figure 5 Design topics in sustainable built environments theses

behaviour. Apart from attitudes, no associations of subjective norms and PBC [perceived behavioural control] with the behaviour were identified." (Maleetipwan-Matsson, 2014)

"No correlation was found between either behavioural attitude or subjective norms, and monitored electricity consumption for the zones." (Menezes, 2013)

"Environmental attitudes, social norms, and perceived behavioural control had no relationship to small power workstation consumption. Therefore future occupant engagement campaigns to motivate energy conservation around small power consumption may wish to focus their efforts on altering people's automatic habitual behaviour." (Tetlow, 2014)

4. Individual

"the design [of light switch interfaces, colour and size] can have a strong effect in encouraging occupants' optimal lighting use to achieve energy savings and provide comfort for individuals in such buildings" (Maleetipwan-Matsson, 2014)

2.2.5 Summary

Whilst behaviour change, energy consumption feedback and gamification are potential and interesting areas of future research which may contribute to better understanding and controls over energy consumption, some of their limitations are summarised above. Critically as well, we currently lack sufficiently detailed empirical data on energy use to inform such user behaviour change programmes. The large scale, long term energy and carbon dioxide equivalent saving expectations from industry require a solution that provides both fundamental insights and ones that can be tailored to individual situations. Reviewing the literature surrounding habits and design shows this to be a growing area with an opportunity to explore mixed methods research in higher education lighting controls and occupancy. It is anticipated that by focussing on the end users, their experiences of light and lighting, and collecting hours of use data for lighting and occupancy that a contribution could be made to how lighting and occupancy are designed in higher education.

2.3 Human factors in lighting

2.3.1 Non-visual effects of lighting

The most significant body of research into the non-visual effects of lighting in the workplace has been conducted by researchers at the National Research Council in Canada and Peter Boyce at the Rensselaer Polytechnic Institute (Veitch and Gifford, 1996; Farley, Veitch and (Canada), 2001; Veitch, 2001; Boyce *et al.*, 2006; Veitch *et al.*, 2008; Boyce, 2013, 2016). The psychophysical effects of visual stimuli and non-visual effects of lighting are huge topics that further knowledge into the end user's perception of their lit environment, circadian rhythms (Brainard *et al.*, 2001) and question the quality of the lighting provided. Large differences in lighting quality perceptions were discovered when controlled and uncontrolled environments have been compared against each other for lighting appraisal assessment (Kim and Mansfield, 2016). Interesting findings from a doctoral thesis found that if office workers could control and select their lighting the 'early morning' types chose a lower luminous intensity in the morning (Borisuit, 2013). These findings were supported by the circadian cycle of early to bed-early to rise workers setting the phase of their light timing and intensity to a lower level (Borisuit, 2013). This work concluded that if the workers had chosen a brighter light and earlier time this could have caused an even earlier waking time and bedtimes (Borisuit, 2013). The important point to potentially apply to this research is the time of day analysis for switching behaviour patterns of lighting habits, which is discussed in greater detail later.

2.3.2 Adaptation

In the most simple of terms light adaptation is based on an increase in light and dark adaptation a decrease in light levels. This is most noticeable when are you walking outside on a sunny bright summer's day and then enter a building with a much darker interior. Light adaptation refers to the psychophysical and physiological effects of a person's detection threshold (or increment threshold) adjusting to an illuminated space (Teller and Palmer, 2011). This light adaptation function goes up when in a lit space and the person loses their sensitivity to dim lights (Teller and Palmer, 2011). Both light and dark adaptation are complex fields, and what we know about dark adaptation is that it takes a longer time to achieve a physiological change as it involves decreasing light levels (Teller and Palmer, 2011). Slow changes in both brightness and the colour of light can be indiscernible to the human eye as the signal processing involved in adaptation blocks these changes (Tregenza and Wilson, 2011). The change in contrast of the lit environments will be explored in relation to the contrast between the corridor environment and the office in the prompt study. The cue or trigger will be discussed in relation to the office and the end user being able to use the light switch. The focus of holistic design and adaptation in the prompt study related the threshold change between the different tasks in spaces having fundamentally different illuminance levels or light states (on or off). The application of adaptation to the prompt study will specifically look at the occupant occupying their office for more than 5 minutes with the lights on (light adapted) and then leaving their office space, again for more than 5 minutes. If the corridor light state is off, the relative light levels between the office and corridor will be lower, however if the corridor light state is on, there perhaps could be little contrast between the two spaces.

2.3.3 Design & nudge

The book 'Design of everyday things' by Norman (2013) features many examples of light switches analysed from a user-centred perspective. Norman's work outlines the need for controls to have **feedback** – in the form of a click sound, or a back light; the need for an **affordance** – say to switch the light on with your elbow instead of your finger; the features of the light switch need to be **discoverable** – a lever up and down may naturally indicate dimming; and finally **mapping** will outline where this control is going to be applied. In terms of a room this would in its most simplistic and accessible way be a room layout with the switches embedded into the plan on a wall.

In the context of a higher education classroom the controls for lighting may vary widely across the estate. In a single occupancy office setting the control is going to be fixed and therefore habits and routines are more likely to develop by the office occupant.

Perceptual cues in our built environment are likely to influence the automatic systems that present as human habit. Thaler and Sunstein (2008) link their "nudge" ethos of behaviour change and 'Choice Architecture' to Norman's work on everyday design which also suggests that behaviour can be promoted and habits moulded by the environment around us (Thaler and Sunstein, 2008; Norman, 2013). Nudges have already been used in attractive and playful lighting and have demonstrated significant changes to behaviour by influencing people to take the stairs rather than the elevator (Rogers *et al.*, 2010). This study used twinkly lights to guide and entice building occupants to the stairs rather than taking the elevator despite building occupant's self-reported data suggesting nothing had changed, the findings actually demonstrated they did use the stairs more frequently (Rogers *et al.*, 2010)

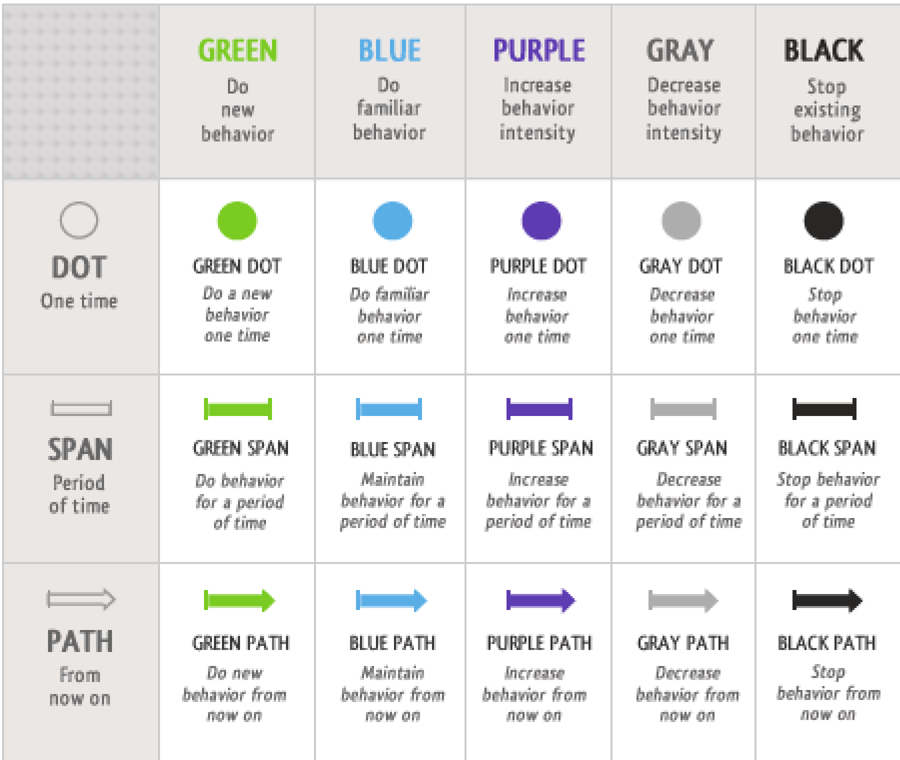


Figure 6 Fogg Behaviour Grid (Fogg, 2012)

The Fogg Behaviour Grid outlines the need for repetition of a habit for it to continue as shown in Figure 6. From the previous Fogg graph in Figure 4, the trigger required to repeat the 'new behaviour', would potentially be the 'cue' from the environment. The trigger Fogg outlines is an add-on to an existing behaviour, for example brushing your teeth the first new behaviour to repeat is flossing one tooth (this would then increase to multiple teeth – from the green dot to the purple path), the trigger here is the act of tooth brushing. In contrast, the choice architecture concept using nudge proposes the design of the environment is the natural cue that leads to the automatic behaviour and habit-web. An area that is most relevant to this research is the act of forgetting to switch the lights off when you exit a room, this leads to wasted lighting energy. For the purposes of the prompt study and looking at long term patterns of light switching behaviours this would be located at the blue path (most likely in an office) or blue span (most likely in a classroom). If we wanted to increase the action of switching off the lights on exit this would move to the right towards the purple path and span areas.

2.3.4 Post completion error

Time based prospective memory is the term used to describe everyday intentions where we plan to remember to do a future action at a particular time, for example when leaving work to remember to stop and pick up groceries for dinner. When our working memory is performing multiple tasks we can be so mentally loaded with these tasks that we forget to complete our desired intentions. An example of prospective memory failure under extra load is a post completion error, I forget to pick up the original document from the photocopier once I have completed my intended action – take a copy - I then forget to pick up the original. Prospective memory has previously been studied for the social effects of shared responsibility for a final future task of remembering to turn off the lights in the laboratory at the end of an experiment. Here researchers Bradimonte and Ferrante found that only 24% of the participants spontaneously switched the lights off (p. 359, Kliegel et al. 2012). Results from a prompt based study investigating differences in switch off found that where a PIR sensor was located occupants manually switched off 13% of the time, in offices where no PIR sensor was present the lights were manually switched off 58% of the time (Tetlow *et al.*, 2014). The automated lighting was actually contributing negatively to make energy wasteful behaviour more likely and the automated lights were left on for longer as they were not commissioned correctly (Tetlow *et al.*, 2014).

In relation to prospective memory, certain future behaviours and actions that occur frequently can become automatic over time. Habitual actions are "automatic" and cued by the environment regardless of cognitive load. Non-habitual actions are more likely to be lost or forgotten if attention is diverted or if a person is cognitively loaded by other concerns regardless of environmental cues. The participants were therefore familiar with their offices and corridor environments. If habitual actions are cued by the environment and its design then it is necessary to consider how we transition from one lit environment to another, as proposed by Tetlow (2014). As a relatively new and bespoke concept this is an area that has not been fully investigated by researchers in field on a large scale. It is therefore in a very early experimental stage and due to the nature of requiring habitual behaviour in field studies are more likely to produce some ground for proof of concept.

2.3.5 Decision Making

The most extensive work on decision making is based on the early work of Tversky and Kahneman (1974). Exploring decision making and judgements in behavioural economics settings, Kahneman, (2011) outlines two systems in operation when we make decisions. System 1 is the automatic, intuitive brain that acts fast, system 2 is the slower more considered part of the brain where we are using more cognitive effort to carefully take time to identify and assess inputs (Kahneman, 2011).

The use of biases and anchoring in decision making will now be explored in relation to lighting and occupancy examples. Bias in the system 1 setting, by say an energy manager, would be influencing their decisions to favour one upgrade as opposed to another based on personal preferences. The way biases work in behaviour economics is that we find it very difficult to differentiate a single snippet of information from the greater more global context based on statistics and facts, as we are presented with only a tiny snap shot in time. An example of this would be a single carbon dioxide saving, rather than looking at what the overall emissions are for an entire estate or country. Anchoring in the system 1 setting in relation to personal preferences for illuminance levels works by placing an anchor in people's minds, say 300 lux, from which the participants then measure their preference. If the anchor is high, people will be balancing the light around that initial high level, if the anchor is low then people will be balancing their preference around the lower range of illuminance levels (Uttley, Fotios and Cheal, 2013). For the purposes of lighting and occupancy in design decision making this could be potentially disastrous to project outcomes. If the automatic processes of system 1, bias and anchoring, are unknowingly used by the designer to make a decision on a) the illuminance outputs (too high) and b) are compounded by the decision on lighting hours of use (too high or too low), this could lead to the design expectations for energy savings not being met in practice. One method that is suggested by Klein (2007) to avoid project failure is the use of a Pre-Mortem technique. This is a method for use in the early stages of project planning where all team members are invited and actively encouraged to speak up about potential pitfalls relating to their design in an open and collaborative way (Klein, 2007). Rather than attempting to control conditions as much as possible, Klein (2009) advocates that we adapt and should expect to adapt in ambiguous situations. He goes on to explain a control-orientated mind set is most appropriate for well-ordered circumstances (Klein, 2009). This is a key part of post occupancy evaluation, which will be explored in the next section. Our buildings need to be adaptable to future uses, and we should be too in how we operate and use them rather that viewing them as a well-ordered machine, there will always be elements of ambiguity in how people behave in buildings.

2.4 Post occupancy evaluation

2.4.1 Practices

Post occupancy evaluation (POE) has evolved in architectural practises since 1960's and having had an extended period (1972-2013) where it was not part of the Royal Institute of British Architects (RIBA) stages of work it was reinstated in the RIBA Plan of Work 2013 (RIBA, 2013), as shown in Figure 7 at stage 7. The "7 In Use" stage involves POE, handover strategy, analysis of project outcomes, project performance assessment and any research and development opportunities (RIBA, 2013)

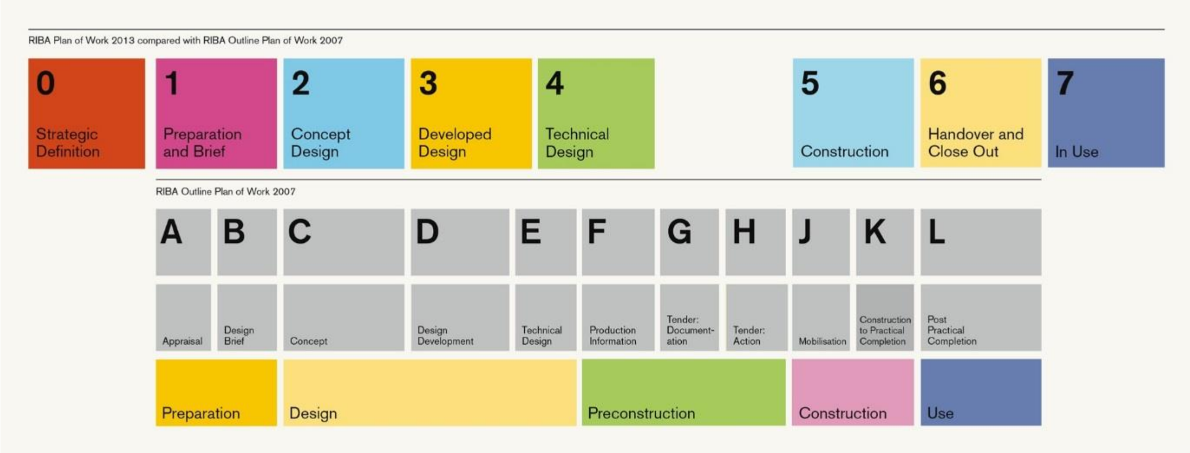


Figure 7 Image displaying changes in RIBA stages of work (Mark, 2013)

This relatively recent re-prioritisation of POE by changing practises with principles has meant that the changes will be seen over a long period of time in future if POE is routinely used. The seminal work of William Bordass and Adrian Leaman, and their co-authors during the period 1995 to 2002 with their suite of studies titled “post-occupancy review of buildings and their engineering” (PROBE) highlight the need for making POE routine and outlines different methods of delivering POE. The final conclusions in study 5 (Bordass, Leaman and Ruyssevelt, 2001) are directly taken from the PROBE findings and mapped against the points from previous theses, in Table 2,

“Factors for success include:

Benchmarks	*a culture of feedback with better benchmarking and constant review against client and design intentions*
Procurement	*and more involvement of the supply side in improving and learning from the performance of buildings in use*
Attitudes	*identifying and managing downside risks*
Individual	*making sure essential features are in place; seeking simplicity, usability, manageability and responsiveness"*

Table 2 PROBE POE factors for success

Higher education as a sector has its own published POE guidance from Higher Education Funding Council England (HEFCE) (AUDE and HEFCE *et al.*, 2006). This guidance outlines the methods that can be adopted by Estates and Facilities departments, the two that will be developed and used in the context of lighting and occupancy are ‘Learning from Experience’ in Chapter 3 and ‘Methods of Energy Assessment and Reporting Method’ in Chapter 4. The POE levels of investigation used will not be ‘indicative’, but ‘investigative’ that leads to deeper diagnostic assessment combining the findings of Chapters 3 & 4. Way and Bordass (2005) outline the principles of 'Soft Landings' in their studies and this is a promising area of future research, however this is outside the scope of this project as the principles were not adopted by the Estates and Facilities Department at the University of Reading. The soft landings approach is perhaps most applicable to landlord and tenant relationships rather than owner occupied spaces. The methods most frequently used by the built environment sector are quantitative analysis from metering, environmental data loggers and building management system data as these involve the minimum of contact with the end users. The Building Use Survey methodology pioneered by Leaman and Bordass (1999) uses 7 point Likert scales to find out comfort levels and other factors from end users which can be conducted remotely. The issue about conducting remote based questionnaire surveys is that response options are limited for the respondent as they are predefined rather than allowing the user to generate their own data more organically. The most infrequently carried out methodology in the higher education built environment sector is semi-structured interviews which are undertaken directly with a sample group from the population. This methodology allows researchers to learn directly from the end users and can provide new insights into the performance gap.

2.4.2 Performance gap

The performance gap is a measure of the difference between design assumptions and actual in field data. The performance gap, originally termed the 'credibility gap' by Bordass & Leaman (2005; Way & Bordass 2005), is well established in the built environment and post occupancy evaluation is a means of addressing this gap by providing designers with actual in-use data (Menezes *et al.*, 2012; Lawrence and Keime, 2016; Min, Morgenstern and Marjanovic-Halburd, 2016). A distinction between the types of performance gap has been proposed dividing into three progressive categories: regulatory performance gap; static performance gap and; dynamic performance gap (Burman, 2015; van Dronkelaar *et al.*, 2016). Respectively these are broadly: the regulatory requirements, for example compliance with Part L2B Building Regulations in the UK; the static performance gap is a snapshot in time at a specific point, for example when the building is first occupied and compared to designer's assumptions or models; the dynamic performance gap assumes a fluid and flexible changing of the space organically throughout time, for example different types of building user or tenants. In terms of case studies within Higher Education, previous performance gap research has found that lighting in 5 higher education case study buildings can vary dramatically compared to regulatory calculations when measurements are taken: 2%, 13%, 14%, 18%, 286% higher than predicted, in absolute terms these are 0.3, 2, 4.1, 4.5, 22.3 kWh/m2 above predicted (Burman, 2015). Imam, Coley, and Walker (2017) recently investigated the internal "mental models" – the psychological representation of a real or imagined system (Craik, 1943)- of 108 thermal modellers and found a wide variability in their approaches to model inputs and ranking input parameters. Their findings include the observation that a quarter of modellers participating were making worse judgements than a random response and even the most experienced modellers, including external consultants, contributed great diversity (including some of the worst performance) to the overall results (Imam, Coley and Walker, 2017). As previously discussed the process of using biases in decision making has been extensively researched by Kahneman (2011). This potentially could be directly applied to these experienced modellers using their automatic biases and anchoring to decide what hours of use and control factors are inputted into the design choices and decisions.

In the commercial sector the CIBSE 'Guidance TM22 Energy assessment and reporting method' is widely used in the UK to assess post occupancy evaluation in four building types: offices, hotels, banks and agencies, and mixed use industrial, but there is no specific guidance for University buildings (CIBSE, 2006). The International Performance Measuring and Verification Protocol (IPMVP) method is adopted predominately in the United States (Borgstein, Lamberts and Hensen, 2016), and in locations where shared savings schemes are agreed, as a way of quantifying the in use consumption of systems and buildings however it is suggested that the cost of measuring and verification should not exceed 10% of the estimated savings and be appropriate for the scale of the project. Other benchmarking tools exist and in the UK the 'Carbon Buzz' project is a collaborative and anonymous database of each sector's actual energy use in relation to initial design predictions (CIBSE, RIBA and BRE, 2017). As a sector the performance gap in university buildings was calculated to be 85% for electricity consumption (kWh/m^2/year) when comparing the predicted energy use against actual energy use in practice through the 'Carbon Buzz' project (Menezes *et al.*, 2011). The performance gap has been explored for lighting in office space where the calculations used 2600 total hours of operation per annum and 11W/m^2 in their initial assumptions, however the final model which most closely matched the actual energy use was 3640 hours per annum and 13 W/m^2 (Menezes *et al.*, 2012). In this study the absolute underestimation of 1040 hours per annum and 2W/m^2 is substantial; this is an additional 40% and 18% respectively relative to the initial model. Corridor space is often neglected in such studies but a City University of Hong Kong building was calculated to have potential to save 69% of corridor lighting electricity when linked to daylight harvesting for a range switch off threshold illuminances between 200-450 lux (Li and Lam, 2003). Li and Lam (2003) noted that the corridor used in this study was illuminated to 450 lux rather than the 100 lux cited as the CIBSE reference level of illumination, hence there was the potential to save even more if the over-illumination of the corridor was satisfactorily addressed (Li and Lam, 2003).

2.4.3 Metering

Despite the UK Part L2B Building Regulations requiring metering and sub-metering for new commercial buildings, there is no requirement for large estate owners to separately meter existing buildings (HM Government, 2010). The theoretical operational and financial constraints associated with metering are outlined in CIBSE literature which aims to assist building managers and owners (CIBSE, 2009). Part of the move towards building level metering was the implementation of the Energy Performance directive under the Energy Act 2011, with most university buildings requiring a Display Energy Certificate (DEC) (European Union, 2010). The seminal "post-occupancy review of buildings and their engineering" or more commonly titled "PROBE" studies discuss metering data being used, but the focus was not on how the metering was installed in the first place and whether or not it was commissioned correctly (Bordass *et al.*, 2001). The only paper that acknowledges some of the significant difficulties with implementing metering and sub-metering in practice is Jones (2012). The financial constraints of installing metering in higher educational institutions on a large scale is acknowledged by So and Richman (2016) where they propose disaggregation of clustered metering data to understand individual building's energy profiles, this is common practice in the absence of large scale metering. In manufacturing processes which have metering facilities that alarm when line faults or production processes reach limits and thresholds, meters have been critiqued and evaluated for informing the selection of metering devices (O'Driscoll and O'Donnell, 2013). A recent study has reviewed 9 static (electronic energy) meters and found that 5 had higher energy readings up to 682% over actual consumption and 2 showed up to 68% over actual consumption (Leferink, Keyer and Melentjev, 2016). There is a systemic lack of robust commissioning, calibration and verification of building energy meters and sub-metering systems, many studies do not acknowledge the lack of meter calibration and CIBSE guidance (CIBSE, 2009) is silent on this topic. Building sub-metering analysis and building simulation modelling is a growing field and the most recent lighting sub-metering study recognised their sub-meters were both complex and expensive (Delgoshaei *et al.*, 2017). CIBSE guidance on methods of metering outline that estimation from hours run provides a good level of building service knowledge without the invasive, expensive and time consuming requirements of direct metering which is the optimal solution (CIBSE Guide F, 2012).

Sub-metering is not always feasible for reasons outside of time and money, the buildings included in this thesis had services on 30 year old distribution boards that were live and unable to have sub-meters safely attached. The office, classroom and corridor lighting was regularly included with small power at the distribution board level so disaggregation was not feasible with sub-metering, this lack of disaggregation is acknowledged by other performance gap researchers (Menezes, 2013). The industry sponsor managed a metering project which ran from 2013 to 2017 to provide 45 new meters to the university's Whiteknights campus buildings. These meters were at a whole building level, rather than sub-metering levels for different services, and exceeded £2m of capital expenditure. There is insufficient literature available that describes the challenges of metering buildings in practice. Meter installations are notoriously difficult to implement in practice as they involve building shutdowns which are related to internal working policies for health and safety. Shutdowns are disruptive to staff and students, therefore most of the engineering work needs to be carried out during weekends or over holiday periods such as Christmas and Easter, costing a considerable amount more in time and money. These access restrictions had the ability to cause metering projects to become severely delayed or never implemented due to the difficulties involved with both buildings and the people who occupy them.

Instead the use of HOBO™ loggers for identifying hours of run time was the most cost effective, unobtrusive, simple solution to determine the lighting and occupancy patterns, these have been used by other lighting and occupancy researchers (Tetlow *et al.*, 2014). Metering data is almost synonymous with feedback as it informs building managers. The most extensive work in energy feedback has been carried out in the residential sector (Darby, 2006) and is now being attempted in the UK commercial sector through the CarbonBuzz platform (Kimpian and Chisholm, 2011).

2.4.4 Metrics

The key metrics considered for post occupancy evaluation performance gap analysis were linked to the requirements for higher education carbon management plan reporting as part of the Carbon Management Plan (Higher Education Funding Council for England, 2010). The carbon dioxide equivalent emissions and kWh were combined with the other metrics from CIBSE Guide F (2012) guidance on using run hours. The run hours considered were:

- Hours of operation
- Hours of lighting
- Hours of occupancy
- Classroom bookings hours

Lighting researchers verifying energy savings have found that measured savings were within 30% of the projected savings estimates (Lee, 2000). It is important to note the distinction between what you measure- a metric, compared to how you measure -a meter or piece of equipment, and these are separated below. These researchers used run hours (metric) and direct kW loggers (meters) to verify the lighting upgrades in an office, industrial plant and hospital building, concluding that measured run hours (metric) can vary significantly with estimates and recommended the use of loggers (meters) for gathering post-retrofit POE data (Lee, 2000). Lighting Guide 5: Lighting for Education (CIBSE, 2011) details use of cylindrical illuminance meters (a meter) however no manufacturer exists to supply these. In the absence of a meter available to purchase the cubic illuminance metric can be used to calculate the cylindrical illuminance metric (The Society of Light and Lighting, 2012) through derivation of formulae. Cubic illuminance is itself derived from taking illuminance measurements at six points each on the face of the defined cube (The Society of Light and Lighting, 2012). This would not be practical for an in field study over a long period of time in offices, classroom and corridor studies and the most widely used are horizontal and vertical illuminance meters for measuring horizontal illuminance E_H and vertical illuminance E_V metrics. For interiors the higher education lighting guidance explains that most people perceive the vertical planes when looking at a space (CIBSE, 2011). A room's complexity of illuminance patterns, time of day, season and other non-visual factors all play a part in how people interact with their lit environment.

2.4.5 Post occupancy evaluation interviews in the built environment

Qualitative methods for understanding sustainability, energy efficiency in the higher education built environment can provide insights that would otherwise be lost in metering or questionnaire data. In

2000, semi structured interviews were carried out at 6 London universities discussing green campus initiatives and difficulties in achieving their aspirations (Dahle and Neumayer, 2001). The sample population of 16 participants was drawn from energy and operations managers and 4 of those were drawn from student eco-champions groups. This study found that long term renewable strategies were dismissed in favour of prioritising quick financial payback projects despite the institutions being in business for long periods (Dahle and Neumayer, 2001). The authors conclude that fundamental change is required in the thinking behind decisions relating to resource efficiency, the institution's ability to change practices and finally call for a change in human behaviour (Dahle and Neumayer, 2001). Cost was also cited as a key finding in glazing size and specification in reviewing the daylighting design of extra-care housing in a mixed methods study using semi-structured interviews and survey data, where 20 people were interviewed which comprised 14 architects, 2 not-for-profit housing providers, 2 commercial developers, and 2 code assessors (March, 2015). Automation in the residential built environment and the role of occupants in the control of energy systems for thermal comfort have been investigated using semi-structured interviews with 14 participants (Karjalainen, 2013). The occupants were the only reliable source of reference to their thermal satisfaction, and both individual and time-dependent differences in how thermal environments are experienced were important (Karjalainen, 2013). The author concludes that individual control should be permitted, factors influencing user's trust in automation relied upon:

"(1) carefully chosen level of automation,
(2) predictability, transparency and feedback,
(3) simplicity and usability, and
(4) suitability for everyday life" (Karjalainen, 2013)

The context of energy behaviours using qualitative methods within a higher education environment have focussed on building designers, facilities managers, procurement staff (Townsend and Barrett, 2013), 'eco-champions' (Hargreaves, 2011), behaviour in the workplace (Greaves, Zibarras and Stride, 2013), and first year undergraduates (Bone and Agombar, 2011). The gap identified was two-fold, the pilot study sample, for the users' experiences study, could be taken from post-graduates and staff which was not present in the literature as a sample population. In addition the pilot study subject could focus on the interaction of these occupants: i) how they control the built environment, ii) what equipment they use within this space, and finally iii) if they could identify energy saving devices from built environment spaces on campus. A full list of all the questions developed for the pilot study are outlined in Appendix A.

2.4.6 Post occupancy evaluation in lighting and occupancy

Kelly (2016), outlined principles of qualitative work, explaining rigour, validity and appropriate applications in lighting recognising that the method has received little attention in lighting practises. This work proposes that qualitative work will provide insights into complex lighting issues and behaviours by addressing unanswered questions, it goes on to illustrate the use of qualitative methods with a post occupancy evaluation case study example (Kelly, 2016). The paper closes by showing how qualitative methods can be integrated with quantitative methods or can stand alone and act as a catalyst for change (Kelly, 2016). Lighting in residential settings has been explored using semi-structured interviews and found that practises had evolved from the ubiquitous single central bulb in the room's ceiling to a greater number smaller lamps creating a better atmosphere and feeling which afforded flexibility and options (Crosbie and Guy, 2008). The same methodology can be applied to academic offices. Semi-structured interviews with 10 heads of faculty at the Universiti Tun Hussein Onn Malaysia were carried out as part of a mixed methods study into space management and occupancy levels (Ibrahim, Yusoff and Bilal, 2012). These researchers focussed primarily on reporting the numerical data however the combined methods led to new understandings of how people use their spaces on campus. The numerical data demonstrated that classrooms were underutilised by 30%, as they were frequently booked but not used (Ibrahim, Yusoff and Bilal, 2012). However it was only during interview the reasons why were explored. Ibrahim et al. (2012) found the classrooms were booked with overlapping schedules and frequently could not accommodate the (larger) numbers of students in the class, this resulted in the university adopting a space charging model (i.e. a school would be charged for space booked) and improving internal communications (Ibrahim, Yusoff and Bilal, 2012). The use of educational technology in state university classrooms was explored in another study undertaking both surveys and in depth interviews with 6 teaching staff, which found that the lighting and location of the projector and light switches was hampering the lecturer's ability to teach (Brill and Galloway, 2007). I will return to the use of classrooms and their lighting later on in the literature review. To conclude the review of using the post occupancy evaluation method of qualitative semi-structured interviews key gaps were identified and these are summarised in Figure 8. A full list of all the questions developed for the main users' experiences study are outlined in Appendix B.

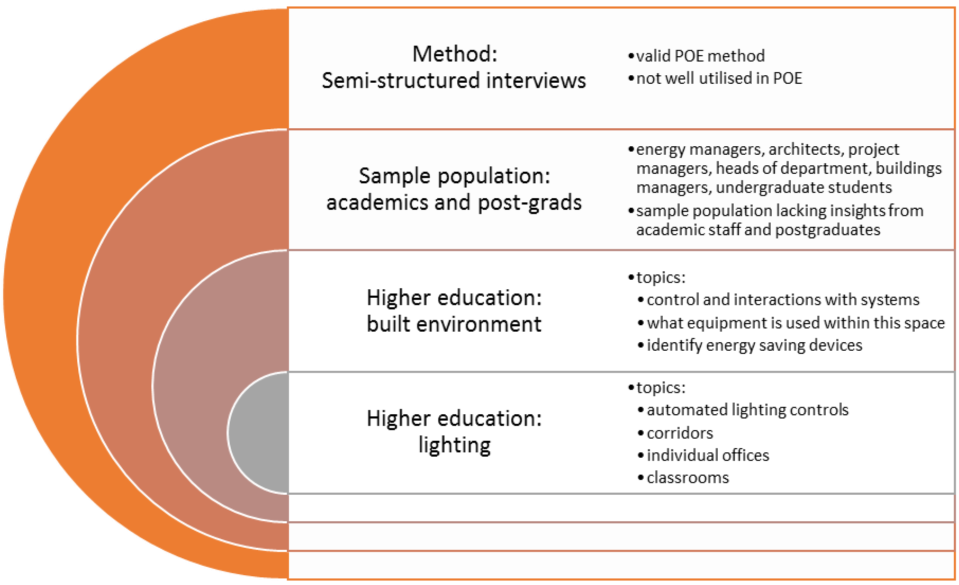


Figure 8 Gaps in qualitative built environment research in higher education

2.5 Lighting and occupancy patterns

The first literature section reviewed energy efficiency on a large scale, human factors in lighting and post occupancy evaluation and found that design was the key area to target. Both of these led to the next topic of lighting and occupancy patterns and how they can be assessed in terms of the performance gap.

2.5.1 Offices

Early light switching behaviours in open plan offices were investigated by Hunt and Boyce (Hunt, 1979; Boyce, 1980) who focussed on shared office spaces and Hunt also examined classroom spaces, as will be examined in the following section. These studies adopted a methodology of inductive exploration where they made specific observations, discerned patterns, which they then tried to broadly generalise to the larger population. This work has been cited many times but few have revisited it and attempted to recreate their methods of observation and empirical research measuring and understanding occupancy patterns, external illumination levels, room illuminance and time of day analysis.

Boyce (1980) employed methods of visual observation and took measurements from other similarly configured rooms to estimate daylight and artificial illuminances (during darkness) in the two open plan offices spaces under observation. Hunt's studies (1979 & 1980) collected data using time-lapse photography every 8 minutes and captured the whole room by focussing the camera onto a convex mirror, from which he took the time of day from a clock on the wall. This assumes the clock was accurate in the first place and, more seriously, the difference between cultural working practices in the 1970's and how the architectural space and technologies have evolved raise the question of whether light switching behaviours changed and if this early analysis is still valid. The important switching factors to consider were identified as daylight availability, occupation patterns, existing conditions and the onset of sunlight as opposed to daylight (Boyce, 1980).

Hunt's work using probit analysis (which is the same as the modern statistical use of logistic regression) found the only statistically significant correlations were with external illuminances although his conclusions focussed on the not so significant statistical findings linking artificial light switching to desktop illuminances (Hunt, 1979). Hunt implicitly assumed a fixed effects model (i.e. there were no dependent effects where the variables were linked) when combining his work in three offices) and two schools. Boyce and Hunt both eloquently describe behaviours and observe their building occupants' actions but do not explicitly point towards habit as a major factor in occupants' behaviour. Boyce found that manual switching occurred most frequently the working day to take advantage of daylight, where such manual switches have been defined by other researchers as 'intermediate switching events', those between initial entry and final exit (Lindelöf and Morel, 2006). This is in contrast to Hunt who found that the switch on and switch off light levels at the beginning of occupation and upon exit were the most important factors in the observed switching behaviours.

These intermediate switching probabilities were researched by Lindelöf & Morel (2006) with the aim of assessing the automatic lighting model based on the "Lightswitch-2000" algorithm (Reinhart, 2004) for defining different users into two types: dynamic and static users.

'*An underlying assumption behind this algorithm is that users use the manual controls at their disposal in a conscious and consistent way, which allows us to predictively model their behaviour*' (Lindelöf and Morel, 2006).

The computer models and algorithms make a priori assumptions about user types which are unlikely to capture important individual aspects of behaviour and could therefore be misleading. Unsurprisingly, the conclusions of Lindelöf & Morel's (2006) research emphasises the individual patterns of behaviour for each of the single and double occupancy offices differ remarkably.

Other researchers have gathered manual office light switching data for probability analysis but have so far left out the time of day analysis that made Hunt's research so accessible and understandable (Lindelöf and Morel, 2006; Fabi *et al.*, 2014). The most recent work in this area (Love, 1998; Reinhart, 2004; Fabi *et al.*, 2014) has built on the current application of Hunt's (1979, 1980) probability curves, analysed using probit analysis to predict lux level switching thresholds at different times of day. Fabi et al. (2014) found considerably lower probabilities for light switch on at similar lux levels to Hunt (1979). This is perhaps not surprising given that users in 2014 worked with backlit laptops and technology screens to a much greater extent than was possible in 1979. Fabi et al. also discussed the stimulus to switch on lights being greater than the stimulus to switch off lights, the authors conclude this is related to the stimulus to switch on when there is poor visual comfort (Fabi *et al.*, 2014).

2.5.2 Classrooms

Hunt's study in 1979 collected data from 2 classrooms over a six month period that covered either January - June or July – December and importantly included occupancy information about these spaces.

"*It was observed that the lights were rarely on when the rooms were empty; such occurrences accounted for less than 3 % of the total use.*" (Hunt, 1979).

Altering the time delay from 20 minutes to 5 minutes for automated light switching in classrooms has been found to only reduce electricity consumption by 6% (Haq *et al.*, 2014). The University of Reading occupancy patterns and the specification for lighting in classrooms differ substantially from these observed in these studies. A centrally bookable classroom in a University where up to seven different lecturers teach in a single classroom over different periods of the day will be occupied and used in different manner to a small to medium school classroom environment with relatively few teachers, as in Hunt's studies (1979, 1980). Automated lighting control is rarely used in classroom spaces at the University of Reading as control is maximised for the lecturers to tailor their environment to suit their teaching activities and student requirements. Consequently, the "ownership" of the classroom space may have a large effect on the overall electricity consumption but this is challenging to quantify in field studies.

Lighting Guide 5: Lighting for Education specifically explains the need for controls to be easy to use (CIBSE, 2011). The guide further explains the space and controls need to afford flexibility for the occupants to be able to control lighting for a variety of tasks such as showing video, under examination conditions, group work, whiteboard work and projection screens avoiding glare in classrooms (CIBSE, 2011). The British Standard recommendation for task illumination in a classroom is a controllable 300 lux and up to 500 lux provided if the space is regularly used for examinations (British Standards, 2011). This is substantially higher than when Hunt carried out his classroom studies which had a design illuminance of 150 lux (Hunt, 1979). Within University classrooms lighting researchers have found that creating more dimly lit spaces promotes students perceived freedom which in turn promotes their creativity (Steidle and Werth, 2013). The intention of creating a lower illumination level has been proposed to have social behaviour benefits and reduce restlessness for a study a 110 pupils and 11 teachers in Hamburg (Wessolowski *et al.*, 2014). This is in direct contrast to a study conducted in a London school with 56 pupils that implied higher light levels increased students cognitive abilities, however no significant statistical findings were reported by the lighting manufacturer who conducted this research (Goven *et al.*, 2010).

2.5.3 Corridors

Corridors represent forgotten spaces for large corporate real estate planning and energy management. Lighting in corridors is designed to enable people to navigate safely from the entrance to a specific room or space. However the corridor space is also used for social interactions and spontaneous conversations particularly in the context of a University. The total built floor area of the University of Reading, in 41 main buildings on the Whiteknights campus, which is used as communal corridors, lobbies and stairwells amounts to approximately 20% of space and totals 30,184 m^2. A considerable amount of energy is used for lighting these un-owned circulation spaces but very little is known about how, when and why they are lit. Ageing campus buildings also pose difficulties in retrofitting energy efficient technologies and this research investigates light switching behaviours and lux levels in the higher educational environment. Across the entire academic real estate portfolio corridor and circulation space represents the highest proportion of built space at 29%, it is labelled balance space in

Figure 9 which is extracted from the report titled Real Estate Strategy (University of Reading, 2014).

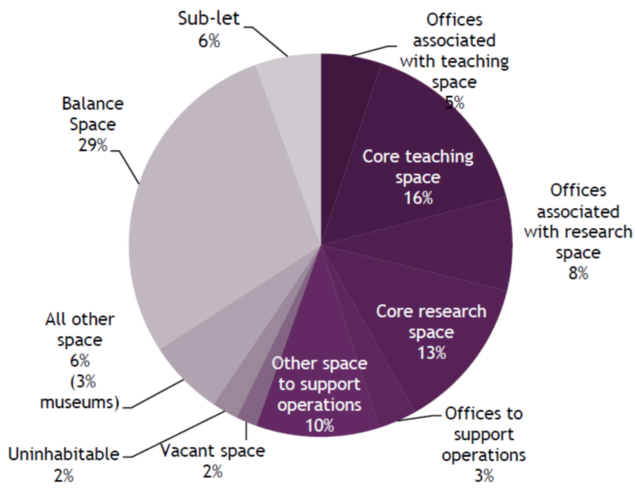


Figure 9 Real estate academic space by space types from University of Reading Estate Strategy 2014 (Appendix A1.2, Figure 3)

Circulation spaces such as corridor areas have previously been explored for lighting control automation from an engineering perspective (Li and Lam, 2003) and for spatial analysis of interactions between people in corridors from an architectural assessment (Sailer and McCulloh, 2012). Behavioural studies investigating their potential for energy saving have been limited to date and this represents an area that could provide effective savings. Previous EngD research investigated the use of contrasting lighting prompts in corridor spaces at the University of Reading this pilot study conducted in June 2014 found encouraging results (Tetlow, 2014). The over-illumination of corridor spaces in an educational context has been recognised by CIBSE and specifically refers to the contrast between corridor and classroom as a potential area of lighting electricity waste (CIBSE, 2011).

Some corridor areas of the campus make use of automated systems with inaccessible controls which leave lights on in corridors and circulation spaces when there is nobody present. As an example, Facilities Managers suspected a recent corridor lighting upgrade was not working as intended as the corridor lights were lit despite nobody being present. Field work found a timer switch (in a locked cupboard) linking alternate luminaires in corridor lighting on three separate floors, the remaining alternate luminaires were linked to ultrasonic detectors. Only the ultrasonic sensors are visible, the timer is locked away so our first assumption was that the system was faulty, this misdiagnosis required a deeper understanding of corridor lighting, its design and how people interact with their environment.

2.6 Summary

Firstly, human factors in lighting were discussed and then broad ideas surrounding the application of psychology and cognition to building energy use and performance were presented. The literature revealed that both adaptation and nudges could potentially be used in the lit environment to formulate the concept that forgetting to turn the lights off could be linked to a lack of contrast between the office and corridor spaces. The use of automatic behaviours, bias and anchoring in decision making was then outlined briefly. This could potentially offer interesting insights into how automatic user behaviour and automatic thought processes of designers together drive energy consumption and energy performance of buildings. The literature review then focussed on the practice of post occupancy evaluation and how the performance gap is defined. For the purposes of this research no regulatory performance gap was measured, it is more likely to fall into the category dynamic performance gap measurement as not all areas had upgrades carried out. The difficulties of metering in practice have been illustrated and the metrics of counting the hours of lighting use and hours of occupancy were deemed suitable to the constraints of the industry sponsor and aligned with industry guidance. The use of post occupancy evaluation- learning from experience- through in depth semi structured interviews with end users was found to be a novel gap. Interviews using verbatim quotes in the form of participants own words could provide good insights into energy consumption and patterns of behaviour. Finally the three main task areas of offices, classrooms and corridors were discussed in relation to lighting and occupancy. Offices and patterns of behaviour in lighting have been comprehensively researched however time of day switching patterns and multiple linear regression of other factors might provide useful insights in these areas. Both classrooms and corridors offer an opportunity to explore the dynamic performance gap for retrofits of lighting by providing in field data. Collectively the factors of: designers' assumptions, decision making, time of day, switching patterns, performance gap analysis and interviews with end users could all provide new areas of understanding in the field of lighting energy efficiency in higher education.

Chapter 3 Users' experiences

3.1 Introduction

The user experiences chapter is comprised of three sections. Traditionally, post occupancy evaluation has subscribed to the use of quantitative data however other methods are equally valid. As identified and explained in Chapter 2 Literature Review, the gap in literature was two-fold, the sample could be taken from post-graduates and staff which was not present in the literature as a sample population. In addition the subject could focus on the interaction of these occupants: i) how they control the built environment, ii) what equipment they use within this space, and finally iii) if they could identify energy saving devices from built environment spaces on campus. Empirical post occupancy evaluation was applied by capturing end user experiences using semi-structured interviews, as illustrated in Figure 10.

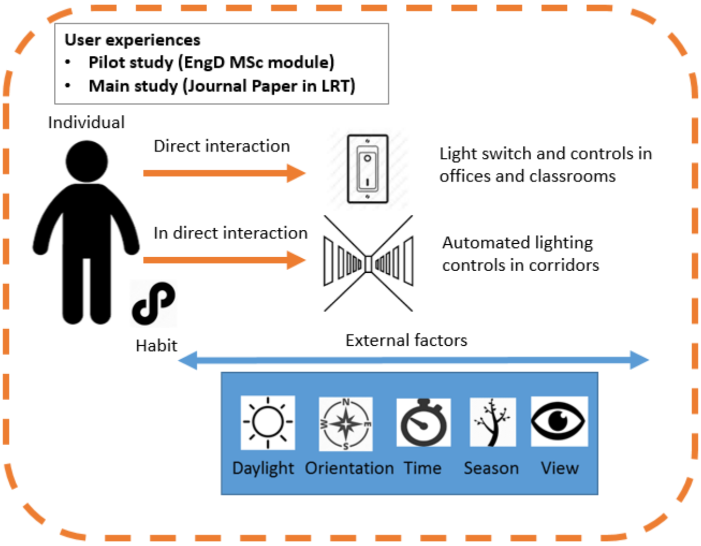


Figure 10 User experiences outline

The first section reviews a pilot study that was carried out in 2014 in which six interviews were carried out with four postgraduates and two staff members. Questions were openly explored relating to external factors of: (1) energy saving devices; (2) orientation of building; (3) tuition fees and energy saving; (4) green and sustainability notices and posters; (5) social and individual aspects of controlling the indoor environment.

The second section was the follow up study and compromises the main body of research carried out between 2014 and 2016. Questions were openly explored relating to more specific external factors, Figure 10, (1) automation in corridor areas; (2) corridor dimming, sensitivity and timing; (3) orientation of building; (4) office daylight, blinds and artificial lighting; (5) office lighting habits and patterns of behaviour; (6) seasons/weather; (7) classroom lighting controls – examples of excellent and poor designs; (8) views and blind use.

The third section proposes that industry could use POE interviews and include this method in lighting guidance. The findings were summarised and outputs presented in seminars and via a workshop to the EngD sponsor and end users. Following this dissemination to the sponsor changes to lighting specifications and POE methods were considered for application in Estates & Facilities projects. Details of future research topics using qualitative methods and selecting people with disabilities to inform inclusive design are explained with barriers to inclusive design. The chapter is concluded by identifying a final future topic through re-examination of the existing interview data for users' experiences of heating controls.

3.2 Pilot study

3.2.1 Background

The purpose of this qualitative interview study was to explore the interactions between postgraduate students and staff and building energy use on campus. Specifically focussing on how occupants control the built environment and equipment within this space and finding out if they can identify energy saving devices. The University of Reading was committed to reducing carbon emissions by 35% from a 2008 baseline by 2015/2016, this is to be achieved through reducing energy waste and introducing energy saving technology on campus (Fernbank, 2013). The context of energy behaviours within a postgraduate environment has received very little attention as qualitative studies have centred on building designers, facilities managers, procurement staff (Townsend and Barrett, 2013), 'eco-champions' (Hargreaves, 2011), behaviour in the workplace (Greaves, Zibarras and Stride, 2013), and first year undergraduates (Bone and Agombar, 2011).

Research Question

What can the end-users of campus buildings teach us about energy saving devices and controls?

Ethics

The questions asked at interview can be found alongside the ethical approval forms at Appendix A. Ethics approval for this study was obtained from the Department of Psychology Ethics Committee.

3.2.2 Method of pilot study

Further examination of this topic was required to develop a richer understanding of building user's motivations and experiences in campus buildings. This qualitative study was designed to include six participants recruited from the Psychology Department's postgraduate students or staff. Each participant gave informed consent and volunteered to take part. Semi-structured, one to one, interviews lasting between 6-19 minutes were audio-taped and transcribed verbatim. A focus group was deemed inappropriate as participants may be embarrassed about admitting energy wastage, commenting on building managers or the University's built environment in a group setting. Topic guide questions included asking participants about their familiarity with energy saving devices, e.g. automated lights, automated computer shutdown, radiator thermostats; and controls in campus buildings and how they interacted with these controls and equipment, e.g. heating, windows, air-conditioning, lighting and computers. Secondary questions surrounded the social aspects of control in shared space, campus energy use being reported in terms of student fees, employability and home vs. work energy behaviours. Importantly however these questions (due to the semi-structured nature of the interviews) were left open and questions were allowed to develop to capture issues outside of the guide.

Transcribed interview data was coded line by line to develop concepts that can link participant's details and information through content analysis. The process of reading and coding was iterative which subsequently led to themes emerging through thematic analysis. Thematic analysis was used as this method does not assume any theories and leaves the data open to dissemination by the researcher. This develops a richer understanding of what participants were communicating in relation to the topic questions. The similarities and differences between themes in interviews was analysed and interpreted.

Using thematic analysis the researcher explores the data with few preconceptions about matching the data into already established theory. It is a good halfway point between quantitative and qualitative studies and can be used as a general qualitative analysis method (Howitt, 2010). Grounded theory was deemed inappropriate at this pilot study stage as we were not trying to create theories or concepts, simply trying to inform a future research strategy.

Following the first short interview I realised my topic questions needed to include examples of energy saving devices to assist my participants with comprehending the areas I was investigating, i.e. heating controls, lighting and window operation. Without these examples some participants found it difficult to conceptualise the controls as being part of energy use in campus buildings. This undoubtedly steered and influenced the conversations towards these topics but participants were able to share in depth experiences of how they interacted with the controls and equipment providing valuable insights. Often instead of using the topic guide I would let the interview flow more naturally probing for specific examples raised by the interviewee. Committing to memory my areas of questioning made the interview flow more succinctly.

My background in physics, surveying and property meant that my biased was focussed on how people used the controls in campus buildings and whether these were functioning as intended. I do not have a psychology background but recognised that semantics expressed by some participants were from a psychology background. In eliciting responses from participants I tried to refrain from using any building jargon and instead used the participant's language to further conversations. Not being based in the Psychology Department and not being registered on the MSc, I felt I was removed from the participant selection which involved interviewees responding to a group email for voluntary recruitment. The diversity of the participants ranged from a part-time MSc student, full-time PhD students and staff members.

I personally transcribed the 14,000 words of the interview recordings for the pilot study which took 2 weeks of full time work. The audio recordings were then listened to several times to check transcriptions. Transcriptions were printed and read through repeatedly to develop an in depth understanding of the data. Line by line the interviews were coded with topics and notes made picking out similar data which represented the meaning conveyed, e.g. visual prompts, notices, signs and emails detailing interviewee's observation and awareness of energy control or automation. Codes were adjusted and improved as the analysis progressed through an iterative review process to collate similar points and contrast differing positions to draw these into overall categories an illustration of this method is shown in Figure 11Figure 11 adapted from (Saldana, 2016) . Thematic analysis drew together these codes into higher-level and more abstract codes to produce themes (Bryman, 2004). The distinct themes emerging from the data comprise the findings of the pilot study and will be explained in further detail with verbatim quotes from the participants.

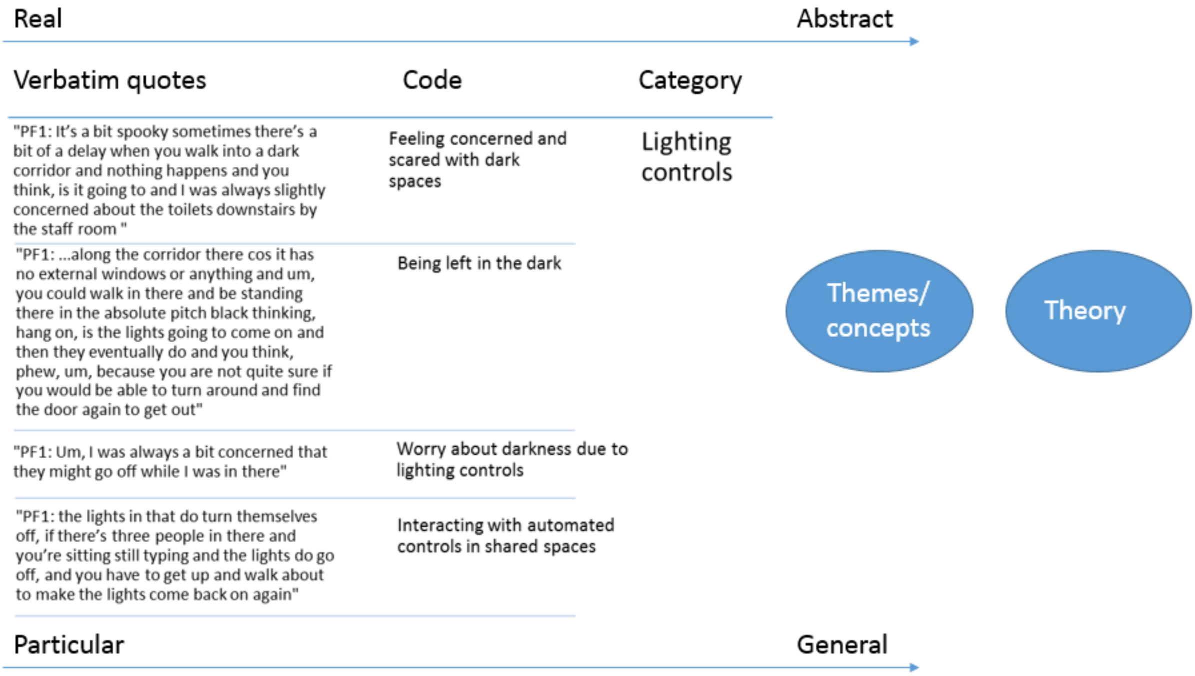


Figure 11 Coding process for thematic analysis of qualitative data

3.2.3 Findings of pilot study

The following categories were found during the initial analysis of the qualitative data: time periods, time of day and movement; proximity to and perceived ownership of building controls; awareness and observation of prompts and energy saving technology; social interactions with building controls and equipment; cultural environment; home, background and parental influence; identity, belonging and ownership within the university; automated and manual lighting control observations; inter-relationship between temperature and ventilation controls; cost of energy when conducting research; links between energy consumption and student fees.

The four themes that emerged from the data were:

A. Home energy habits
B. Social and individual control
C. Lighting controls
D. Responsibility and identity

The findings are outlined by each theme and evidenced with quotes to provide examples. Theories and summaries of each theme are given to demonstrate the application of this method to the built environment in energy efficiency projects.

A. Home energy habits and attitudes

The theme of home energy habits was an unexpected finding from this pilot study. Four of the participants referred to their home environment or country as a reference point for their habitual behaviour regarding energy saving or wasteful practices.

PF1 it's always good to engage the kids in it [energy saving], and, when you show them that if they turn the skybox off, look what a difference it makes

One participant explained that she was teaching her children to be energy conscious when at home. This participant describes transferring her home energy saving habits to her work place.

INT: it's interesting that you say that, do you think your home energy use and work energy use are similar in your behaviour and approach to it?

PF1: I think so, yes, I would always turn lights out, computers off at home and I would always do the, same here. Um... Even I suppose, at home I try not to you know re-boil the kettle or put too much water in or things like that, and I do tend, to do the same here

This participant's home of Greece was used as his reference point for his energy attitudes.

MM2: no, oh a, another thing that I should probably mention is that I am Greek err, and in Greece at least they don't push energy saving as much as they do here, so it's not very common, to see it, errm, a lot okay, it's not very ubiquitous, here you see more of it, but I haven't really been paying attention it's just one of those subjects that, erm..

INT: do you feel that that country has influenced your own perceptions of energy use

MM2: Oh absolutely, yeah, definitely, there's way too many problems there without energy saving being an extra one of them so

A staff member expressed self-awareness and acknowledgement of leaving monitors on and electrical items on standby.

SF4: yeah, I don't turn off the tv on standby at home, eer, I do things that really annoy my husband like leave the microwave door open, so that the light on the microwave is on, which winds him up quite a it, I know it almost, I know at some level I'm doing it, it's not, completely forgetful and I don't particularly you now I don't know why I don't switch my monitors off I just can't bring myself to press another three buttons, yeah my life is full, three buttons, I know that it's not like I forget.

Another postgraduate explained that her father highlighted energy consumption at home.

PF2: I remember by father was, ooooh it's consuming energy

B. Social and individual control

The theme of social and individual control was an expected finding of this study. The interesting finding was the social aspect in a shared space – the person nearest to the control can 'acquire ownership' purely by proximity. Examples of this were given for waving at the automated lights in IT computer workshop rooms, here the person nearest the sensor would stand up and wave at the sensor. One participant explained discussing lights going on in a classroom when it gets dark later in the day and other participants gave examples of asking others to open windows or alter heating in shared spaces. For the participants that had access to individual spaces they articulated frustration at the speed of feedback of the heating system. Some examples of the verbatim quotes relating to the social and individual controls are presented below.

PF1: **the lights in that [shared office] do turn themselves off, if there's three people in there and you're sitting still typing and the lights do go off, and you have to get up and walk about to make the lights come back on again**

PF1: **Um, you can control, individual radiators, I mean like in rooms like this [turns and gestures to radiator],**

PF1: **Although this one seems to be either blaring or, off, there doesn't seem to be a middle ground so I suppose proper maintenance and things like that would be helpful, um, and quite often the heating is broken so there isn't, err, any, which isn't very nice when it's freezing, um. But a bigger issue in like, a shared office is it just gets too hot with all of the computing equipment they don't have um proper air conditioning, or anything in there and sometimes they will put in a portable one in the summer when it's really hideous but it's not very effective, I don't know how you could, save energy under those circumstances apart from by having a, proper integral, air conditioning system in the entire building, but that's not going to happen.**

PF2: **they [radiator controls] are very easy, but they are very slow to heat up, so, eh, and I don't know if the control is really working properly because sometimes it says its 22 degrees and you say, I'm freezing (laughing) how can it be possible? But err, so we tend to put it to very very high till it heats up and then we, err, yeah, we put it in the normal temperature**

MF3: **I think we have had that a few times when as the day's gone on the lecture's gone on towards getting towards four o'clock, five o'clock its getting dark and darker. You can generally hear mutterings from the back of the room, buttons start being pressed, and something happens eventually, but as I say it usually takes more than one person to sort it out [lights being put on in a classroom].**

PSM1: **[shared space] I can open windows, and I can probably turn the radiators off although there is a strong social norm against that.**

PSM1: cold people moan that I turn the radiators off, and I might have to turn them back on again,

INT: so, are you the main person controlling the heaters?

PSM1: I'd like to think so.

The surprising finding from participants PSM1 and SF4 was that they both expressed feelings of slight embarrassment at their behaviour towards individual control. Participant PSM1, was aware of his ownership of other people's comfort being the 'acquired owner' of both the heating and windows. Participant SF4, clearly articulated her own energy waste habits around individual controls and frustration with the systems and management decisions.

SF4: I'm terrible, I leave the radiators on and open the window, I know I do that, and then it takes me ages to realise why I'm really hot and then I finally will turn it down the heating. I think, oh, to be fair, it's really good in my office, it's really controllable in my office which I like, cos, I know the other corridors have a, they can't control their heating very well at all so that's good, umm. It bugs me that the university decides at what times of year the heating comes on and off and they are not sharing the same office as me because there are times it's freezing and times you wonder why it's on.

Opposing views were put forward by participants that did not feel able to control their indoor environment, or who asserted they were not influenced by other people's energy behaviours.

MF3: no, I mean it's the same with the heating, I wouldn't know how to adjust the heating, the yellow radiators are quite off putting (chuckles) its sort of like, almost like a repellent

MF3: I have never tried to open a window, I have to say I would be slightly discouraged, I would feel it was, you know, a bit like getting up the courage to open or close a window on a bus, you know, you just hope that you know what you are doing, but not quite the same.

INT: okay, and do you feel influenced by other people's behaviours towards energy saving and energy use.

MM2: no (chuckles) I've got nothing to say to that

C. Lighting controls

Lighting controls were an easy example to give participants to start the interview as this often elicited more examples and experiences of controlling their indoor environment. The sole expert in the built environment PSM1 expressed frustration with other people's ability to take responsibility and switch off.

PSM1: if people knew how to turn off lights, then [the University] wouldn't need timers and they would be optimally controlled because people would turn on a light when they need it and turn it off when they don't need it. This would also avoid some of the concerns that have been raised in the psychology building, err, where there is, anxiety studies being conducted, erm and people don't like, who might have, suffer from anxiety related illnesses, might not like walking out into a dark corridor, or have the lighting flash on immediately

MF3: I think in the past we have tried to adjust the lighting in one of the big rooms downstairs [Psychology Building], I forget it's, G, G79 or something, and it took about five of us to work out how to do it, because you need to press one button and then another and it's not actually labelled very clearly, it wasn't straight forward at all

Participant PSM1 suggests that a 'well-trained' finger is required to operate the lighting switches. In contrast another participant, MF3, who struggled, with assistance, to use the complex lighting switches in classrooms rooms. It is implied that training is required to operate these switches however it is highly probably that people are already familiar with simple lighting controls prior joining the University. Having recognised that the Psychology Building is not appropriate for automated lighting given the research studies into anxiety, participant PSM1 suggests that if people were better behaved in turning switches off then the University would not have to resort to automation.

Movement, stillness and darkness were all moments when participants expressed feelings of being afraid or being left in the dark.

MM2: the fact that the light goes off if you don't move around (laughs) through direct experience, rather than me actively looking

PF2: that's not very cool actually because you are there you are working at your PC so you are not really moving and they go [gestures, opening fingers from palms], yeah, the light goes off and you must start waving or doing stuff, and that's not very nice, I would change that one. They, go off if they don't see any movements

The automated system seemed to be disruptive and intrusive in participant's workflows in both classrooms and offices. Almost all participants mentioned the speed of the reaction time for automated lights coming on when they moved into a space or automated lights switching off when they were in shared corridor space and even in toilet facilities.

PF2: it's ok but it's just that it's very very dark and, they keep like, a couple of seconds before starting and you have to be in the dark for a second, its ok. I mean you can manage that.

SF4: I am pretty good about turning my lights off in my office, I don't like the corridors being dark, and it's not cos I'm scared or I think I am going to have an accident it's just I like as a human being, I like light places, more than dark places. And I do feel like I when, cos I do tend to work very late, and I leave at 9 o'clock, half past nine at night, and you are leaving a really dark building especially at this end of campus. I really dislike that and I know there are the lamps but, you know it's not sort of particularly, yeah it doesn't you know, you kind of come down these corridors and there's lights flickering on and flicking off, it just feels like it's sort of 'The Shining' if feels like that. Umm, (chuckles) it's not good is it?

PF1: It's a bit spooky sometimes there's a bit of a delay when you walk into a dark corridor and nothing happens and you think, is it going to and I was always slightly concerned about the toilets downstairs by the staff room…along the corridor there cos it has no external windows or anything and um, you could walk in there [toilets] and be standing there in the absolute pitch black thinking, hang on, is the lights going to come on and then they eventually do and you think, phew, um, because you are not quite sure if you would be able to turn around and find the door again to get out. I was always a bit concerned that they might go off while I was in there [toilets].

Participant's unease and concerns about being left in the dark were very apparent. Their vibrant descriptions of 'spooky', 'The Shining' (psychological horror film by Stanley Kubrick), 'absolute pitch black', depict a rather eerie and unsettling environment. However, in distinct contrast one of the participant's reported to be unaffected by entering the 'very very dark' corridor.

The suitability of the automated lighting requires careful consideration as it can foster feelings of unease if building users are left in the dark unexpectedly. The automated lights could be considered a distraction creating frustrations amongst some occupants. The experiences these participants recalled were all within the Psychology building with examples of rooms where they had faced being left in the dark unexpectedly.

D. Responsibility and identity

The final topic that emerged from the data was responsibility and identity with green behaviours and energy saving practices.

MM2: I do think that we are systematically destroying the planet, there is too many of us, and we are wasting energy faster than locusts would waste a field (chuckles), so, I do think in the long run we are going to have problems, I am not an expert on the subject but it just seems that intuitively it makes sense for that to happen. I try not to waste too much energy a) because it obviously has a direct impact on the electric bill, but

at the same time I haven't implemented any measures to you know decrease the amount of energy usage, through let's say intelligent design or anything like that I just tend to be a bit more careful but no, other energy saving technology.

PF1: I am essentially a green person, I like to be green I have my energy monitor plugged in at home, I know what we are using.

PSM1: In my office space, I have light switches, which get used, so we are good at turning the lights off, we are good at turning PCs off. We use the green impact award scheme to motivate people and that provides social incentives, it creates a social norm.

SF4: I don't like turning my monitors off, it's weird, I don't know why. I turn my, I turn my computer off but I never turn my monitors off it's some kind of timesaving device [activity] I am sure when I come in, so I don't do that.

The honesty of participants revealed interesting views. Despite participant MM2 knowing the underlying reasons for energy saving to mitigate the impacts of anthropogenic climate change he did not act on this. Participant SF4 was honest explaining that she was frustrated at having to switch off individual electrical items and therefore left them on to save time when she used her office the next day. Other participants identified as being energy conscious, PF1 was self-labelled as a 'green person' and took actions in her own home and at work as previously outlined in the previous topics. The shared responsibility of PSM1 expressed how their office created a social identity of being part of a wider social impact programme for promoting green behaviours.

3.2.4 Evaluation of pilot study

Qualitative studies assess the rigour and validity of this data collection method using four criteria for evaluation: credibility, transferability, dependability and confirmability (Guba & Lincoln 1985 & 1994, cited by Bryman, 2004). Given my lack of experience with psychology and qualitative research methods, I acknowledge that my interpretation of the data could be biased towards building operation and management and could lack the nuances and subtleties of understanding human behaviour. Qualitative data analysis is open-ended (Bryman, 2004) and can be repeated to develop different layers of rich information, practicing this process with other themes was deemed appropriate before a main study was designed. The data presented above concentrated on the lighting controls topic to provide detail for discussion. To develop the pilot study findings further the interview transcriptions were re-analysed for the thesis to explore the other topics for broader insights.

The data collected followed the prescribed methods outlined which would be auditable given the transparency of the process described. The responses of participants were discussed in a group setting with some participants to provide feedback. To robustly check the validity and rigour of the data collected I could have summarised findings and checked these with all participants, this is a limitation to the pilot study but respondent validation could be part of further analysis. MSc, PhD and staff participants all provided in depth information regarding their interactions with lighting controls which triangulates well given their differing backgrounds. Investigating this research question through qualitative methods broadened my understanding of how people use energy controls. The transferability of these findings to the EngD sponsor was made clear in review meetings. The diversity and detailed experiences participants described has provided greater clarity and understanding of the complexities involved in their relationships between person and building.

In conclusion the pilot study set out to test and learn about qualitative methods in the built environment and to discover end users views and experiences. This study identified four topics that were analysed and these created the platform for the main study concentrating on lighting controls and individual control. The pilot study was intentionally without reference to previous qualitative studies in the built environment to allow a truly open and inductive approach, which is a limitation of the pilot study. A dedicated future study regarding the topic of 'acquired proximity to indoor environment controls' would be worthwhile and interesting. The topic of home energy saving habits and behaviours applied to new places could be a further extension of this pilot study when explored for light switching behaviours and practices. This topic has since been investigated by researchers focussing on a newly built halls of residence building at University of Southampton where occupants' 'home' thermal history and preferences for using controls to regulate indoor temperature was been investigated (Amin *et al.*, 2016). The findings from this study recommended placing students by climatic preference, for example, a student from a warmer 'home' climate on a higher floor in a sheltered positon and a student preferring cooler temperatures on a lower floor with greater air flow (Amin *et al.*, 2016).

The pilot study had a number of practical implications. The automated controls in the Psychology building were clearly not meeting the expectations and requirements of its end users. This building was one of the first on campus to receive automated lighting controls over 10 years ago and at the time sensor controls were not as ubiquitous or well tested in industry and in field. The practical implications of this primary era of control technology was shared with the industry sponsor and other estates and facilities staff members. The topics of lighting controls and individual controls became to focus of thesis and form the main study of this chapter.

3.3 Main study

Participants were directly recruited via staff email group lists. Nine academic teaching staff participated. Seven of the nine staff were researchers in the built environment. During recruitment and in the briefing sheet provided participants were informed that the purpose of the study was to explore their lighting preferences in their working environments. Academic teaching and research staff were selected as they represent a less transient population than undergraduate or postgraduate students and are more likely to have experience manipulating the light and lighting conditions in a variety of university spaces. A small sample was appropriate because this research aimed to collect a rich description of detailed information about each individual's experiences and views. Data collection is deemed sufficient when theoretical saturation is achieved at a point where no new themes emerge from interviews. Ethics approval for this study was obtained from the Department of Psychology Ethics Committee.

Participants were interviewed at a convenient time and date in their own offices or a location convenient to them. Being able to conduct the interview in the individual's offices allowed the occupants to directly show the interviewer their preferences. Participants had typically occupied offices within the same buildings for periods between 3 – 26 years. In two interviews the recording was split into two separate periods, one because the participant started to talk again about light and lighting after the interview finished, this discussion was paused and recording resumed; the other because the participant wanted to relocate to their laboratory to demonstrate their difficulty with using the retractable light switches that were linked to the automated lighting sensors.

3.3.1 Method of main study

A semi-structured interview procedure was formulated from a previous pilot study. The questions were decided upon as specifically focusing on lighting, lighting behaviour, and the use of campus spaces. The topic guide comprised eight main areas:1) Automation in corridor areas; 2) Corridor dimming, sensitivity and timing; 3) Orientation of building; 4) Office daylight, blinds and artificial lighting; 5) Office lighting habits and patterns of behaviour; 6) Seasons/weather; 7) Classroom lighting controls – examples of excellent and poor designs; 8) Views and blind use. The questions can be found alongside the ethical approval forms at Appendix B. The questions were not limited in scope and the researcher actively sought to keep the question open ended to encourage opinions and further examples to be expressed.

Lighting automation (topics 1 and 2) in the corridor areas was chosen as this was found to be a topic generated by an earlier pilot study conducted with four postgraduate students and two staff members in initial semi-structured interviews. The orientation of the building (topic 3) is a factor linked to daylight and artificial lighting design. Questions were also posed about the individual's working environment (topic 4), their office, whether that is open or single occupancy and how much control they have other the lighting in this space. As seven out of nine participants were recruited from the

School of the Built Environment, they were mostly familiar with the 2013 lighting upgrades in corridor and classroom areas as part of the university's Carbon Management Plan. Two participants were deliberately sought from other independent Departments to triangulate the collected data and provide insights from a wider range of participants. Their usual patterns of behaviour and habit (topic 5) were also explored in both their office environment and familiar classrooms. Seasonality (topic 6) was included as this impacted their use of blinds and artificial light – especially when teaching – and varied according to the daylight availability. Topic 7 related to their classroom spaces and was investigated by asking participants if they could recall specific examples of good lighting controls that were easy to use and understand, and also those that suffered from poor design and were difficult to use in practice. Finally, participants were asked about their perception of their office and classroom views (topic 8) and how this related to their blind use.

The interviews were recorded using a Sony audio recorder ICD-PX312 audio recorder. The audio files in .mp3 format were sent via a file sharing site to an external agency for transcription. The written transcription was received by the researchers and then checked thoroughly, three times in total, for errors whilst the researcher listened to the audio file. Notes were also made during the interview.

The 30 teaching and learning buildings on this university's main campus amount to 122,000 m^2 of gross internal area floor space. Reporting the individual offices, hundreds of centrally bookable classrooms and their respective corridor floor plans, lighting levels and light sources was outside of the scope of this study. The focus of this study was instead on the participant's responses to their lit environment in all of those spaces. All of the spaces mentioned were lit with fluorescent lighting, re-commissioning infrequently took place in practice as specialist external commissioning engineers charged up to £1,000 per day. The quality of good lighting has been discussed alongside the very real goals of time and budget constraints, whilst acknowledging that indifferent, adequate and even bad lighting is unfortunately a norm for some (Boyce, 2013).

A thematic analysis approach and initial coding method was used. This assumes the researcher has no preconceived theories about how people use their space or how they choose to light it. There are no hypotheses given as it starts from an open point of view about letting the participants speak candidly about their position and viewpoint. The process of data analysis followed the flow chart detailed in Figure 12. The initial analysis was conducted using process coding (also known as 'action coding') (Saldana, 2016), to identify the main categories found when summarising participant responses.

Analysis Action	Analysis Description
Transcribe	Audio files sent to third party transcription service and returned as MS Word .doc files
Listen & Read	Listen to the audio files for each participant and read through the transcript at the same time to check for errors
Iterative	Read all of the interview transcripts thoroughly
Make notes	Write initial notes and codes – process coding, selecting salient quotes
Iterative	Re-read all of the transcripts with initial notes and codes seeing if there are new codes and if there are common themes
Produce themes	Develop themes from the codes that are interpretive at a higher level than the specific codes – thematic analysis
Focus	Utilise focussing strategies (Saldana, 2016)
	1) Select three themes that summarises the codes
	2) Top ten quotes
Iterative	Re-read the transcripts again to ensure the themes are emerging from the data
Write results	Write up results and tailor focussing strategies to suit data analysis and interpretation

Figure 12 Process of conducting thematic analysis of this study

Thematic analysis uses initial codes which are then collated and developed into themes from the data. Outputs were refined using two focusing strategies (Saldana, 2016) which sought three main themes and a top ten list of extracted quotes that were particularly relevant. The results were reviewed through iterative stages to identify a total of four themes that emerged from the data as the strategy was a starting point to further develop the interpretations as the analysis progressed.

The British Medical Journal's checklist for qualitative research (Mays and Pope, 1995) was followed. A key characteristic of qualitative research is the desire to seek a personal opinion and judgement from the participant. Using topic guide questions and open ended questions inherently alters the perspective and answers of the participants. If the researcher wanted to remain outside of the research they would choose surveys and quantitative statistical methods that seek to be unbiased. The interviewer's background in physics, surveying and specialism in lighting controls meant that focus was on how people used the controls in campus buildings and whether these were functioning as intended. In eliciting responses from participants the interviewer tried to refrain from using any building jargon and instead used the participant's language to further conversations. The participants chosen were not unbiased in their prior knowledge and ability to describe the built environment as many were from the School of the Built Environment. However the two participants that were not 'experts' in this field provided similar insightful and comprehensive accounts of their use of light and lighting in their spaces.

Negative findings and divergent cases are also reported here, for example when a participant's contribution did not fit the general conclusions arrived at once analysis was completed. A comprehensive paper trail of interview notes, initial codes, themes, interpretations and findings was developed throughout the analysis. Validation was achieved through means of an in-house seminar where intermediate analysis was presented to the participants and they were invited to give private feedback to the researchers.

3.3.2 Findings of main study

Participants were encouraged to discuss specific examples, such as buildings and classrooms. Photographs of some of these are given below to illustrate participants' observations. Four major themes naturally emerged from the data on light and lighting: control and choice, connection with the outdoors, concentration, and comfort.

Control and choice

One of the most commonly asserted themes was having control over the light and lighting. Previous work has suggested blind use is linked to direct sunlight and solar gain prevention (Reinhart and Voss, 2003). This study raised the issue of window blind use with academic staff who occupied offices. These interviews demonstrated that blind use was not only affected by these two elements but also management practices in different buildings across campus. For example, the different university buildings are subject to different window cleaning frequencies, which are managed by individual Schools and their respective budget constraints, rather than centrally.

Int: **And your blinds, they're half open at a bit of an angle now, do you alter them between the seasons at all or?**

P9: **Not really, sometimes in the summer I just open them completely so I can gaze at the blue sky but they're only there because the windows are fairly ugly so they're edge on to take your eye away from the blind aluminium finish of these ugly windows. It's pockmarked, when the glass is dirty the university doesn't pay for window cleaning, the windows are dirty, the aluminium is stained and past its best so I want to see the view but if I'm focusing on the window frame the vertical blinds pull my eyes to the blinds rather than the window frame. It's strange isn't it really but they add to the feeling of, I suppose it's a feeling of being in control of the environment, overriding the decisions that were taken by some faceless building services engineer in Estates and Facilities who's got no idea what these things feel like to work in. [Expert in the built environment, academic]**

One of the ways that office users could influence their environments directly was their use of small power lighting in their offices. All but one participant explained that they would use small power direct and indirect lighting in preference to the ceiling lighting installed (fluorescent T12 lighting in the Built Environment offices). Piecemeal installation of retrofit lighting to the corridors and classrooms did not include upgrading the individual offices or areas such as coffee spaces, kitchens, print rooms and some toilets and in some instances, 1980/90's office ceiling lighting produced flicker and noise which interviewees felt affected their ability to work comfortably. Lighting professionals should be wary of piecemeal upgrades when faced with a client that is financially constrained – as most public sector clients are likely to be post-2008 – and how this will affect both the post occupancy evaluation of this space and end user's perceptions.

The use of direct control over lighting has been suggested to increase office worker's satisfaction with their physical environment (Boyce *et al.*, 2006). The small indirect uplighters and direct task reading lamps allowed them to create different moods and areas for carrying out different tasks.

> **P2: Yes, so this angle poise lamp is very much here at the work station so it's very much a reading lamp. The one in the corner is purely an ambient lighting thing to make it look pretty. The other one on the desk is that, because they're all compact fluorescent bulbs and they're quite low wattage CFLs they don't give out masses of light, so without that one on, then you're coming to this kind of grey area between a nice ambient environment and sitting in the dark, and so that one on the table is very important in the sense that when I have students coming in that I supervise, the idea is that that table is normally empty and the only thing on it is the lamp and it's purely to get them feeling relaxed so that we can have a conversation. I do feel that having that nice mellow lighting helps to put them in a calmer frame of mind, that's the idea, and that's why I've got the nice pictures around there as well. [Expert in the built environment, academic]**

The office occupants perceived that they were able to take control of their environments by choosing to bring in different lamps to counteract their discomfort with the installed ceiling lighting as detailed by participants 2 and 9 above. Control and choice are two key elements in dual processing theory, system 1 involves automatic unconscious elements, whereas system 2 the conscious mind is involved in control and choice (Norman and Shallice, 1986; Kahneman, 2011). One participant (an academic expert in the built environment) reported that he was unaffected by the installed artificial lighting and chose not to bring in personal lighting, but this view was not shared by the other interviewees. Designers could include options for individual desk lamps to suit the visual and control needs of the end users.

Interviewees also explained their difficulties with using the light switches when controlling lighting for teaching/lecturing in classrooms. They described their habit of selecting the appropriate artificial light levels by trial and error at the beginning of the lecture period. The theory of planned behaviour which is based in rational choice theory is widely established, yet there is still a gap between automatic unconscious habitual patterns of behaviour and the end result (Ajzen, 1991; Ajzen, Brown and Carvajal, 2004). The lack of consistency and continuity with the light switch interface across different buildings and teaching spaces was repeatedly raised. Despite explicitly mentioning classrooms recently upgraded with dimmable T5 fluorescent classroom lighting, only one interviewee reported being able to use these in practice as they were fitted with retractable switches, a situation discovered by the interviewee through trial and error.

> **P8:** If they were dimmable I probably didn't know. So I would probably just use as on or off. Now, like if there is a slider that goes up and down, that's pretty obvious that I can control that, but no, if the switch looks just on or off I would probably just use it like on or off.
>
> **P5:** I just know how to use them through trial and error. One of my particular complaints about these things is in some parts of the university you have an on off switch which is simply there and what you don't realise about that on off switch is if you hold the on switch, it brings the lights up and if you press the light switch off it brings the lights down. Great once you discover it but it is entirely by
>
> **Int:** Accident?
>
> **P5:** Accident that you find that out, and that's just irritating apart from anything else. [non-expert in the Built Environment]

The Chemistry building's lecture theatres were cited by a few participants as being able to use easily and quickly, as shown in Figure 13. This light switch is not dissimilar to others used which were cited as being difficult. The key difference is the labelling, with button 1 = Lecture condition, this fixed label is salient, placed directly above the switch and easily mapped to the buttons allowing easy use by the end user. The light switch settings 1-4 are illuminated when pressed to allow feedback to the user about which setting is currently being operated.

Figure 13 Chemistry lecture theatre light switch

Finally the participants mentioned that their use of multiple teaching tools: video, presentation, exams, group and individual exercises necessitated different lighting conditions and control over these different teaching styles was often made difficult by the design of the lighting controls.

> **P5:** **It's really quite important, especially as I tend to use video clips and other tools in my lectures that I can actually vary the lighting in the room. The difficulty being is if you want to show a clip you need the lighting to be right on the screen, there's no point in showing people a clip if the, it's, the screen is possibly washed out by an unnecessary light. [Non-expert in the built environment, academic]**

Although best practice guidance states that classroom and educational lighting design should be flexible to enable the present and future teaching and learning styles (CIBSE, 2011), it appears that in practice at this university, this frequently does not happen.

Connection with the outdoors

Unsurprisingly the participants had a preference for daylight in their offices and classrooms. Their enthusiasm for occupying a space that had access to daylight was not only important for themselves but also their students. Previous research has shown that for children in classrooms the effect of daylight impacts non-visual effects such as health outcomes and circadian response (Küller and Lindsten, 1992), and it is reasonable to assume that the same may be true for adult learners and teachers. There was a willingness to consider teaching outside as a viable option for lesson plans. The lighting in the classroom spaces and student's ability to see the screen, make notes and see the lecturer was perceived as important to participants. Some of the classrooms specifically referenced are located in 1960's and 1970's style buildings with few or no windows, or conversely large south facing windows with black blackout blinds (Figure 14). These spaces were depicted in some of their opinions as oppressive environments for both lecturer and student, particularly when teaching for a full week, eight hours a day.

> **P1:** **So I mean it's horrible for lots of reasons, one of them being there's no sense of connection with the outdoors. Now if your lectures stimulating enough and interesting enough, perhaps it's something that you can forget about but they're in there all day and also you might be teaching them all day as well. And I just think from that perspective it's nice to see, have a connection with the outdoors, to see how the day is progressing you know. Not going in at nine and it sort of quite dim outside and then leaving at five and its dark. [Expert in the built environment, academic]**

A few members of staff interviewed teach outdoors, with site visits, and one participant preferred this to indoor teaching spaces for student learning and engagement.

> **P6:** **One of the classrooms I was describing to you in systems engineering, that's where I would have those six hours with the students, and it's horrendous. They're falling asleep within the first 20 minutes. I could be doing breakdancing on the stage, they'd still fall asleep because of the environment that they're placed in. But outside they're absolutely on it, engaged, interested etc, so they're wide awake. [Expert in the built environment, academic]**

Figure 14 Classroom used for lunchtime research seminars in the School of the Built Environment

Empathy was expressed for the students and how they were affected by the classroom environment. Some lecturers suggested that this affected their learning outcomes but no measure of this was offered. Participants were directly asked about their perceived importance of a view in both their office and classroom environments. Undergraduate student learning experience and student results at the end of term have been shown to be positively influenced by access to outdoor views, although perceived stress or directed attention may be mediating the positive effects of outdoor views found in this study.

> **P3:** It's not only trees and birds and flowers and nice things it's, even the road, there's a road just out there. I think part of the job of being an academic is daydreaming, you've got to think of things, you've got to imagine things, you've got to try and come up with ideas and resolve issues in your mind and I think a good way of doing that is to look at things outside. [Expert in the built environment, academic]

In some individuals' opinions, not only was an office view important for their problem solving, thinking, conceptualising and contemplation, but they also wanted to afford the same privilege to their students. Most expressed the belief that perhaps sometimes their students also needed to take a five minute break and stare out of the window to take a brief mental rest. The idea that nature provides a restorative opportunity when you are fatigued has been explored by researchers looking at views and directing undergraduate attention in dormitory halls of residence, they found that students reported a perceived increase in their own attentional functioning when viewing nature, however further and longitudinal studies are needed to support these effects (Tennessen and Cimprich, 1995).

The individual who declared they were unaffected by the lighting in their office also explained that the view was not important to them and this individual did not think it affected the performance of their students in a classroom environment.

Concentration

Some individuals explained how their perceived concentration was affected by the daylight and artificial lighting in their offices. Allowing office occupants to have this flexibility of control over their task lighting offers different opportunities for concentration and productive work outputs.

P4: **I've got a desk lamp there, so if I need to read something on, I would still rather read it on paper than on the screen. Now, I've got quite a big screen. So, if I'm really doing some serious marking of something I will sit under that, and I've got an old fashioned bulb. [Non-expert in the built environment, academic]**

Int: **And you would choose that over the preinstalled?"**

P4: **Yeah, I like a really bright light on the paper. And it's down there. I, there's the light, here's the paper.**

Although this individual had a preference for performing tasks under a desk lamp, this does not necessarily influence how effectively the person performs the task in practice. The office occupants who have installed ceiling lighting that is over 20 years old with poor colour temperature and unsatisfactorily maintained (with references to dead flies being cited, and bulbs blown) were specific in pointing out that they perceived their ceiling lighting was detrimental to their productivity and increased their sense of tension, anxiety and stress. In conjunction with poor luminaires, lighting controls can also be a means of distraction and result in a difficulty when lecturers try to use different teaching methods, examples are photographed in Figure 15.

Figure 15 Two specific examples of poor classroom light switches that were explicitly mentioned in relation to participant's difficulty using the controls

P2: **but then I want to show a video and so I want to reduce down the light even more and so I start fiddling, I've got no idea which buttons to press and then you end up all of the lights go up in the classroom and then they all go off and it's a nice distraction and people find it funny, but realistically this digital light switch thing is a nonsense, because even though I've been here two and a half years I've never actually been shown how to use these switches properly [Expert in the built environment, academic]**

As previously stated the effects of both control and a connection with the outdoors was explored and a few of the participants considered that this might influence their student's ability to concentrate. The multiplying effect of being in a space that lacks fresh air and daylight and an inability to control the lighting or window blinds leads to this participant's exasperation with teaching in some of the spaces.

P9: **So I imagine the student's performance would also suffer. They can see it on their faces, they're sat there and they're just desperately trying to stay awake and struggling to, with the environment, it's awful, no fresh air, no fresh light, no daylight, not even, there's no air con I don't think. If there is it doesn't work. But they're stuffy and unbelievably uncomfortable rooms. [Expert in the built environment, academic]**

The type and control of the window blinds also affects students. Blackout blinds in some classrooms were reported to contribute to feelings of claustrophobia and constraint preventing a view and connection with the outside space in some classrooms. Designers should note that using blackout blinds has multiple unintended consequences, the dark surface is hot and it totally inhibits views of outside though providing a means of controlling solar glare it can severely impact perceptions and wellbeing.

P9: **I know the room from the lunch time seminars [classroom within the School of the Built Environment, with 3 metre tall south facing single**

> glazed windows]. It's a horrible room....you've then got people wanting to close the blinds to make it even more claustrophobic and uncomfortable. Now, if the classroom is moving, like on water you'd have everything to be uncomfortable, wouldn't you? You'd have, you'd be nauseous. And I know, we've sat in there for lunch time seminars, and it's been, people have wanted all the lights off, and other people haven't. I don't know. It's quite high ceilings there as well actually, which probably has some kind of impact, I suppose. But you don't have fixed desks either. Those desks can all be moved in that room, so the room can be configured differently, but you go into some of the classrooms or some of the lecture theatres and all the seating is fixed, so you've got to work with that order unless you're going to do something serious and move everything. But that as a classroom and as a presenting room, it's too long, too thin, terrible heating, poor windows, and yeah, black out blinds, it's not nice. [Expert in the built environment, academic]

Comfort

Specifically considering how the office occupants personalised their office space the subject of cosiness was frequently cited. Participants wanted to create a sense of comfort and consequently used their lighting, artwork, plants and books to reflect a room which encourages a calm state of mind and ambience.

> P8: Yeah, don't everybody, well, most people like to personalise their office, but I'm very sensitive to creating a cosy environment, and lighting is a big part of it. I'm very particular about lighting that stimulates me to sit and work or makes me want to leave as soon as possible. [Expert in the built environment, academic]

The interviewees explained how they sometimes worked late hours and wanted an office which would foster the productivity they sought. The combination of interior décor, colour and lighting was important to their feelings of ownership and direct control over their environment, which designers could enable and encourage. Previous research has found this creativity and personalisation of academic offices plays an important role in an academic's sense of self and considers future design requirements that may lack this ability to personalise one's office could be detrimental (Belk and Watson, 1998).

> P7: I think the flowers has [sic] been the key to personalise my office, and that poster. The books will definitely absorb a lot of light, so that's not where I want to sit. I want to sit away from the books because that side will always absorb the lighting. [Expert in the built environment, academic]

3.3.3 Evaluation of main study

Two elements connect the four themes above: design and management, but discussion of these must be preceded by an acknowledgement of pre-existing constraints to action.

Constraints

This study has discussed the opinions of a small number of academics in this UK University, other user groups clearly need to be part of the wider discussion about the four themes highlighted and it would be interesting to study the views of the more vulnerable users who have additional access and support requirements. The views of the original designers, administrative staff who acted as building managers, and maintenance team although valid would not have provided the insights of the end users, an important factor for designers to remember and apply in practice. There are limitations to implementing lighting changes across an environment (such as the one documented) which comprises a large estate spread over three campuses in the UK and contains listed buildings alongside much newer educational buildings. Notably, few of the lighting retrofit upgrade buildings were amongst those cited as poor in their control systems, but there were clear discrepancies between building users' ability to use the controls and the 'design intent'.

The financial implications of retrofitting classroom spaces to standardise the control systems has not been investigated. It is a current requirement that the university's energy efficiency retrofits must achieve between a five and eight year payback period to be considered financially acceptable and this form of financial constraint is common. Replacing lighting control interfaces, such as switch plates, on an estate wide basis is unlikely to achieve this payback period as the savings would prove difficult to quantify or empirically measure in practice. The lack of consistency in replacing and upgrading only parts of a lighting system within a large building highlights the financial pressures constraining management decisions but nonetheless it has observable consequences.

Design

The design of the control interfaces for light switches is one of the most consistent outputs of this qualitative research with participants reporting their many trial and error patterns of behaviour in classrooms and lack of ease controlling the light on the screen. It is frequently left to the contractor to decide upon the switch location, style and complexity the light switches as reported by participant 9 (P9). As reported the light switches in classrooms regularly confuse and delay the building users from achieving their desired light settings.

> **P9: Nobody seems to have thought about lighting at all, they just throw these lights in and put some switches in without really thinking. It's the same mentality that leads us to have projector screens in front of whiteboards. So again you can't use both, it's really weird that people are installing things into teaching spaces where the folks who are installing them have never spoken to anybody that uses them or imagined how they might be**

used, it's terrible. The lighting is appalling. [Expert in the Built Environment]

The majority of the light switches studied would fail to meet basic visual impairment and accessibility requirements for disabled staff and students if the accessible design criteria for interiors (Bright and Cook, 2010) was applied to occupant's interaction with controls. For example, the light switches shown in Figure 16 have little to no contrast between the scene numbers and background, the switches are sometimes the same colour as the back plate and lack of feedback with the luminaires leads to many trial and error events.

Together with many different control settings that differ between classroom and also building, the user faces the difficulty of learning each new system shown in Figure 15. Hence it is not surprising that many asked if they could be standardised and consistent throughout not only the classrooms and buildings but amongst the different campuses across this university's estate. It is well-established that consistency is a key component of learnability of many systems (Payne and Green, 1989). A key implication for the wider lighting profession is to draw upon the cognitive mechanisms at work when artificial lighting is used or daylight is controlled through blinds, these involve explicitly acknowledging the differences between intention, execution and habitual behaviour (Corradi *et al.*, 2013).

Int: Do you think you'd change anything about these controls if you had a chance? What would you want to change about the lighting?

P5: I'd standardise it, I'd standardise it across the university so in one go everything works in the same way in all the rooms, I think that's one aspect of it. And I think clear instructions and yeah, as much feedback built into the device and as much intuitiveness in the design, so you don't have to think too much about it and that it makes sense. So I think I would imagine that would take quite a lot of trialling, however I think maybe there are some parts of the university as the one that we've already talked about, in Building 22, there's already some good practice there that maybe even could just be rolled out. [Non-expert in the Built Environment]

The interviewees were also directly asked about their perception of automation in corridor areas and their response to this type of system. Interviewees were largely in favour of such control strategies however a few of the academics in the School of the Built Environment expressed their dismay that retrofit upgrade of lighting in 2013 excluded personal spaces (offices, kitchen area, coffee area and the toilets) which were left with the 1980's luminaires.

Lack of inclusive thinking and thorough design process, has led to frustration and adaptive behaviours amongst the interviewees, who comment upon how this has affected their teaching and student learning, the most notable of which was one individual's preference for teaching outside as they believe this assists with their student's concentration. This belief cannot be assessed given the absence of direct evidence but it does provide some interesting elements to the discussion of including the academic teaching staff within the design process, which is not without precedent and there is evidence that – within higher education – building users can substantially influence the design with positive effects (Lock, 2015).

Management

CIBSE best practice guidance emphasises that lighting controls require qualified commissioning engineers and adequate training should be provided to building users to operate these controls[1]. Conversely, if prior design and lighting knowledge of occupancy patterns and building orientation was used by pre-commissioning the controls and sensors this could potentially reduce the installation time. Intuitive well designed lighting controls negates the need for training (Norman, 2013) which may be impractical to provide, particularly in a transient environment where there are multiple system users and lighting controls are simple in function even if the few functions intended are not adequately conveyed by their appearance. Norman explains the use of signifiers, constraints, mappings and a conceptual model in the 'Gulf of Execution' where a user tries to understand how it works and what it does; and the use of feedback and a conceptual model in the 'Gulf of Evaluation' where a user assesses what current state the system is in and if their actions achieved the intended goal (Norman, 2013).

Utilising human centred design concepts, Figure 16 illustrates the gulf between the designer and user's conceptual system models of how a retractable light switch functions in practice.

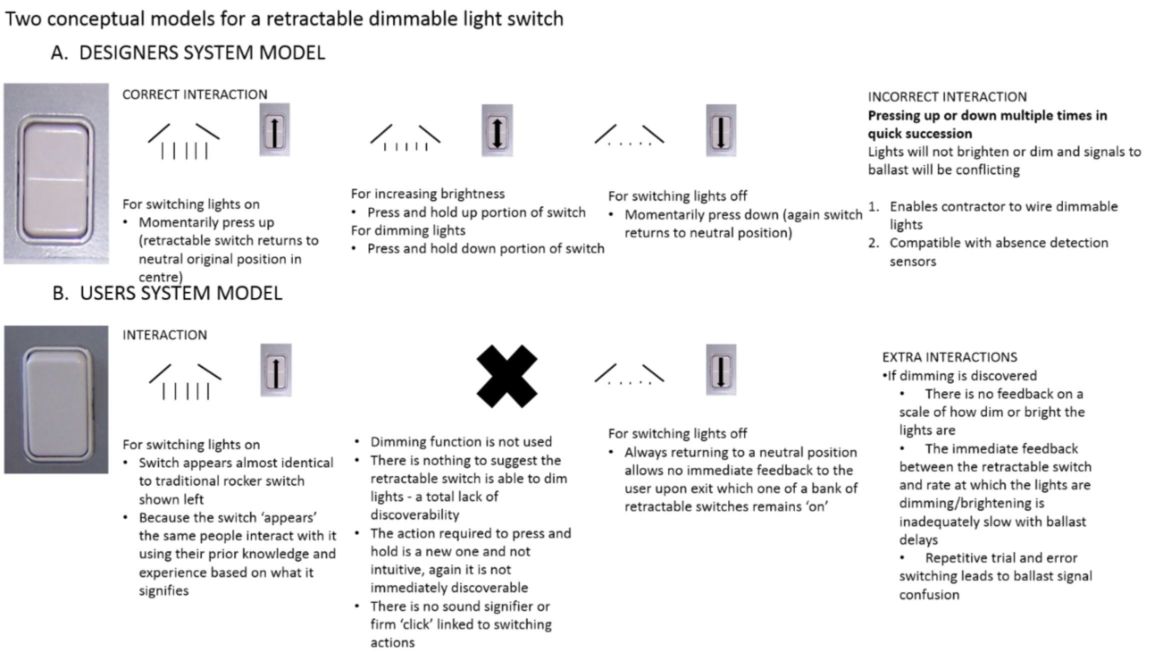


Figure 16 Two conceptual models for a retractable light switch

The management practice of installing retrofit lighting upgrades only in specific parts of the building (e.g. corridors) where the payback was under a 5 year period, also resulted in an experience of inconsistency. Failing to ensure blind controls were functioning and of suitable style, colour and quality, and a lack of a consistent window cleaning strategy impacted upon the building users control and comfort in both offices and upgraded classrooms. Management decisions resulting in an inconsistent end-user experience have unintended consequences for occupant behaviour. Broken blind controls and dirty windows can lead to a sense of occupying a neglected and poorly managed building. The lack of maintenance of office light fittings and blinds frequently led to occupants adapting their behaviour and personalising their offices to maintain what they perceived to be a suitable level of comfort. Adaptive behaviour in the built environment in relation to blinds and lighting controls includes covering illuminance sensors with tape in automated lit environments to override the control systems (O'Brien and Gunay, 2014).

These results suggest that the opinion of academic staff is that the student learning experience is impacted upon by the light and lighting in university classrooms. Access to a view and daylight for student comfort and concentration was deemed valuable by most of the participants. Designers need to consider the multiple users of the space and the flexibility that these spaces afford for different scenarios by different users, be it students, academics, guest speakers, cleaners or administrative staff.

The control over classroom lighting was articulated by six of the participants who described trial and error events at the beginning of every lecture slot to set the lighting to their satisfaction. The fluorescent lamps installed in the university's classrooms take a minimum of two minutes to reach an almost constant light level, if like Figure 15 there are many possible permutations (scene settings and on or off), this would require arriving early pre-lecture time to find the appropriate setting. The blinds in classrooms also prevent a connection with the outdoor space and despite enjoying daylight, the use of blackout blinds creates claustrophobic feelings and spaces that are deprived of sensory experiences. The influential work of Leaman and Bordass still continues to educate designers by grounding itself in systems being simple, intelligible, affording feedback and crucially designers respecting people's comments when evaluating building performance (Leaman and Bordass, 2001).

3.3.4 Conclusions of main study

The main study aimed to elucidate how occupants perceive their lit environments in university buildings and how they interacted with lighting controls using a qualitative research approach. A strength of the main study is the collection of rich descriptions from building occupants – the end users. Revealing the difficulties in a tightly constrained financial environment and how this impacted the feelings of neglect, frustration and adaptive behaviours it reveals a voice that is seldom given exposure in end user's own words. A weakness was the use of a case study which highlights bespoke campus specific management and design issues which might not be transferable to other campuses. Nonetheless, conducting interviews with staff rather than designers or project managers allowed for opinions and experiences to be expressed openly especially as the study started from an exploratory, inductive reasoning position with no prior assumptions. The lighting community could take away a number of insights based upon human centred design and using small sample interviews as a method of post occupancy evaluation. Without the end user's voice in the conversation of lighting design, gulfs between the designer's conceptual model of lighting and the users' (Figure 16) are not only unbridged but unacknowledged. The user sample employed here incorporates a wide range of experiences because many end users were experts in the built environment. It is plausible that the built environment experts perceived and overtly judged the poor management and design with a more critical eye than staff from other schools, however, there is no direct evidence for this, and we note that the lighting environment experienced by these users is common to all. Arguably, experts in the built environment are the most informative group to approach because their expertise enables them to articulate concerns common across multiple users. The lighting profession should consider all the vulnerabilities and difficulties end users perceive and experience when interacting with lighting controls rather than ignoring them. Explicitly exploring the switch plates, control and management strategies at the very start of the design process with end users being included in the discussion would enable a solution with meticulous attention to detail. This study highlights the gap between the designer's intent and actual use of lighting and occupancy, which will be further explored in a quantitative study in Chapter 4.

3.4 Industry outputs and further research

The two studies reported in sections 3.2 and 3.3 revealed new empirical findings through original research. The contribution to knowledge in the lighting discipline has been supported by a publication of the main study findings in the leading CIBSE journal Lighting Research & Technology. Qualitative research offers an insightful and valuable addition to other post occupancy evaluation methods (Tookaloo and Smith, 2015). The strength of this method can be realised by validating the results with the participants and through industry feedback. The results of these studies were combined and presented to the industry sponsor which were described in detail with the examples presented in Figure 13, Figure 14 and Figure 15 and others. The findings of both the pilot and main study were disseminated to the industry sponsor in seminars and a workshop. The consequence of these outputs resulted in: a new specification for lighting controls, revised specification for classroom lighting and assurance that semi-structured interviews were a valid method of POE deemed appropriate for future use by the Estates & Facilities team. A reasonable approach to tackle this issue at a policy and industry level could be to include interview methods in the CIBSE guidance for lighting.

Firstly qualitative methods can be misunderstood and are not entirely in the domain of social science, rather they form reliable, valid and rich empirical evidence alongside existing methods. There are a number of ways the user experiences chapter and studies can be developed. A carefully and fully designed focus group study was produced to follow on from qualitative in depth semi-structure interviews with students and academic staff members. Existing research into creating inclusive and accessible, suggests that when you design for the more vulnerable users (Bright and Cook, 2010), all users benefit from being able to use the space more effectively and safely. A frequently neglected user group such as staff and students with disabilities could provide valuable insights into how these controls are used in practice to inform and improve future designs on campus. Ethical approval was granted to carry out two focus group studies where both students and staff with disabilities would be treated separately, with the intention of using existing human resources email lists for both groups to recruit participants. The researcher would not have knowledge of who was contacted and therefore would remain outside of the research participation process for data protection purposes until the participants contacted the researcher to take part, However the University's Human Resources (HR) were not comfortable with targeting staff with a disability via their email lists, despite the confidential design and data protection protocol of a Chinese Wall (Ma *et al.*, 2012) in place to prevent personal data sharing and this investigation did not proceed. There are many barriers to new knowledge and this remains an undervalued and under researched area that holds much future potential in light and lighting design. Further investigation and experimentation into how people with disabilities are able to use lighting controls in practice is indicated. Continued efforts are needed to make lighting controls more accessible and the only way to do this is to *include* people in the design process rather than exclude them.

The existing qualitative interview data, as previously discussed, can be re-analysed as qualitative data is open ended (Bryman, 2004). The topics that potentially could be examined from the existing data for future publications are user experiences of heating controls. Users from both the pilot and main study frequently expressed problems with the heating, thermal comfort levels, blind use for solar glare, windows for ventilation and needing to completely relocate in summer months as a direct consequence of overheating. The sample population for this work was drawn from eight experts in the built environment [7 – main study, 1- pilot study], three of the staff members were non-experts [2 – main study, 1 – pilot study] and four students were also non-experts [pilot study]. Collectively they all provided rich, insightful observations and views by sharing their experiences, regardless of their prior knowledge.

Chapter 4 Waste avoidance

The waste avoidance chapter provides quantitative empirical studies that were carried out in field. The office and corridor data is used again later in Chapter 5 for the prompt study. First, a methods section outlines the details of in field data collection and provides context. The findings are presented as separate studies by section and use type: office, classroom and corridor. The objectives were defined in the earlier thesis structure section and are reiterated to act as a reminder.

The objectives of this group of studies were to:

Objective 2: discover any interesting patterns of lighting on use and occupancy in offices

Objective 3: measure the performance gap of lighting in classroom and corridor environments

Objective 4: investigate external factors to see if they influenced lighting, occupancy and wasted lighting;

4.1 Data Collection

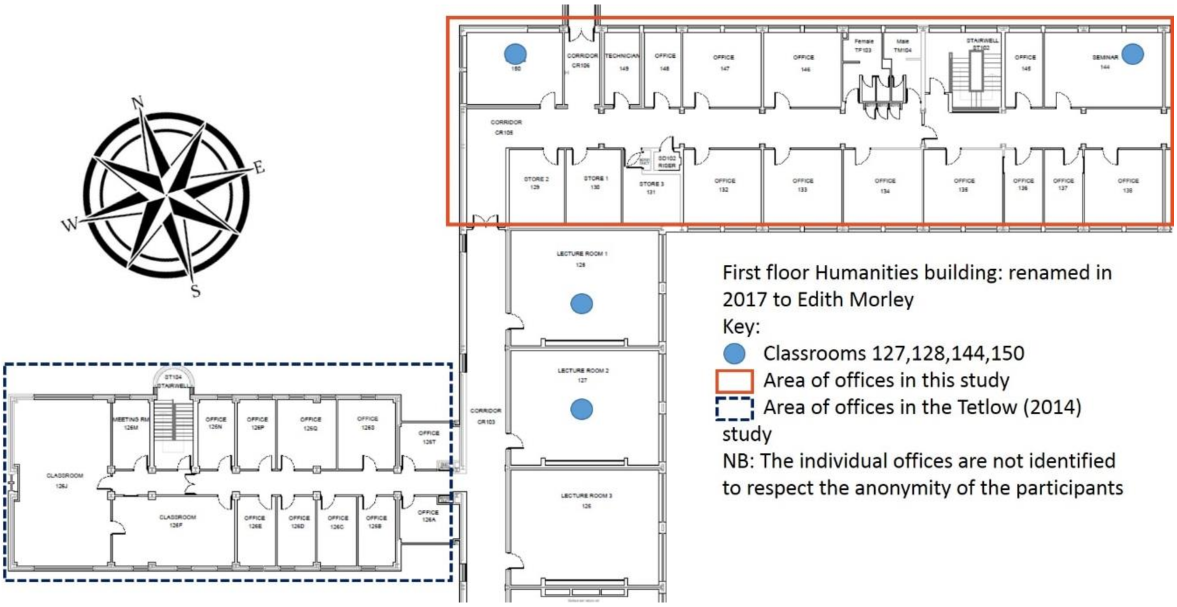
Environmental loggers were reviewed and the HOBO™ UX90-005 occupancy (PIR detector 5 metres), or UX90-006 occupancy logger (PIR detector 6 metres) and lights on/off (photocell) and, HOBO™ U12-012 light intensity data loggers were procured through the EPSRC Doctoral Centre Training fund. Other lighting and occupancy researchers have used the ONSET HOBO suite of environmental loggers for indoor studies (Popoola *et al.*, 2015; Ali *et al.*, 2016). These loggers were also deemed appropriate by the EngD industrial sponsor as they were recommended for commercial applications for the International Performance and Measurement Verification Protocol and are used in energy efficiency post occupancy evaluation (Richman, 2012).

4.1.1 Sample

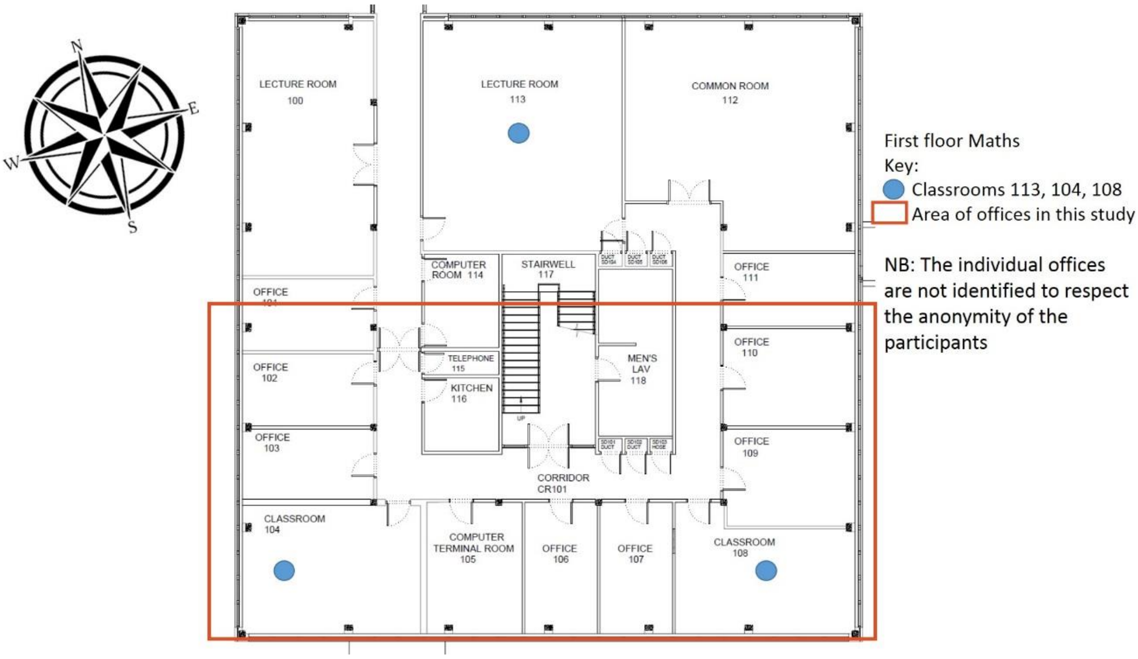
The sample size chosen was based upon the number of participants willing to take part, their office location and the total number of loggers available at any one time. A total of 10 office participants were recruited directly through email and 13 classrooms all with adjoining corridors (14 in total) were chosen for the 6 month studies.

4.1.2 Building Plans

Humanities

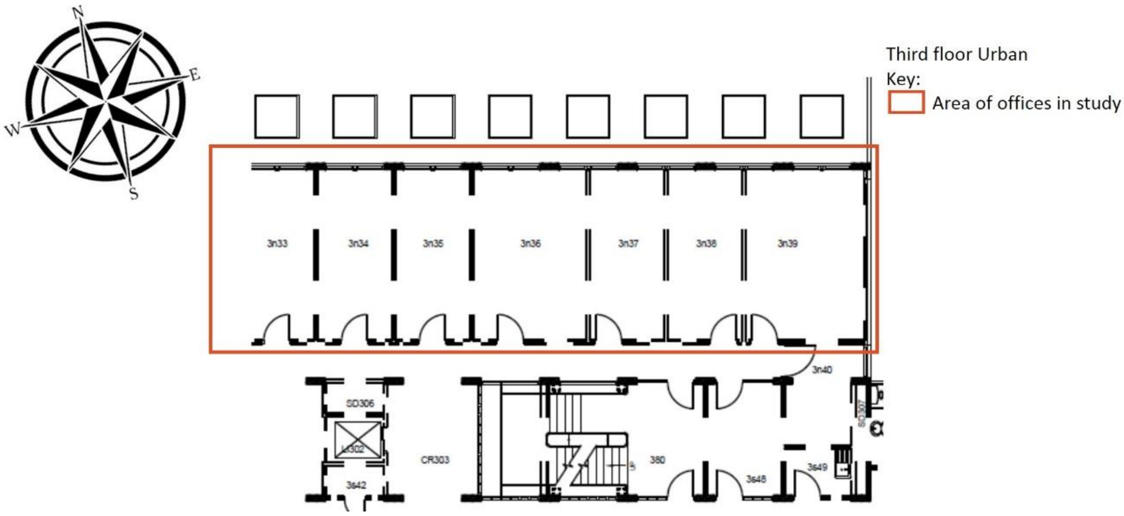


Maths



Urban 2

Urban 3



4.2 Method

The procedure for collecting data followed this systematic routine is shown Table 3.

Step	Action
1	Check initial building logger installation is acceptable to Industry Sponsor & Building Manager
2	Submit School ethics forms for scrutiny and comment
3	Gain ethical approval
4	Email possible single occupancy participants from identifying office name plates and building plans for orientation and layout of floorspace
5	Receive participant feedback with consent to take part and arrange suitable time for initial meeting and installation
6	Prior to deployment set up loggers with HOBOware software, take blank ethics participation forms, laptop, spreadsheet with logger locations, extra loggers, batteries, hook & loop tape and notepad
7	Install loggers (and receive back signed ethics forms from office participant) explain to participant, the researcher will need to return in four weeks for data download and redeployment with this approval
8	Make note in logger location spreadsheet of time and date of deployment, set up calendar reminder for logger readout of data and redeployment
9	After approximately 25 days of data collection email participants at least 3 days in advance of downloading the data
10	Arrange data download times with office participants and also check centrally bookable classroom timetables (posted on the doors) for vacant times to download the logger data that will not affect teaching timetables, download the data
11	Download the data (as HOBOware files and CSV files) for each month into a separate labelled monthly folder, ensure the logger serial number and location is recorded for each and if it is a corridor, office or classroom and if it is lux or occupancy
12	With the logger still connected from the data download, re launch the logger for the next deployment using the same settings for time intervals and check the battery life, hook and loop tape and re-calibrate the occupancy logger with the artificial ceiling lights on
13	Backup the data files onto a separate hard-drive
14	Make a note in the logger spreadsheet if the batteries need replacing in any loggers, and if there were unusual circumstances during the data collection period
15	Repeat steps 9-15 for 6 months or less if the participant wishes to end their involvement in the study
16	Review the data for each of the loggers and conduct exploratory data analysis
17	At the end of the study, remove the loggers at a convenient time download the data and thank participants for their involvement, giving them a study debrief form (part of the ethics suite of forms)
18	Review the collected data and analyse

Table 3 Outline of procedure for collecting logger data in field

4.2.1 Occupancy logger

The occupancy logger records two pieces of data simultaneously, occupancy and light state, Figure 17. The specification sheets from HOBO™ are included at Appendix C. The occupancy logger was configured to record on events (when an occupant leaves or arrives) and when the light was switched on or off was recorded every one minute. It must be noted that the occupancy records any occupation based on photo infra-red (thermal) detection and the logger cannot record how many people are in a space, only that the logger detects a presence or an absence. In a corridor environment the UX90-005/6 occupancy logger was placed on the wall at a height of approximately 1.80 metres adjacent to the office or classroom space. The loggers were labelled to explain their purpose – environmental monitoring. The installation was at an appropriate height for a publically accessible environment where the loggers could be stolen if they were placed within easy reach or at eye level. In the single occupancy offices the occupancy loggers were either placed directly above the occupant's desks attached to the ceiling with a light pipe into the artificial light fitting for the photocell, or they were attached to the wall within two metres of the desk without a light pipe. In the study classrooms these loggers were located so that the area with the lecturer nearest the projection screen was picked up by the logger. The range and sensitivity of the UX90-005 occupancy logger including deployment guidelines was detailed in the manufacturers specification documents (ONSET, 2013). These guidelines were followed for calibrating each of the occupancy loggers for every deployment in situ each time the data were downloaded and redeployed.

The occupancy logger's lights on/off sensor is a photocell located at the top of the logger, this requires a minimum of 65 lux to toggle between lights being detected as on or off. The HOBO guidelines detail how the sensor switches between these two states and deals with light levels at the threshold.

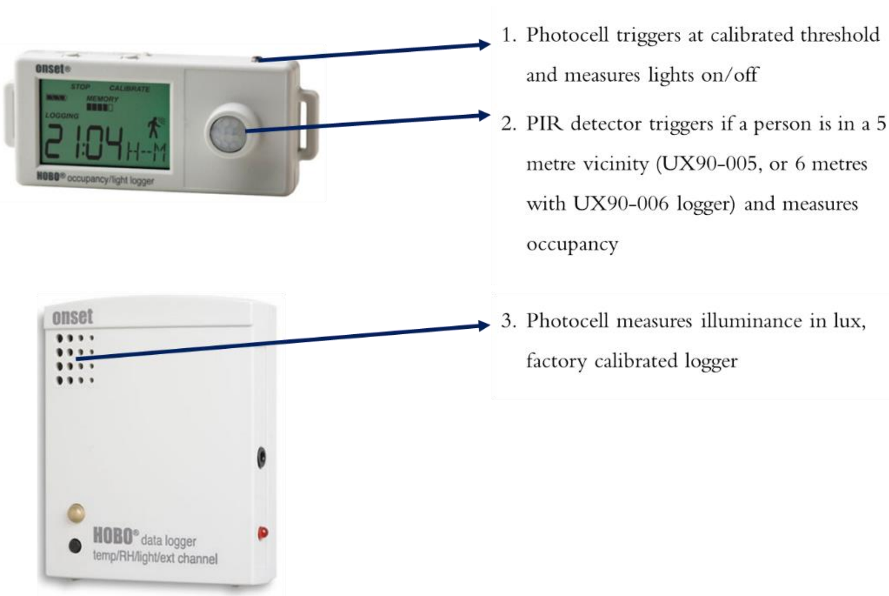


Figure 17 HOBO™ UX90-005 occupancy/lights on logger (top) and HOBO™ U12-012 illuminance data logger (bottom) used in the prompt study

4.2.2 Light intensity logger

The light intensity logger is a general purpose environmental logger and was set to record the illuminance in lux every 1 minute. The logger was placed on the wall adjacent to the light switch if this was possible in classrooms and offices. In corridor spaces the light intensity logger was located at an appropriate (circa 1.8 metres from finished floor level) height to prevent theft or obstruction. The light intensity logger is factory calibrated by ONSET and cannot be altered. The location of the light intensity logger was cited specifically where the ambient light level would be recorded for the occupant on exit or entry of the room or space. Horizontal illuminance was not appropriate to record for these studies as task illuminance requirements are now standard practice for lighting design (CIBSE, 2011). The task (action) that is pivotal to the aim of these waste avoidance studies (and prompt study) was the occupant action of switching on or off the artificial ceiling lighting and not the light levels at occupant's desk or standing at a projector screen. Vertical illuminance was deemed an appropriate method of collecting data for measuring the ambient light intensity for the purposes of this study. CIBSE guidance for lighting in education explains that people pay attention to the vertical surfaces, rather than working areas (2011). Unfortunately although cylindrical illuminance photocells are recommended by Society of Light & Lighting and CIBSE guidance documents it is not possible to procure these in the commercial market for commercial installation. The ONSET loggers provided appropriate measurement and recording method for the purposes of determining the level of contrast in lit environments to meet the aims of this study. The vertical illuminance in this case is being used as an approximate proxy for ambient brightness. The loggers used were HOBO™ loggers and are shown in

Figure 17, with the specifications at Appendix C.

4.2.3 Serial numbers

Each logger has a unique 8 digit serial number on the reverse side to the sensors. In order to keep track of the loggers deployed an MS Excel spreadsheet was configured to detail which logger serial number was deployed in each of the exact locations, if the logger required a new battery or any other unforeseen circumstances, such as low battery loggers, or if the logger had been tampered with or dislodged, or if furniture had been placed in the way.

4.2.4 Software

The HOBOware software package is available free or the Pro version can be purchased with additional applications. A USB cable is required to connect the laptop to the mini-USB socket in each of the loggers. HOBOware includes the ability to determine preferences for how the data are exported to other formats of files, such as Microsoft (MS) Excel and Comma Separate Variable (CSV) files. The preferences chosen for this study were automatic download to MS Excel files as the majority of the studies involved total hours analysis. The other preferences chosen included the format of dates, with day, month, year chosen and; separate time and date columns.

4.2.5 Data logger memory

The occupancy loggers set at events for occupancy and lights on or off being recorded at 1 minute intervals, indicated that the memory would be filled within 90 days of deployment. The light intensity loggers set at 1 minute recording of lux, indicated the memory would be filled within 28 days following deployment. The data loggers also record whether there is an error event, such as a battery that is failing. Given that the light intensity logger had a shorter deployment time period than the occupancy logger, the shorter was used and both loggers were downloaded every 28 days where access permitted. This meant that some of the data files could be shorter or longer (to account for weekend/bank holiday/holiday) periods where access was not possible especially to single occupancy office and classrooms.

4.2.6 Fixings

The loggers were attached to the walls and ceilings using hook and loop tape with sticky back surfaces. The hook and loop tape was positioned or cut to the reverse of the logger so that the serial numbers could still be easily read. The advantage of using hook and loop tape was the ease and speed of deployment, as opposed to permanent screws or nails being used to hang the loggers. The disadvantage of using hook and loop tape was the paint on the surfaces was sometimes pulled off with the tape at the end of the study, likewise remediating the screws or nails would have required filler and paint.

4.2.7 Batteries

The loggers are powered by a single CV 2032 flat cell batteries that last approximately six months. The display within HOBOware indicates how much of the battery remains and if the battery failed whilst the logger was deployed. The batteries are easily replaced with a small Phillips screwdriver.

4.2.8 Locations

The location of the exact logger placement was determined ad hoc based upon the intricacies of each building, floor, orientation and circuit layout of the lighting. An occupancy and light intensity logger was installed into each of the individual offices and classroom spaces, an occupancy and light intensity logger was also deployed in the corridor area adjacent to the office or classroom. As some of the corridors adjacent to the office or classroom shared the same lighting circuit and conditions, only one logger of each type was deployed in this area.

Buildings were chosen as they were part of the long term real estate strategy for the University of Reading and were not part of redevelopment works. The Urban building on floors 2 and 3, offered centrally bookable classrooms and single occupancy offices respectively on separate floors. The Urban building on those two floors was home to the School of the Built Environment. The Maths building on floor 1 offered centrally bookable classrooms and single occupancy offices with corridors on the same floor, the offices were occupied by Mathematics staff. The Humanities building on floor 1 offered centrally bookable classrooms and single occupancy offices with corridors on the same floor, the offices were occupied by History staff.

4.2.9 Limitations

The environmental loggers chosen were the most appropriate for these studies, readily available in the commercial market for industrial application and within the budget provided. They were easy and quick to deploy, small, unobtrusive, did not interfere with other services and did not require hard wiring or access to secure LAN or Wi-Fi networks and configuration therein. Other lighting and occupancy researchers have prototyped the use of open source building science sensors for these types of studies in determining in use patterns (Ali *et al.*, 2016). The occupancy logger was limited by the constraints of the PIR sensor direction and positioning relative to the area of interest to the study. In the classrooms desk and projector layouts varied therefore these required different logger positions. In some classrooms where the lectern was at a considerable distance from the nearest adjacent wall, this meant positioning the occupancy sensor on a projector (so that it could pick up the artificial ceiling lights) and facing the PIR detector towards the lectern for the lecturing area. An example of the in field installation is shown in Figure 18.

Figure 18 Photo of loggers circled in red, installation in Urban classroom 2c01

If the occupancy logger was located too close to the windows, the natural light would lead to the photocell being triggered to potentially record the lights being switched on. If the occupancy logger was located too far both horizontally and vertically out of range of the main area of occupation in a room then the PIR sensor for occupancy could toggle between 0 and 1. Alternatively there may be people present in the room but not in the selected zone of occupancy covered by the PIR sensor. It should be noted that if the projector was used (as is frequently the case for lectures, rather than in exam circumstances) then the illumination from the projector was adding to the ambient illumination in the room. Where possible and in most circumstances the lux logger was placed on the same wall as the switch panel. In some of the older classrooms the ceiling lights were controlled from two separate switch panels, for example the classroom in Maths 113 there are two doors and two switch panels opposite each other and accessed from different corridor areas.

The continued use of the light pipes was difficult for deployment where the finished floor to ceiling height was over 2.5 metres as this posed a Health and Safety risk and would have required a ladder for each deployment, download and redeployment. The practical philosophy of deploying one of each logger type in each location and at a sensible height was based on what the energy officers or other sustainability team members would find feasible on a day to day basis, as this work was seeking to assist them with future in field data collection.

Access to loggers & obstacles

The loggers deployed in corridor areas were the most readily accessible throughout the study period. The loggers within single occupancy offices required prior communication with the occupant to determine a time that was suitable for data download and redeployment. Where occupants were comfortable they gave the researcher access to their offices via administrative staff who held keys and passcodes, to accompany the researcher for the data collection. If the occupant was not comfortable doing this a time and date was found for data collection, this could be some two or three weeks of waiting to collect the data due to the occupant's unique occupancy pattern which might involve lengthy holidays or international conferences. On occasion there were unforeseen circumstances that interfered with data collection, some examples of these are:

- A logger in the pilot study in the Urban building on the third floor in a corridor area became dislodged and fell onto the floor. A member of administrative staff was informed by the cleaner that the building porter had the logger. The logger had been tampered with and the battery removed and replaced upside down. The logger was inspected, the battery replaced and the logger redeployed.
- A logger in the pilot study in the Urban building fell from the ceiling of the office occupant and required reinstallation.
- Both loggers in a Humanities office were obstructed by a new piece of furniture arriving, a 2 metre high book cabinet that was placed adjacent to the door and wall where the loggers were located. These loggers were relocated and a note made in the data collection spreadsheet.
- A logger in a Humanities office fell off the wall as the old chipboard acoustic wall covering in this office had deteriorated to such an extent that it had started to decay. This logger was changed to a smaller PIR occupancy logger (UX90-005) and a note made in the data collection spreadsheet.

4.3 Data tidying

The data tidying process is not often explained or discussed fully however in the interest of creating reproducible research this will be detailed.

The downloaded data were saved as .hproj files using the proprietary onset HOBO software and as MS Excel files. Through trial and error it was easier to merge the data using the HOBOware software as it is possible to overlay the illuminance and lights on/off occupancy logger data, an example of this is shown in Figure 19. In this example the logging starts in November 2015 and finishes in May 2016, the gaps in the green show where the illuminance was either not collected or the data did not merge. In this instance the logger battery needed to be replaced so the April 2016 data for illuminance was separately merged. The filter icons in HOBOware allow the user to create a subgroup of data filtered by say, hour, or week, or day, in Figure 19, per hour was selected.

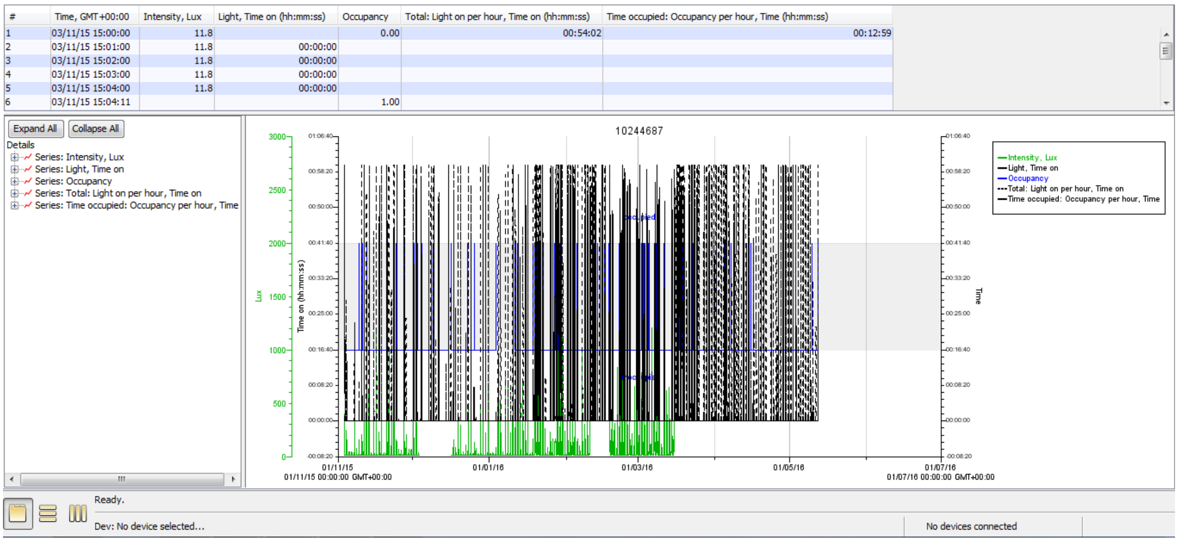


Figure 19 HOBO software merging of lights on, occupancy and illuminance data for a Maths office

The options for exporting the data from HOBOware depend upon the preferences set up initially, for example dd/mm/yyyy as opposed to the American formatting of dates. One of the export features is that it allows you to select which series to include in the export, one, a few or all. To export this at an hourly basis only the last two series in Figure 19 were selected for the purposes of the waste avoidance chapter as this gave sufficient detail for to answer the questions posed. The per hour filter aggregated the total lights on and total occupancy each hour. This was then exported into MS Excel where a further filter was applied using pivot tables to gather the daily and weekly data that will be later presented. At this stage the data is for a single office, or single classroom and without any of the metadata such as building etc. This was populated using the vlookup function and linking sheets to the metadata in Table 4. Other data such as the daylight hours in Reading were downloaded from available meteorological data and again cross referenced in MS Excel.

4.4 Offices

The focus of the offices section was objective 2 to discover any interesting patterns of lighting on use and occupancy in offices; and objective 4 to look at external factors to see if they influenced lighting, occupancy and wasted lighting. This section will commence with an overview of the data collected, exploratory data analysis and a comparison between lights on and occupancy. The results are developed with scatterplots and time of day analysis for each office. The final analysis involves reviewing the external factors of building, size of office, seasons and daylight hours, using linear mixed modelling where appropriate.

4.4.1 Daily data analysis for 10 offices

The data was collected for 10 single occupancy offices over a six month period. The 10 offices were selected from the 3 case study. There are 11 variables that have been considered: building, office number, orientation of office, gender of occupant, size of office, day of year, lights on hours, occupancy hours, season, daylight in time hh:mm:ss and daylight hours in decimal time. The breakdown of offices and buildings is shown in Table 4.

data type:	categorical	categorical	categorical	categorical	[not used]	[not used]	categorical
variable name:	building	office	orientation	gender	size of office	size range for category	Category
examples:	urban	office 1	north	male	19.08	15-20	medium
	urban	office 2	north	male	19.08	15-20	medium
	urban	office 3	north	male	19.08	15-20	medium
	humanities	office 4	south	male	22.75	over 20	large
	humanities	office 5	south	female	11.38	under 15	small
	humanities	office 6	north	male	22.48	over 20	large
	humanities	office 7	north	female	11.37	under 15	small
	humanities	office 8	north	female	11.37	under 15	small
	maths	office 9	south	male	17.78	15-20	medium
	maths	office 10	south	male	13.34	under 15	small

Table 4 Office dataset by data type and variable

The uploaded data into R is revealed using the head() function and can be seen in Figure 20.

```
head(dailydata1)

##   building   office orientation gender sizeoff day lightson  occ waste
## 1    urban office 1       north   male  medium 350     2.80 2.81  0.01
## 2    urban office 1       north   male  medium 351     0.00 0.00  0.00
## 3    urban office 1       north   male  medium 352     8.52 6.67 -1.85
## 4    urban office 1       north   male  medium 353     1.94 1.68 -0.26
## 5    urban office 1       north   male  medium 354     0.00 0.00  0.00
## 6    urban office 1       north   male  medium 355     0.00 0.00  0.00
##   season daylighthms daylighth
## 1 winter   0.3281366      7.88
## 2 winter   0.3276968      7.86
## 3 winter   0.3273264      7.86
## 4 winter   0.3270255      7.85
## 5 winter   0.3268056      7.84
## 6 winter   0.3266551      7.84
```

Figure 20 dailydata1 example of R print out of dataset

The raw data was read in as .csv files and a second dataset made which omitted the data points where there were missing values, for both daily and weekly datasets. In the absence of any individual office having the lighting upgraded a different type of analysis was carried out compared to the corridor and classroom performance gap studies to be reported in later sections. The main aim of this study was to identify if the lights on and occupancy varied according to the variables detailed and also to review the time of day switching on and off patterns. The second aim was to identify wasted lighting, for example when the lights are on and the office was vacant.

Daily aggregation of total hours of lights on and occupancy dataset was selected due to it providing more data points that are different for modelling and this in turn provides more robust conclusions. Daily aggregation was chosen despite the 1 minute resolution of data, due to previously run minute by minute data analysis having an auto-correlation issue with multiple lines of almost identical data. The lower resolution weekly data has been explored and this aggregates the weekly values of lights on, occupancy and daylight hours. This weekly aggregation effect whilst useful for exploratory data analysis, was not suitable for modelling despite having a number of different points across variables, had the drawback of not having as many data points in total. For each office the data was collected for 6 months = approximately 26 weeks = approximately 180 days, a total of 1770 point of data after missing values were excluded. The first stage of this empirical study was to plot the exploratory data analysis to identify how the data was distributed and to provide summary statistics. The exploratory stage identifies the distribution –e.g., normal or not-normal – and also if there are any outliers or peaks in the data that could require further transformations for analysis.

4.4.2 Exploratory data analysis

Daily & weekly lights on hours for each office

Plotting the daily lights on hours for each office and using colour as an indicator of building. Red is urban, purple is humanities and green is maths, as shown in the boxplots in Figure 21. The same colour format is used for the weekly dataset for lights on hours. Summary statistics are also presented for the datasets. The data in Figure 21 show that each office has a different distribution of lights on hourly patterns across the study period. Offices 1- 4 all have median values of zero lights on hours an indication of energy saving behaviours, the circles display the outlying data points where lights were used, hence the boxplots are so condensed that they cannot be seen as the values are centred around zero. An example of the function called in R, for Figure 21, is below:

```
boxplot(dailydata2$lightson~dailydata2$office,          data=dailydata2,
  col= colours1, ylab="Lights on hours per day", las=2, main= "Daily lights
on hours for each office")
```

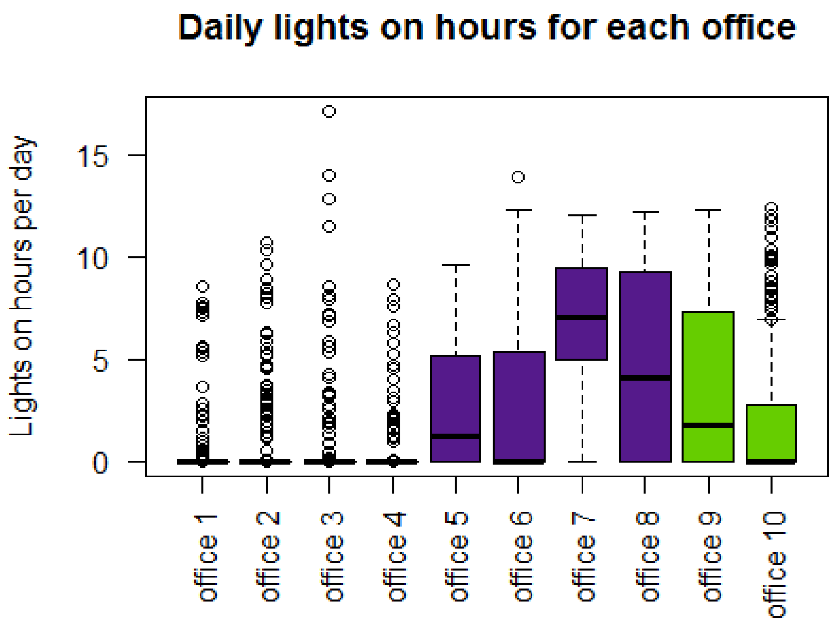


Figure 21 Daily lights on hours for each office

The remaining offices 5 – 10 show box and whisker plots where the box represents the distribution of data as illustrated in

Figure 22. The offices have different distributions of lights on hours use and this was an expected finding as each occupant operates unique daily and weekly patterns.

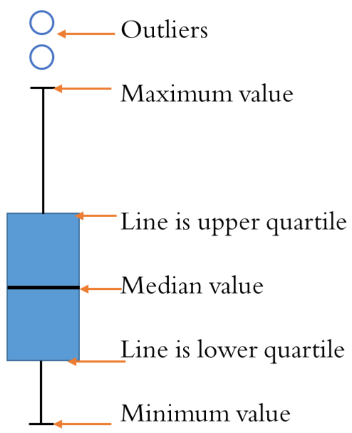


Figure 22 Boxplot illustration

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0	0	0	2.284	4.298	17.104

Table 5 Summary statistics of daily lights on hours in offices

The summary statistics for the daily lights on hours is shown in

Table 5, mean lights of hours of 2.284 hours. One of the limitations of the office dataset was that without further data manipulation inflated zero hours data was prevalent, where the offices were not occupied at weekends and holidays a disproportionate number of zeros were collected. A histogram of frequency density for daily lighting hours is shown in Figure 23.

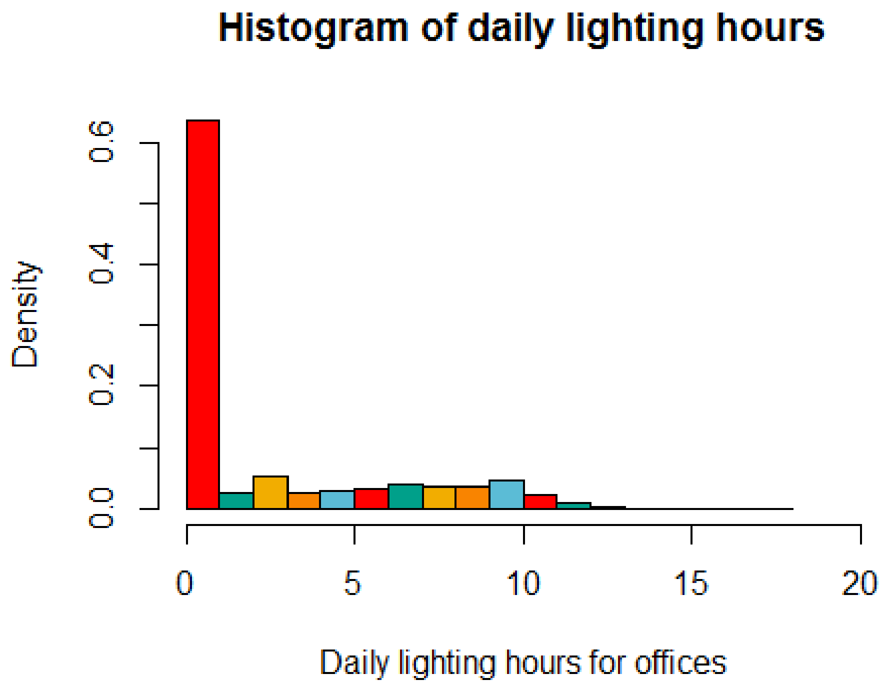


Figure 23 Histogram of daily lights hours in offices

A method of displaying the data that accounted for the daily variation was required therefore weekly plots were more suitable for ascertaining the weekly patterns of lighting use and occupancy. The weekly boxplots for each office are shown in Figure 24. As previously mentioned the buildings are indicated by colour, red is the Urban building, purple Humanities and green Maths. The weekly pattern of lights on use with the boxplots shows large variations between office occupants and even variations in the same building. The mean lights on hours per week is 14.47 hours and boxplot statistics are shown in Table 6.

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0	0.06	10.79	14.47	24.48	57.64

Table 6 Summary of weekly lights on use in offices

The reason the daily data were plotted and are shown is because quite frequently in designer's assumptions for calculating annual hours of use a 'daily' hours figure is used. This daily figure is then multiplied, however these findings suggest that in a higher education setting a more appropriate 'weekly' hours of use be used as there is such a varying pattern for each office. For completeness the daily plots are shown to highlight this pattern.

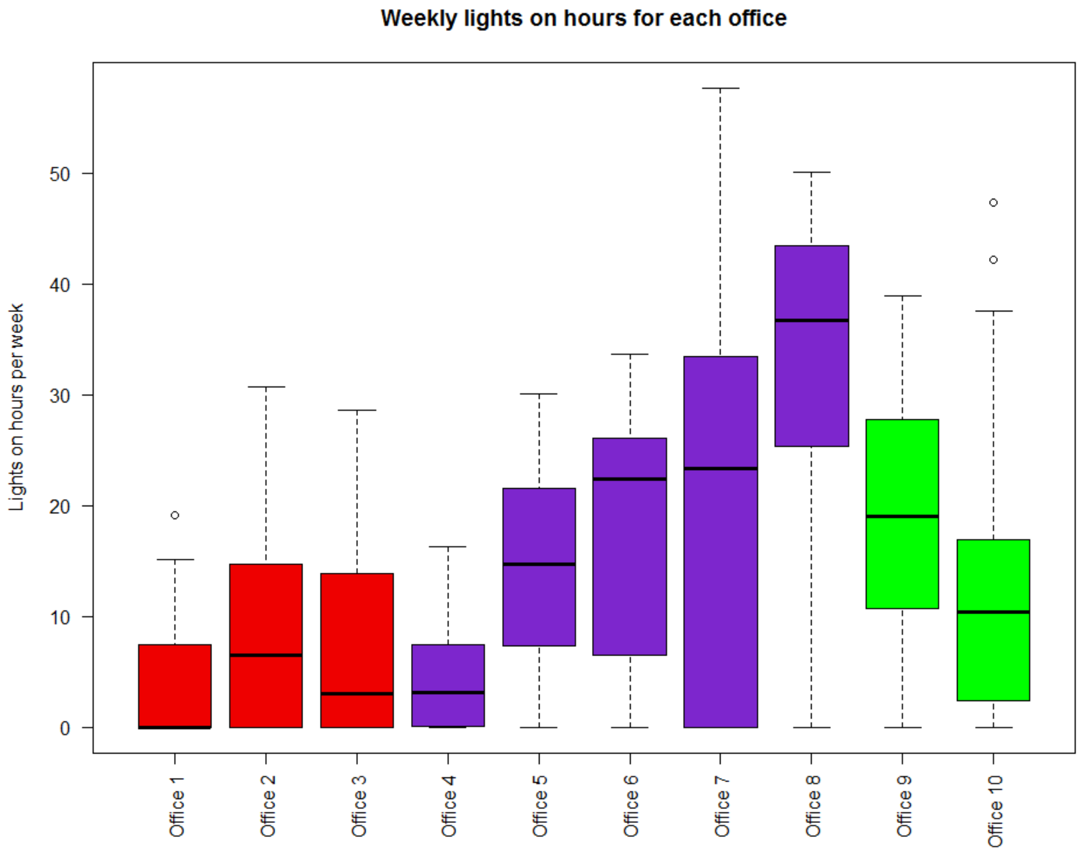


Figure 24 Weekly lights on hours for each office

Comparing the daily to the weekly data for lights on hours it is clear that each office has very different pattern of lights on use at a daily and weekly level. The daily patterns for offices 1,2,3,4,6 and 10 have lights on median values close to zero over the study period. This analysis is somewhat misleading as the weekend days are counted in this dataset as well as holidays, however there are still periods when staff work weekends, for example on open days or for other reasons. The weekly lights on pattern gives a greater indication of what is happening with each occupant's office lighting use. From initial inspection it appears there are variations in both the minimum and maximum values for each office and the median lights on hours are at almost zero for Office 1 and up to 38 hours for Office 8.

Daily & weekly occupancy hours for each office

Plotting the daily occupancy hours for each office with colour again representing the three different buildings occupancy patterns the colours are altered to avoid confusion with the lights on analysis. The Urban building is coloured blue, Humanities building yellow and Maths building pink.

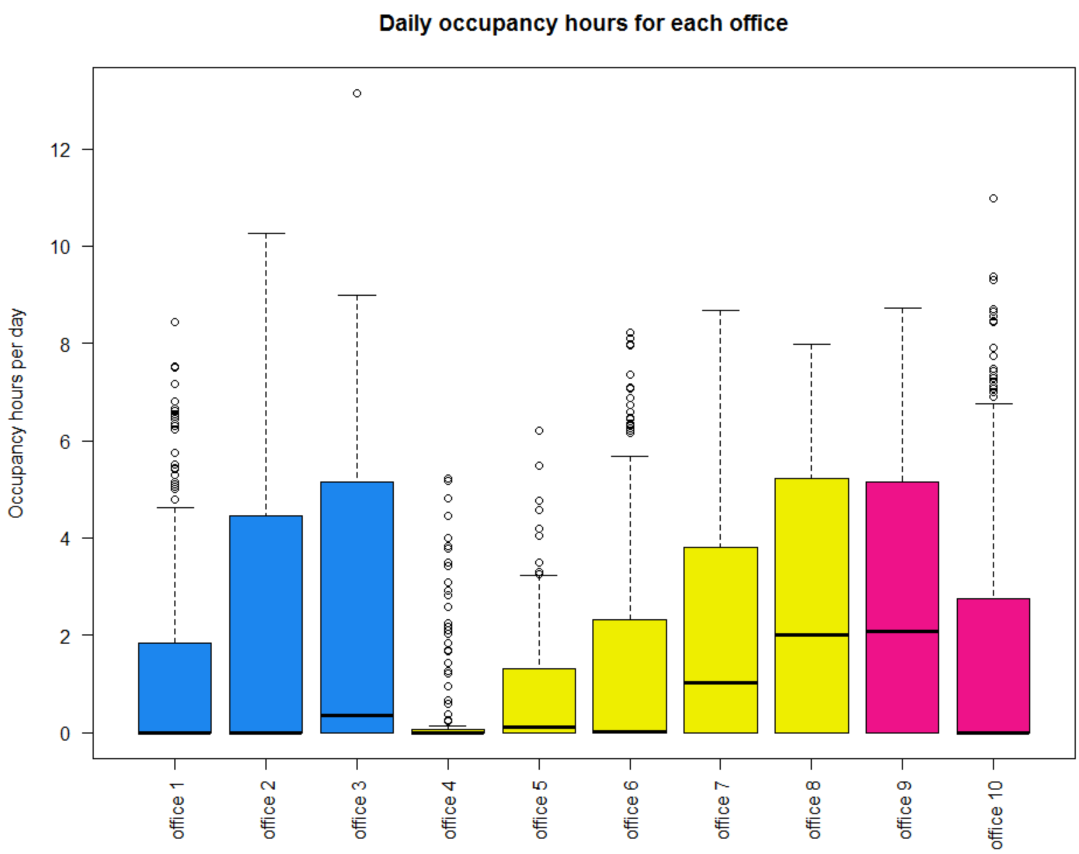


Figure 25 Daily occupancy hours for each office

The daily boxplot of occupancy hours over the study period is shown in Figure 25 which identifies that the offices are not used for long periods over a daily time period. The daily analysis does show the spread of the daily hours patterns, with offices 8 & 9 having the greatest median occupancy hours. As with the previous analysis the most interesting parts are the minimum and maximum daily occupancy hours spread for each office. Again zero inflated data where the occupants are not using their offices is evident from the summary statistics shown in Table 7 with a mean 1.834 hours of daily occupancy.

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0	0	0.02	1.834	3.851	13.137

Table 7 Summary of daily occupancy hours in offices

Weekly occupancy boxplots in Figure 26 reveal a wide variation of occupancy patterns for each of the individual offices and again within the same buildings, summary statistics for the boxplots are detailed in Table 8.

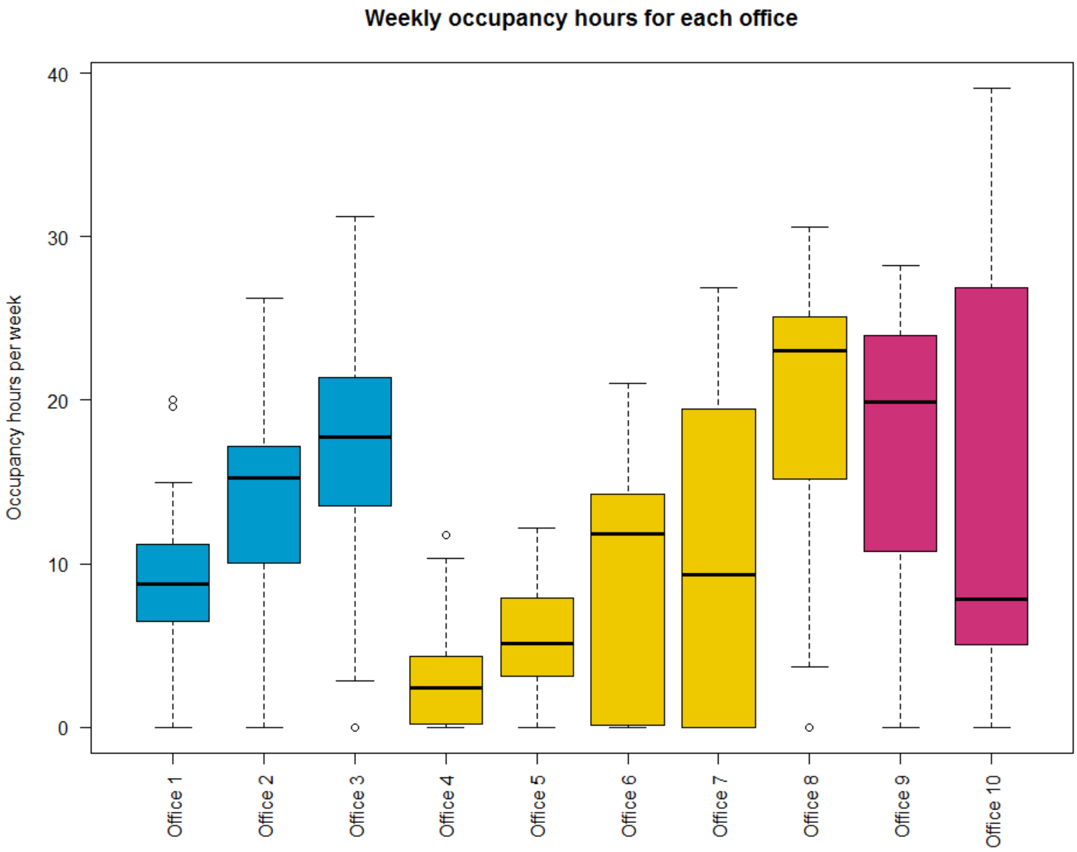


Figure 26 Weekly occupancy hours for each office

Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
0	3.515	10.725	11.971	19.602	39.08

Table 8 Summary of weekly occupancy hours

Comparing the daily to the weekly data for occupancy hours it is clear that each office has very different pattern of occupancy use at a daily and weekly level. Interpreting these results for the purposes of informing design and engineering solutions for energy efficiency, it is quite obvious that a one size fits all sensor, logger or control system would potentially not suit all of these diverse office patterns of lighting use and occupancy. The daily data for both lights on and occupancy indicate that this dataset suffers from 'zero-inflation', however the weekly dataset does not appear to have these same issues.

4.4.3 Comparing weekly lights on and occupancy

A comparison between each office lights on and occupancy hours is shown side by side in Figure 27. The use of colour is used here to identify the offices as individuals rather than by grouping them by building.

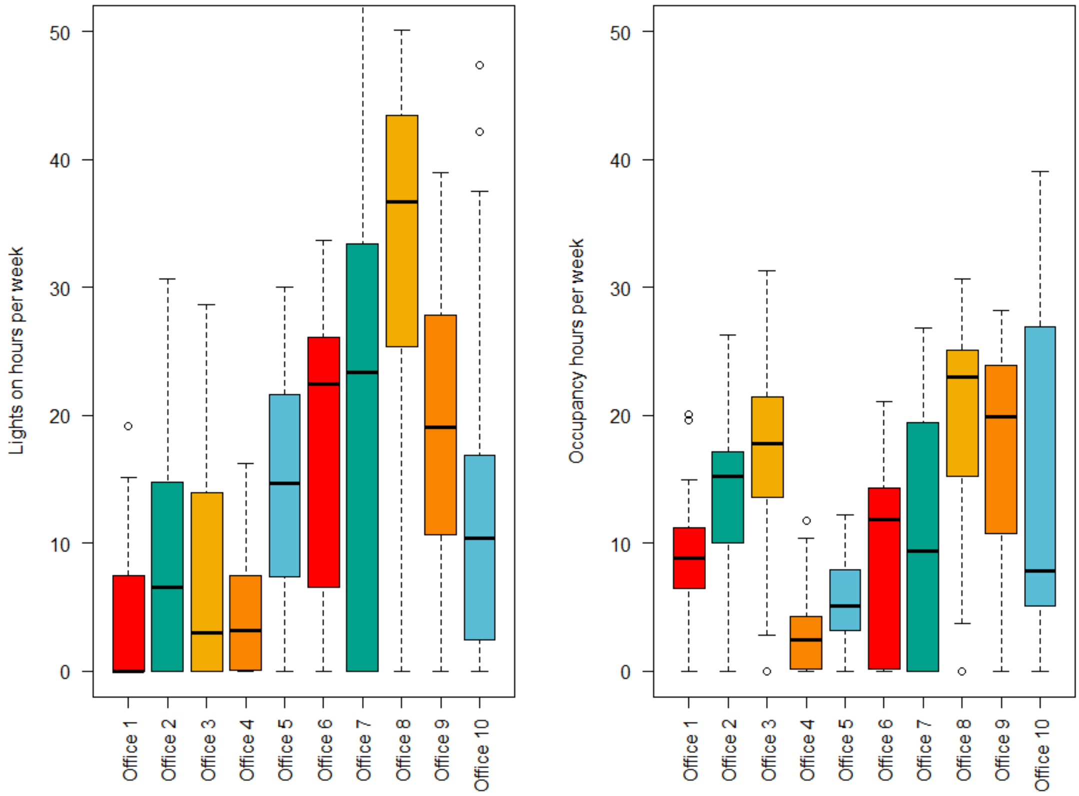


Figure 27 Comparison of weekly lights on and occupancy hours for each office

4.4.4 Scatterplots of offices

Scatterplots are a useful exploratory data analysis tool to visual determine whether the relationship between daily lights on hours and occupancy hours is consistent across the 10 offices, the plots are shown in Figure 28.

The code for executing the scatterplots uses the lattice package:

```
library(lattice)

xyplot(lightson ~ occ|office, group = building, data =dailydata2, type =
c("p", "r"),ylab="Lights on (hours))",xlab="Occupancy (hours))", layout
= c(5,2),
    par.settings = list(superpose.symbol = list(pch = 20, cex = 1,
                                                 col = colours)))
```

From the plots in Figure 28 showing daily lights on hours against occupancy hours it is clear that there are very different relationships between the two variables for each office and also each building. Offices 1-3 are green coloured circles for the Urban building, offices 4-8 are red coloured circles with a blue line for the Humanities building and offices 9 and 10 are purple coloured circles and a pink line.

For example offices 4,5 and 8 the data points quite closely match the occupancy hours. However offices 1, 2 and 3 it is clear that the lights on and occupancy hours have a different relationship where the office is occupied when the lights are at zero hours. The finding that single occupancy offices are occupied and not using the installed lights is consistent with other research (Maniccia *et al.*, 1999).

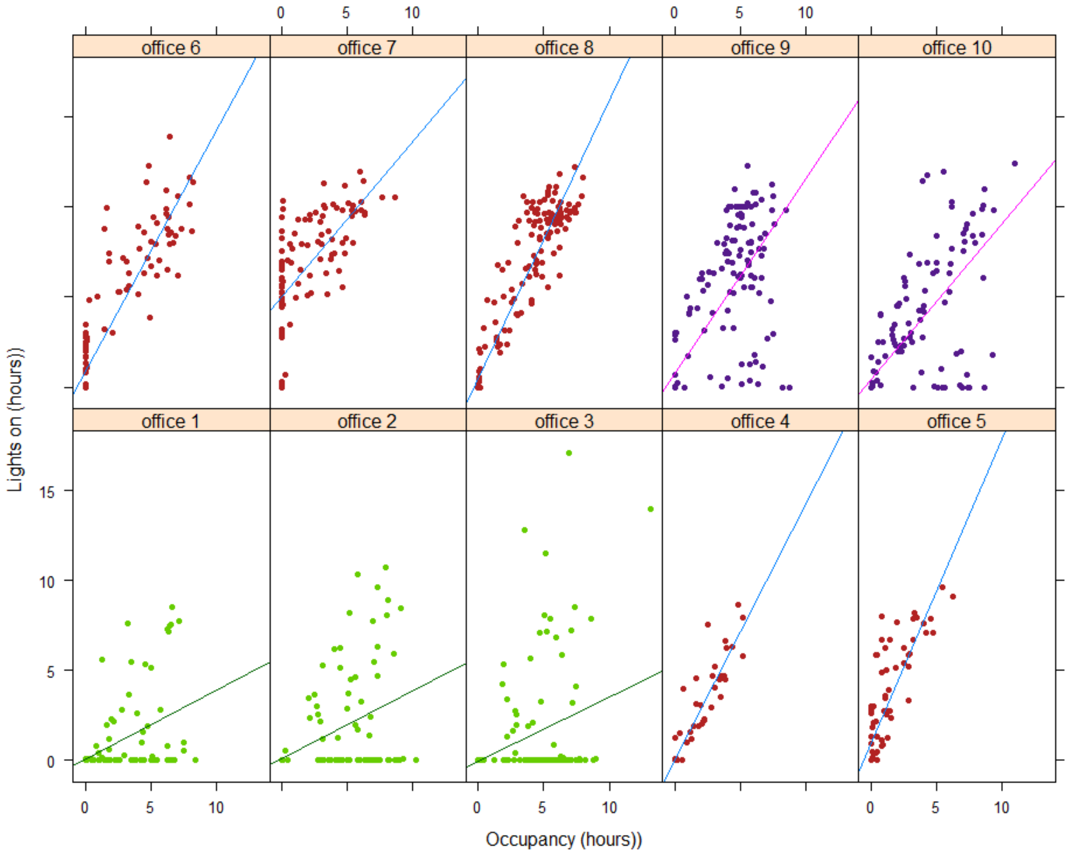


Figure 28 Scatterplots of daily lights on and occupancy hours

The difficulty of analysing this dataset is due to the fundamental differences in each office. Plots for each office show that each line follows a different gradient in Figure 28. The distribution of daily lights on hours and occupancy shows a different intercept with the lights on (y axis) and gradient across all offices. The time of day analysis could provide further insights into the patterns of each individual's habitual behaviour relating to their operation of the ceiling lights.

4.4.5 Time of day analysis

Time of day analysis is one of the most indicative ways of visualising when occupants are present in their offices. The time of day analysis was used by Hunt (1979, 1980) to explore patterns of light switching behaviour in shared offices and classrooms.

Time of day analysis – Urban building

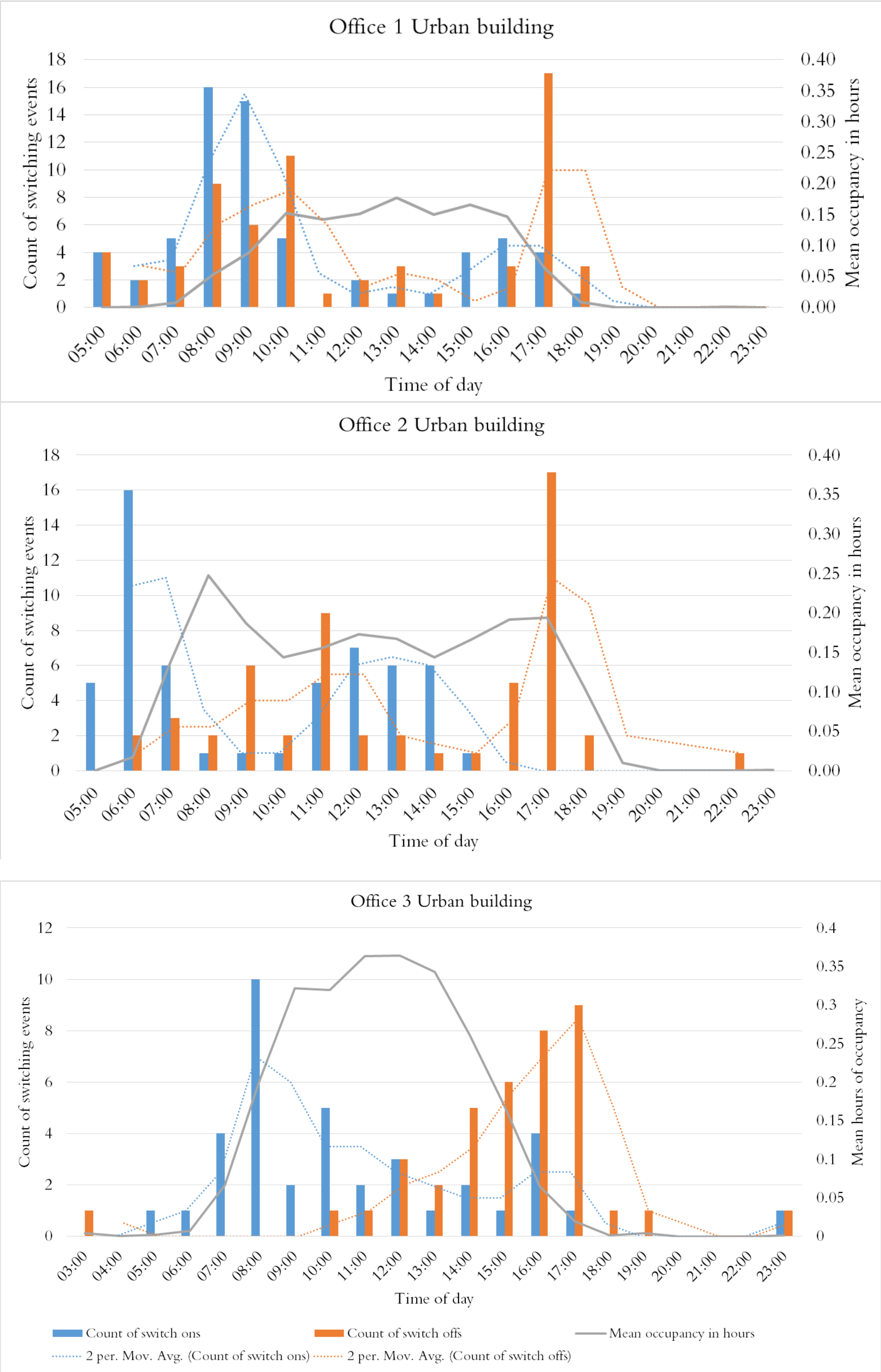
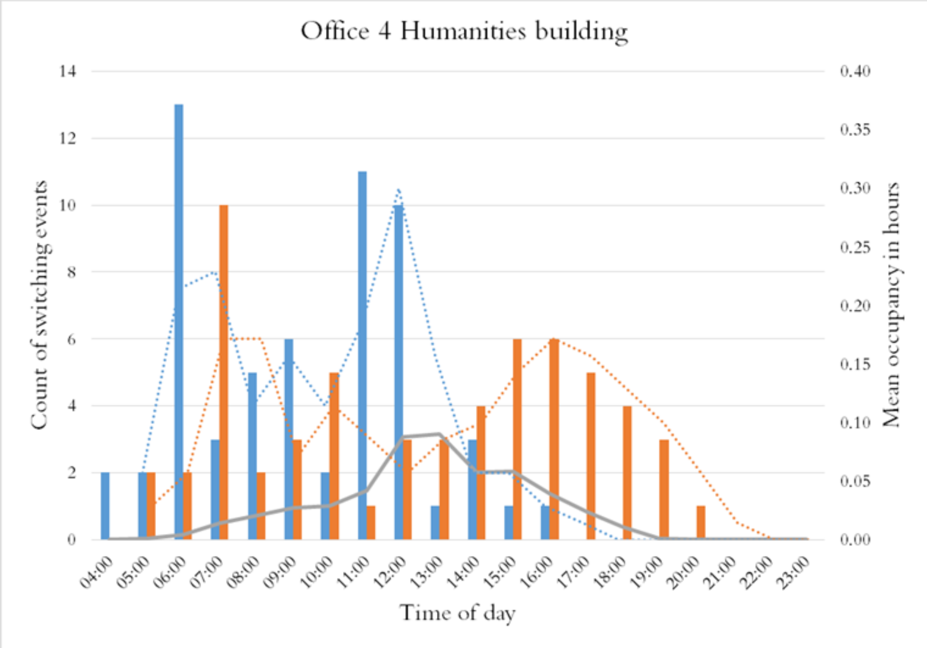


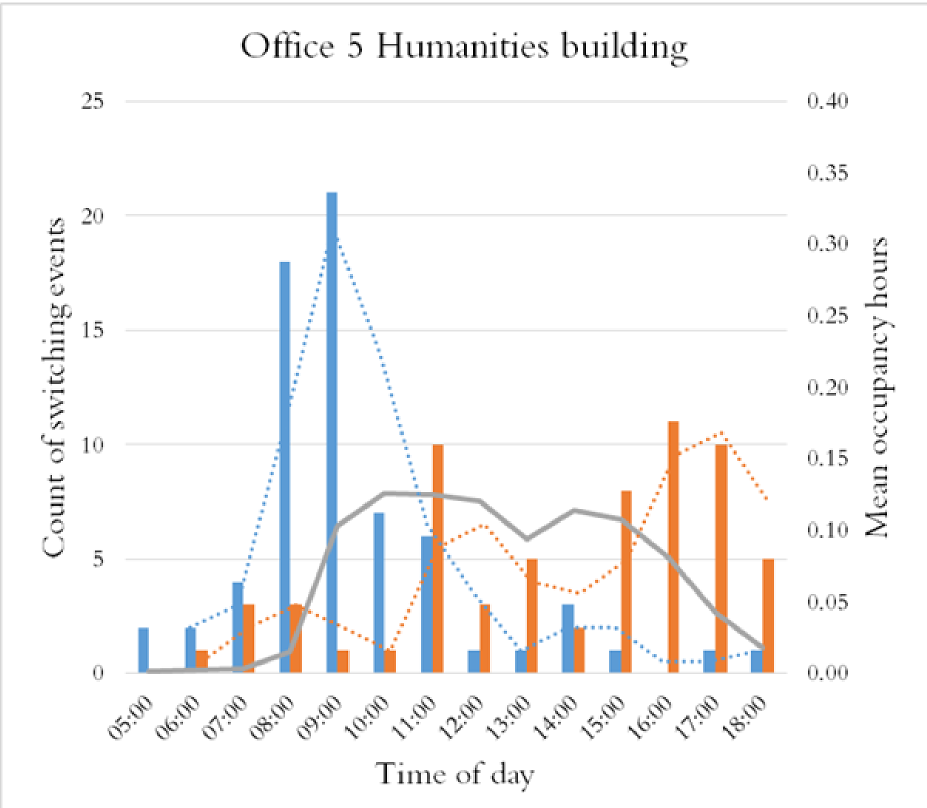
Figure 29 Plots of 3 time of day of light switch on and off with mean occupancy in Urban offices

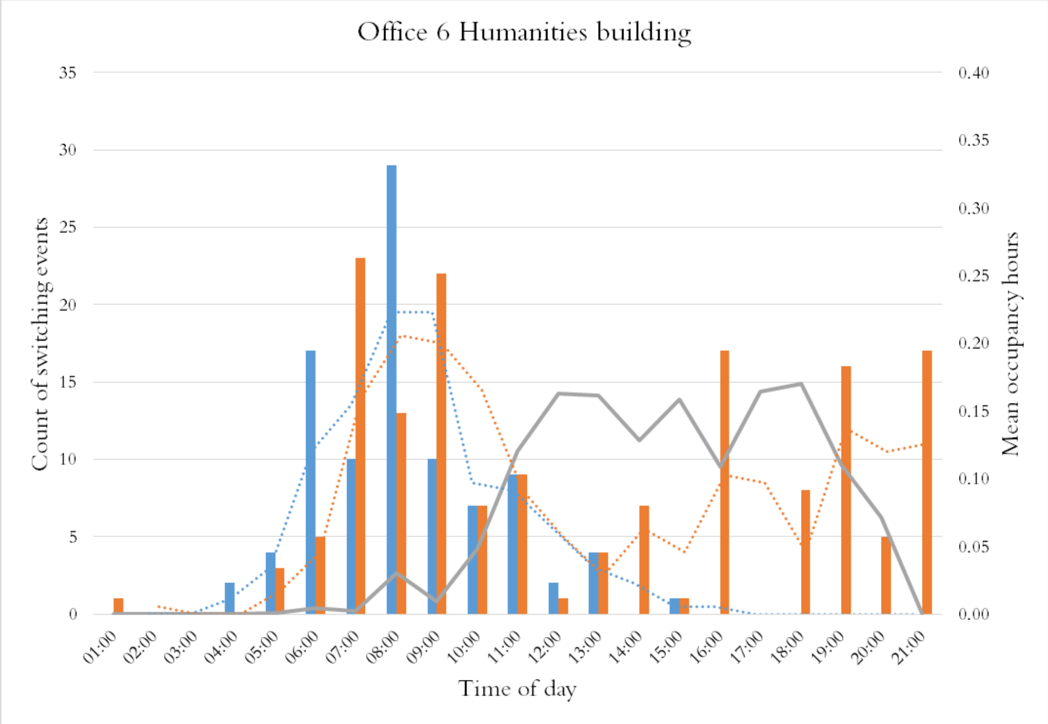
The 3 plots shown in Figure 29 reveal the very different patterns of switch on and switch off behaviours against time of day on the left axis. The right axis reveals the mean occupancy in hours and both are plotted against the time of day. Office occupants in Office 1 and Office 2 show two peaks of switch on and two peaks of switch off patterns of behaviour. These light switching patterns relate to occupancy and are noticeable with three peaks in mean occupancy hours for Offices 1 and 2. The Office 1 and 2 two patterns are similar however office 3 in the Urban building is distinctly different with a unimodal distribution of switching behaviour and occupancy.

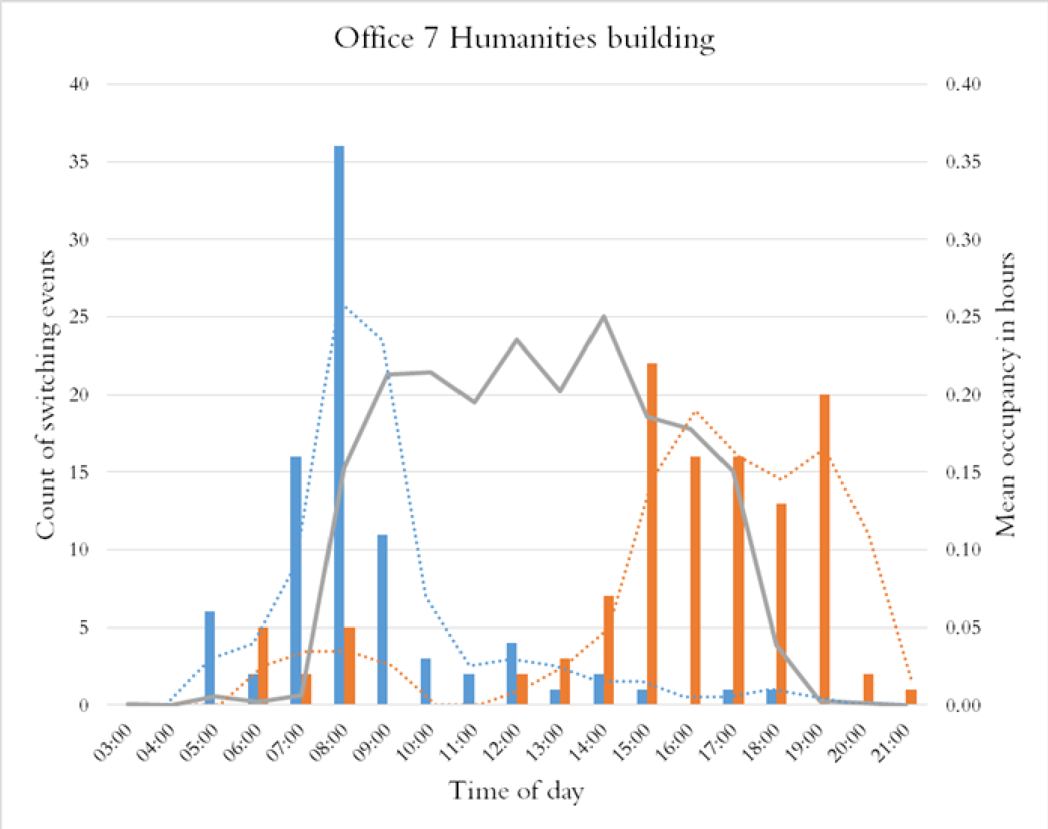
Time of day analysis – Humanities building

Count of switch on
Count of switch off
Mean occupancy in hours
2 per. Mov. Avg. (Count of switch on)
2 per. Mov. Avg. (Count of switch off)









Count of switch on
Count of switch off
Mean occupancy in hours
2 per. Mov. Avg. (Count of switch on)
2 per. Mov. Avg. (Count of switch off)

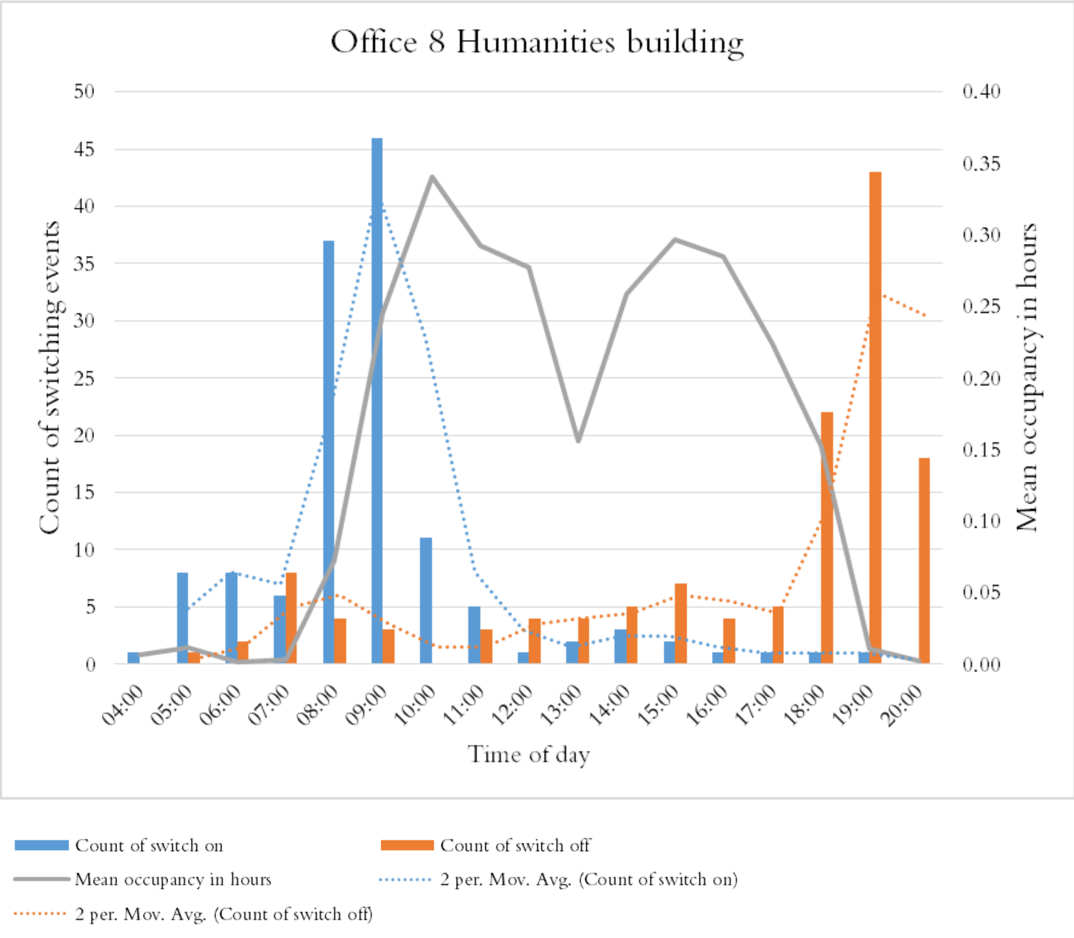
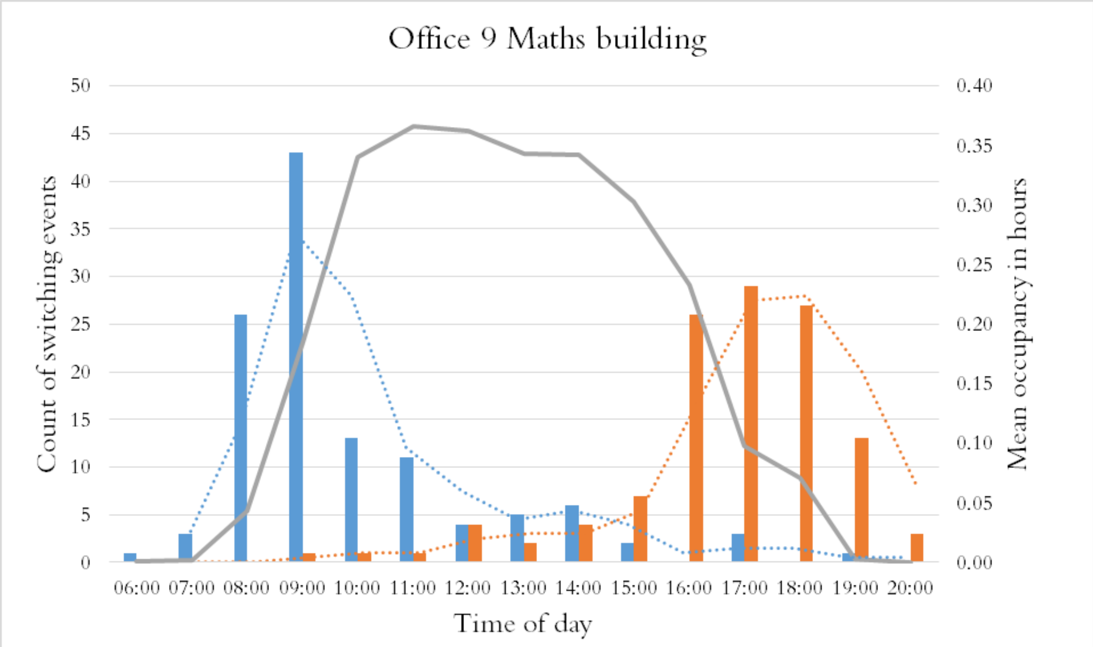


Figure 30 Plots of 5 time of day of light switch on and off with mean occupancy in Humanities offices

The 5 plots shown in **Error! Reference source not found.** again reveal very different combinations of light switching on and off patterns with occupancy behaviours against time of day. The office occupant in Office 4 has bimodal switch on and bimodal switch off patterns of behaviour. Office 5 has unimodal switch on and bimodal switch off, Office 6 is similar however the switch off times are separated into three peaks of switch off periods. Offices 7 and 8 reveal unimodal switch on and switch off patterns. It appears the occupant of office 7 remains in their office during the lunch period in contrast to the occupant in Office 8 where a dip in occupancy at 1300 hours is noticeable.

Time of day analysis – Maths building



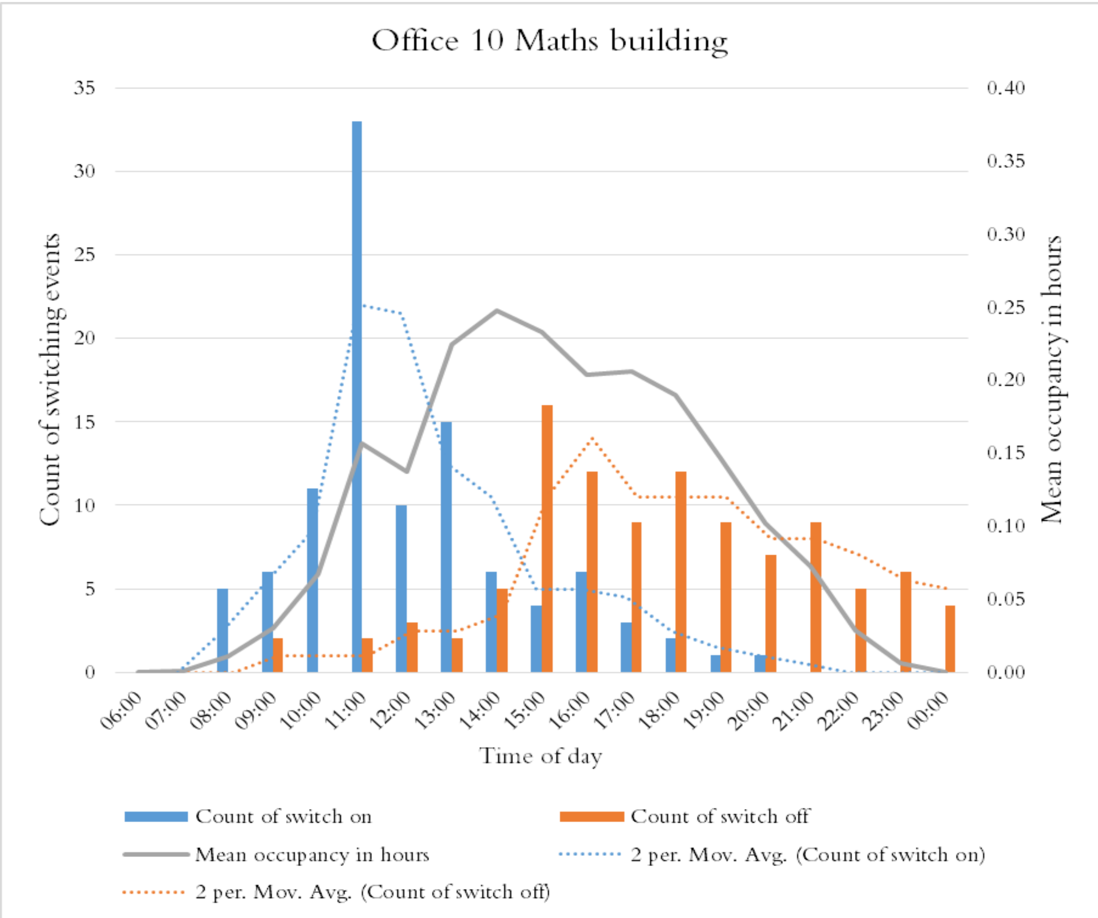


Figure 31 Plots of 2 time of day of light switch on and off with mean occupancy in Maths offices

The 2 plots shown in Figure 31 reveal two similar combinations of light switching on and off patterns with occupancy behaviours against time of day. The office occupant in Office 9 has unimodal switch on and unimodal switch off patterns of behaviour. Office 10 has the same unimodal switching however the time of day the switch off happens peaks at 16:00 hours. The time of day and length of occupancy is different when the two Maths offices are compared with Office 10 occupant having a longer day with less intensive occupancy.

To summarise the time of day findings it is apparent from the observed data points that two groups exist. One group of active users (the bi and tri modal switching patterns) and a separate group of passive users (the unimodal patterns), this is consistent with previous light switching behaviour research (Reinhart, 2004). However the time of day switching pattern findings are being affected by the cleaners entering some of the offices very early on in the day. This is nevertheless a real environment in field and is not based on laboratory findings. The cleaners need light to see for their work and are legitimately using the switches, ditto when another staff member drops off post, say an administrator with access when the office occupant is out. The occupancy findings according to the time of day follow two patterns, the first is an intensive day with little vacancy from the office, the second is a longer day with less intensive periods of occupancy where dips are seen which could coincide with more breaks from the working environment or teaching patterns. The office lights on and occupancy data set was further explored for external factors, such as building and size of office to identify if these were influencing the lighting hours of use and occupancy hours. The size of office could be linked to restrictions on the design criteria for the lighting in these spaces. Designers are likely to select identically sized luminaires (and bulbs) across multiple size offices in one building or upgrade, it is simply the number of fittings that are installed that will vary. At the same rate the number of windows available in each office varies widely too and both were factors out of the control and scope of our study.

4.4.6 Offices: External factors

First, the dataset was rationalised to find the waste and waste=occupancy-lights on hours used was to define this variable:

$$\text{waste} = \text{occupancy} - \text{lights on hours}$$

Equation 1 Waste equation

A negative indicates waste, a positive number indicates a saving.

Wasted lighting is defined as lights on when the office is vacant. A saving is made when the office occupant is present and the lights are off. A second data transformation was performed in the form of removing excess zeros, which have previously been identified as causing issues with summary statistics. Here when lights on = 0, occupancy = 0 and waste = 0, this data point across all variables has been removed and was separately renamed the 'unoccupied hours dataset'. However for example when the lights on = 3 (hours), occupancy = 3 (hours), waste = 0 hours, this data point for each variable has been retained.

The external factors such as building, size of office and orientation will be considered separately and displayed as dot violin plots with summary statistics. Dot violin plots show the details as described in the boxplot example in

Figure 22, however the advantage of dot violin plots is that they explicitly show the distribution of the data. Following the individual plots of external factors a multilevel regression model will be applied to the waste dataset.

Building

The results of the exploratory data analysis for each office revealed that there could be large differences between the buildings as an external factor. The patterns of use, culture and working practices of the occupants in each building are likely to be different. Dot violin plots for the lights on hours by building are shown in Figure 32 and daily occupancy hours by building in

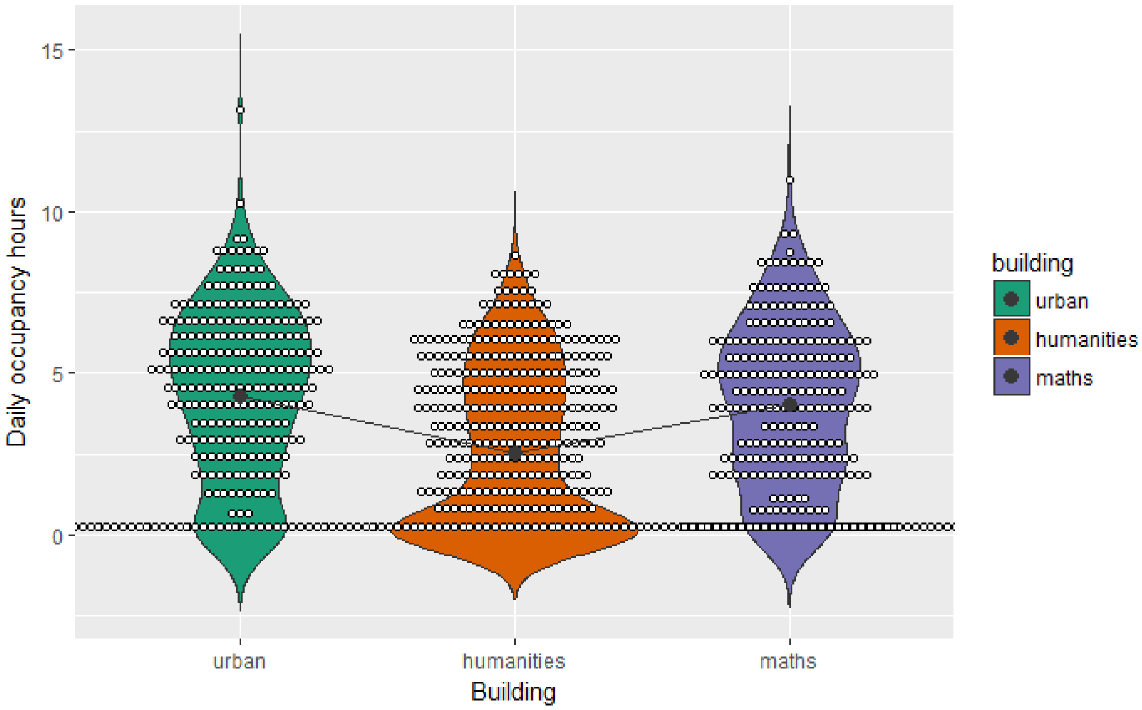


Figure 33. The two separate plots reveal different patterns of daily lighting hours of use and occupancy hours, the mean and standard deviations are outlined in Table 9. The humanities building offices in the study use the most light and yet these are the least occupied offices. In contrast to the urban building where the highest occupancy is found with a daily mean of 4.27 hours per day and mean daily lights on of just 1.65 hours. The maths building has a closer relationship between mean daily lights on hours and occupancy.

Building	Mean of daily lights on hours	Mean daily occupancy hours	StdDev of lights on hours	StdDev of occupancy hours	Number of data points

urban	1.65	4.27	3.00	2.65	264
humanities	5.34	2.52	3.66	2.46	447
maths	4.93	4.02	3.50	2.50	235

Table 9 Mean daily lights on and occupancy by building

The R code and functions to produce the dot violin plot was:

```
waste1 <-read.csv('wastedailyofficescsv.csv',header=T)
waste1 <- na.omit(waste1)
waste1$office <- factor(waste1$office,levels(waste1$office)[c(1,3:10,2)]
)
p <-ggplot(waste1, aes(x=building,y=lightson, fill=building))
p  + geom_violin(trim=FALSE) + scale_fill_manual(values=c("#1b9e77", "#d
95f02", "#7570b3")) + scale_x_discrete(name ="Building") + scale_y_conti
nuous (name="Daily lights on hours")  + geom_dotplot(binaxis='y', stackd
ir='center', dotsize=.5, fill="white", position=position_dodge(1), binwi
dth = .5) + stat_summary(fun.y=mean, geom="point", shape=16, size=3, col
or="grey22")+ stat_summary(aes(y = lightson,group=1), fun.y=mean, colour
="grey22", geom="line",group=1)
```

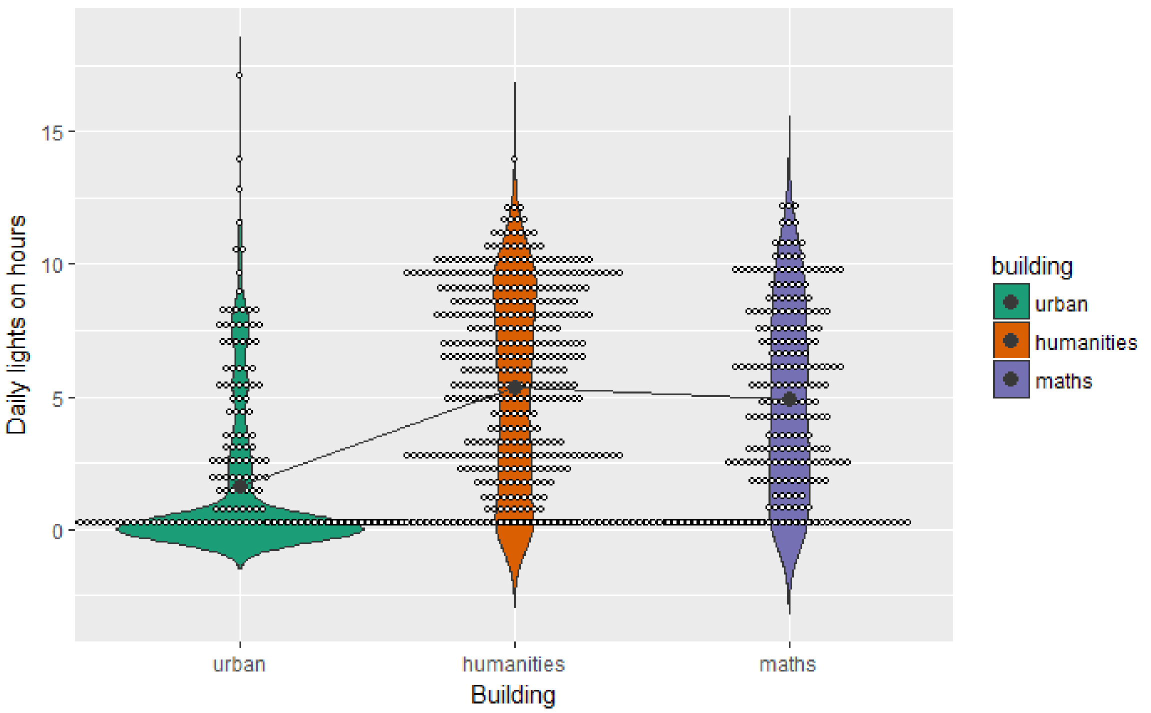


Figure 32 Daily lights on hours by building

Linear fixed effect models were utilised using building as an independent variable and office as a random effect. The equation to model the outcome of daily lights on hours being predicted by building, using office as a random effect on the dataset where the zero inflated data was removed, the data now comprises 946 observations: model1 ← lme(lightson ~building, random=~1|office, data=waste1). The lme function was used from the nlme package as it allows for nested random effects and the within-group errors are allowed to be correlated or have unequal variances (Pinheiro and

Bates, no date). The data collected for each building were of unequal variance and therefore this was deemed the most appropriate model to use. The results are shown in Table 10.

```
Fixed effects: lightson ~ building
                   Value Std.Error  DF   t-value p-value
 (Intercept)    4.977520 0.8209746 936  6.062940  0.0000
 buildingmaths -0.017828 1.5305988   7 -0.011648  0.9910
 buildingurban -3.324379 1.3401987   7 -2.480512  0.0422
```

Table 10 Linear mixed effects model of daily lights on by building

There is a good relationship between the building and lights on, the standard errors are within the expected range for describing the relationship between the individual observations and population mean. The intercept in Table 10 is for the humanities building (alphabetically first) and this is compared to the maths and then humanities is compared to the urban building. There is a statistically significantly difference in daily lights on hours of use when the humanities [value 4.978] and urban buildings [value 4.978– 3.324= 1.654] are compared with a p-value of 0.0422, the urban building uses less lighting, circled in red in Table 10.

```
Fixed effects: lightson ~ building
                               Value Std.Error  DF   t-value p-value
(Intercept)                 3.863451 0.6204717 936  6.226635  0.0000
buildingmaths-humanities   -0.017828 1.5305988   7 -0.011648  0.9910
buildingurban-maths        -3.306550 1.6705887   7 -1.979272  0.0883
```

Table 11 Linear model contrast analysis to compare urban and maths in daily lights on hours

The contrasting model was run to identify if there was a difference between the urban and maths buildings however this was not significant [buildingurban-maths: p-value 0.0883], Table 11.

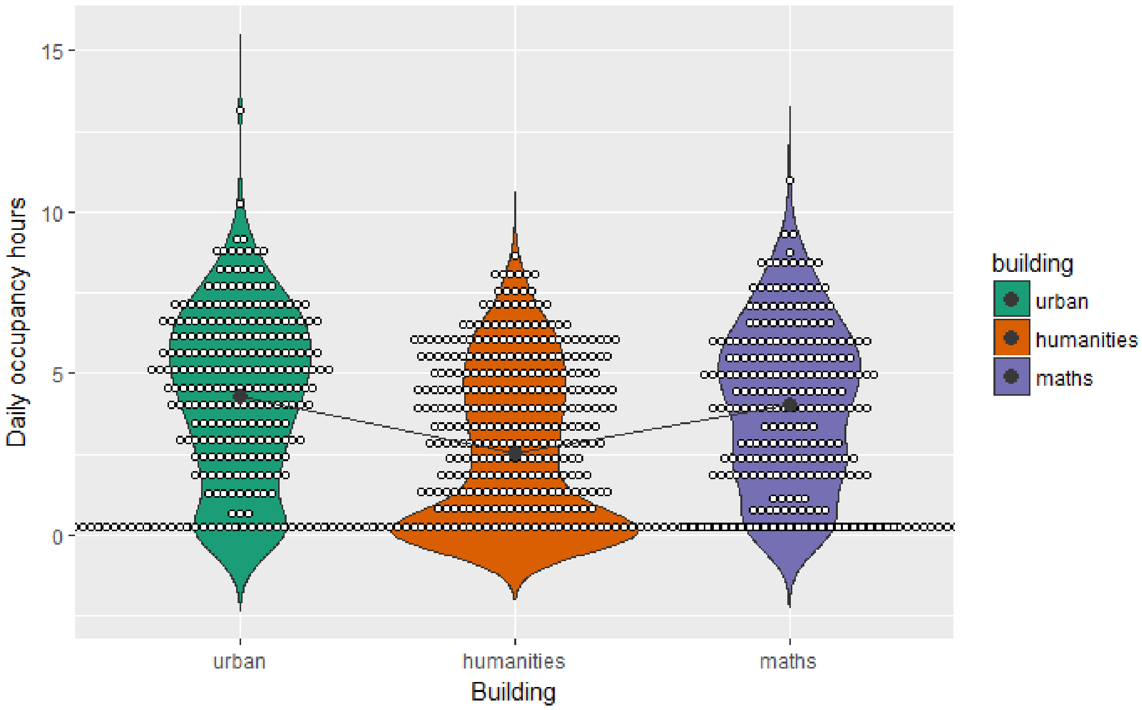


Figure 33 Daily occupancy hours by building

The identical model was carried out for the occupancy by building, as shown in

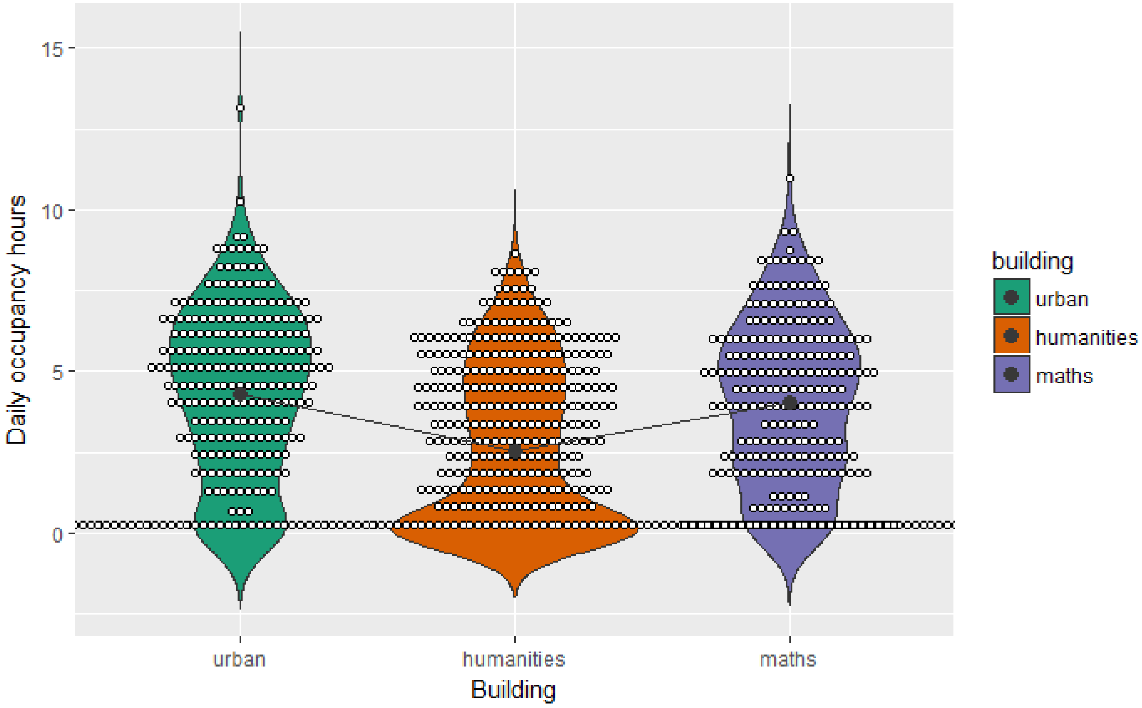


Figure 33, again using contrasting analysis to compare the buildings that were not compared in the initial model.

```
Fixed effects: occ ~ building
                 Value Std.Error  DF  t-value p-value
(Intercept)   2.310530 0.4762754 936 4.851248  0.0000
buildingmaths 1.725973 0.8857621   7 1.948574  0.0924
buildingurban 1.924467 0.7773262   7 2.475752  0.0425
```

Table 12 Linear mixed effects model of daily occupancy by building

A statistically significant difference was found when comparing the humanities and urban building, p-value 0.0425, Table 12, the urban building has a greater daily occupancy humanities [value 2.31 hours] urban [value of humanities 2.31+ urban 1.93=4.24 hours per day]. No significant difference was found between the urban and maths building when contrast modelling was applied.

Size of office

The size of office was another external factor considered in the analysis of lights on and occupancy patterns. The means and standard deviation of daily lights on and occupancy are shown in Table 13.

Size of office	Mean of daily lights on hours	Mean daily occupancy hours	StdDev of lights on hours	StdDev of occupancy hours	Number of data points
small	5.59	3.05	3.51	2.53	406
medium	2.97	4.33	3.70	2.51	378
large	3.63	2.02	3.57	2.48	162

Table 13 Mean daily lights on and occupancy by size of office

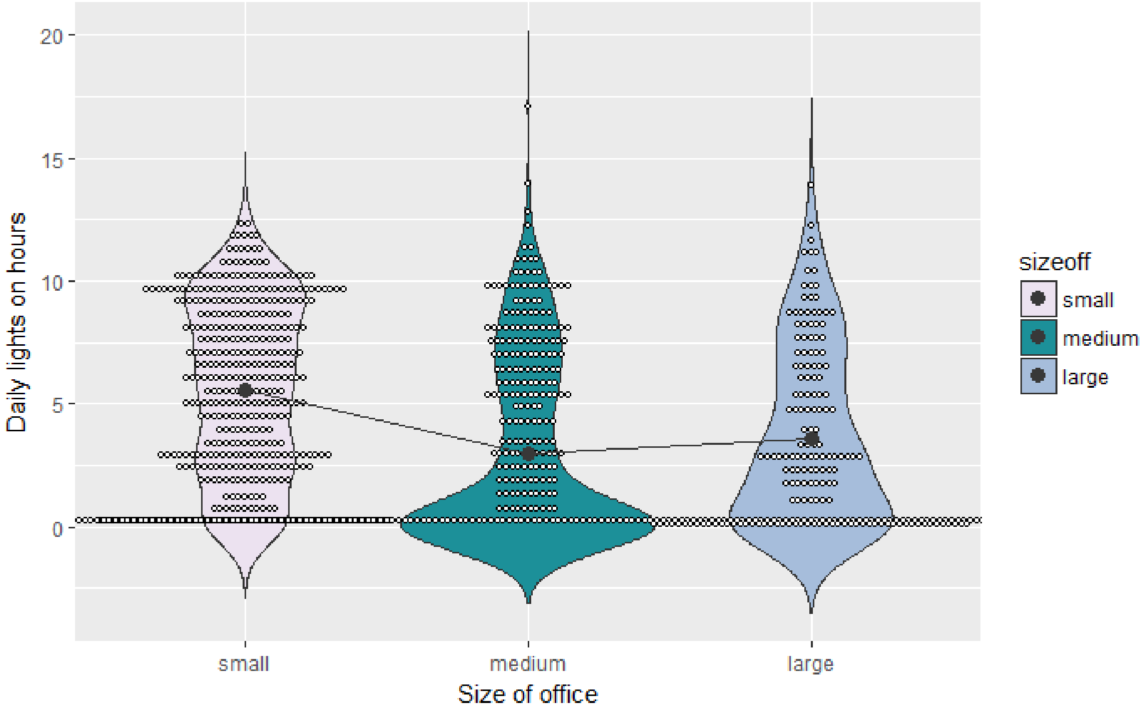


Figure 34 Daily lights on hours by size of office

The daily lights on hours were plotted for the three different sizes of office defined in Table 4. A linear fixed effect models was utilised using size of office as an independent variable and office as a random effect. The results of the model are shown in Table 14 compare each size against the large category again as the model reviews each in alphabetical order. No significant differences were found in this model or the contrasting model comparing small and medium sized offices for daily lights on hours.

```
Fixed effects: lightson ~ sizeoff
                  Value Std.Error  DF    t-value p-value
(Intercept)    3.513007  1.509697 936  2.3269606  0.0202
sizeoffmedium -0.759482  1.847957   7 -0.4109846  0.6934
sizeoffsmall   1.915721  1.847887   7  1.0367092  0.3344
```

Table 14 Linear mixed effects model of daily lights on by size of office

The size of office category on the dependent variable, daily occupancy hours, was modelled in Table 15 and is shown with dot violin plots in Figure 35.

```
Fixed effects: occ ~ sizeoff
                  Value Std.Error  DF   t-value p-value
(Intercept)   1.9662164 0.7591280 936 2.5900988  0.0097
sizeoffmedium 2.3257594 0.9285397   7 2.5047495  0.0407
sizeoffsmall  0.8444508 0.9284396   7 0.9095377  0.3933
```

Table 15 Linear mixed effects model of daily occupancy by size of office

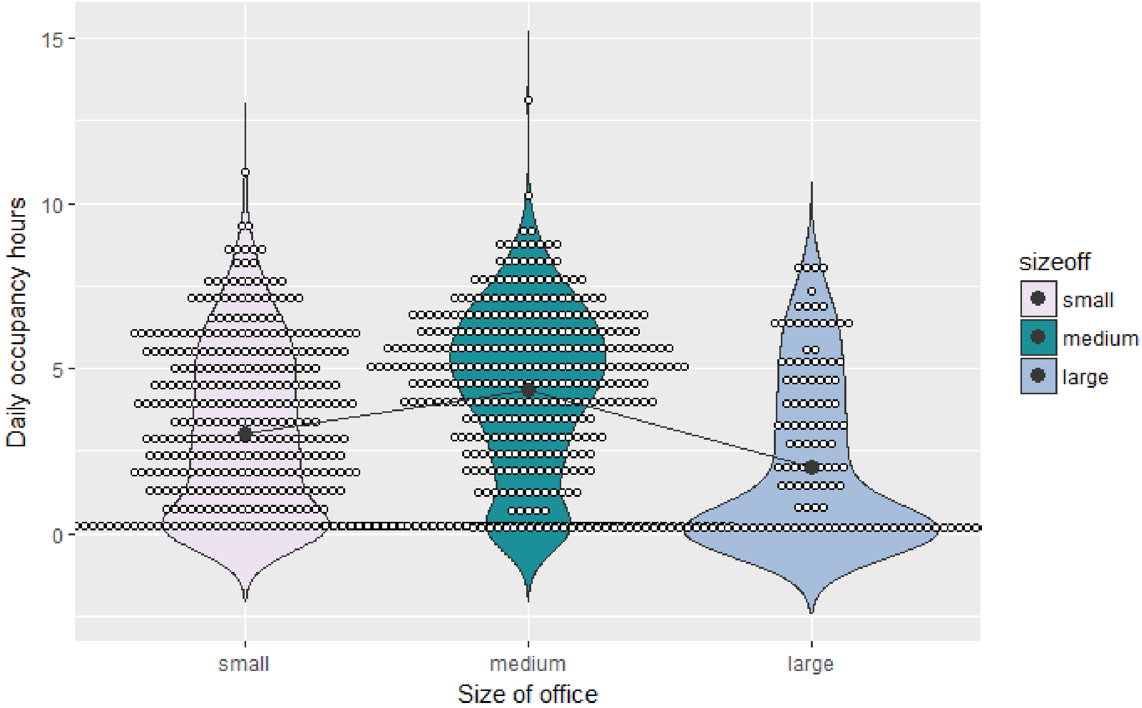


Figure 35 Daily occupancy hours by size of office

The results in Table 15 show a statistically significant difference, circled red, p-value 0.0407 in the daily lights on hours between the large category of office over 20m^2 and the medium category 15-19.99m^2. No significant difference was found between small and medium sized offices for occupancy.

Orientation

The external factor of orientation was considered, graphed and modelled however there was no significant difference in daily lights on hours or occupancy hours between the north and south orientations of the offices in the study.

Seasons

The seasons were considered as another external factor, however the majority of the data points were collected in the period November – June with some extending into the summer period after 1 June. The lighting waste (defined in Equation 1) was plotted against season, as shown in Figure 36, the differences should be treated with caution due to the limited data points in summer as indicated by the number of dots (individual data points).

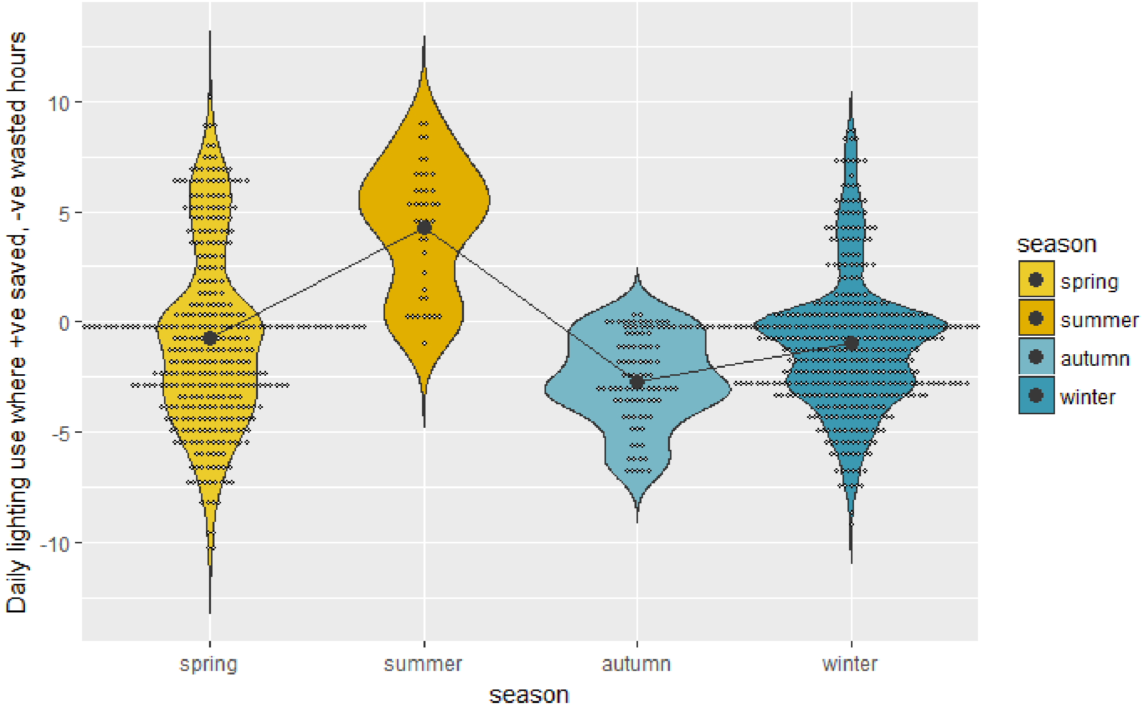


Figure 36 Daily lighting use plotted against season

Daylight

The final external factor to be considered was daylight hours. The daylight hours per day for Reading were taken from metrological data for each day, month and year and cross referenced to the relevant data point for each day and each office in the study. The daylight hours per day were plotted for each of the individual offices against their efficient lighting use where – negative indicates waste and positive indicates a saving – in daily lights on hours, as shown in Figure 37.

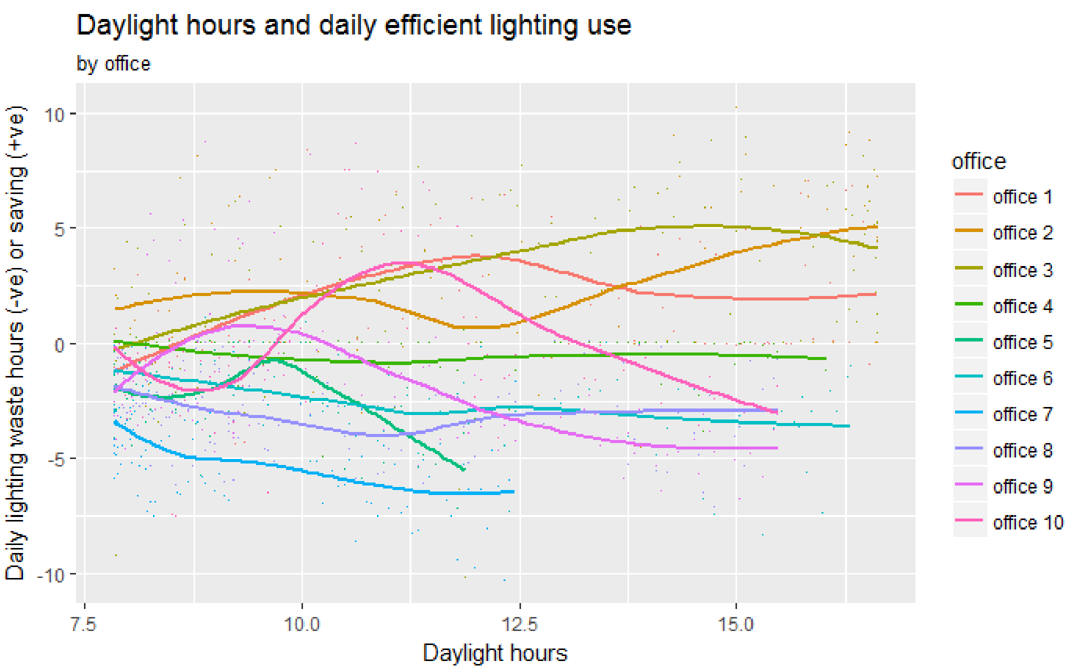


Figure 37 Daylight hours and daily efficient lighting use

4.4.7 Conclusions

The office waste avoidance study aimed to explore two objectives, the first, objective 2 to discover any interesting patterns of lighting on use and occupancy in offices. The findings from the data collected indicate a wide variety of patterns in both daily and weekly lighting hours and daily and weekly occupancy in the study offices. Differences between buildings lights on hours did not follow a distinct pattern, it appears that in the study conducted that each individual office occupant has a unique profile of lighting and occupancy. The scatterplots of individual offices showed how lights on related to occupancy, the gentler the gradient the more energy conscious the occupant, conversely the steeper the gradient the more energy wasteful the occupant. Time of day analysis supported the idea of very distinct patterns for each office with unimodal and bimodal patterns displayed. The time of day occupancy, length of daily occupancy and intensity of occupancy was again individual. To summarise the individual office study, the findings from this data suggest that it would be very difficult to apply a one size fits all model or even a passive and active user based model (Reinhart, 2004) to single occupancy offices. Simplifying the lights on and occupancy hours into a single aggregated number would not explain how the office is lit or occupied in practice.

Objective 4 was to look at external factors to see if they influenced lighting, occupancy and wasted lighting. This section used the condensed dataset where zero-inflated data was removed. The external factors reviewed lights on and occupancy by building, size of office, season and daylight hours of natural light. The results of linear mixed effects model revealed some significant findings where both building and size of office were influencing the dependent variables studied. In the context of the industry sponsor these new findings could lead to targeted behaviour change or rethinking existing strategies relating to size of office and lighting provision. Many of the School of the Built Environment participants in Chapter 3 (user experiences main study interviews) explained how they preferred to use their own lighting in the form of desk lamps or uplighters, it is therefore not surprising that the quantitative studies corroborate this idea, the participants. It should be noted that the participants were different in each study. Differences in season and lighting efficiency (waste or savings) were identified and it is not surprising that lights were used less during the summer period. The limitations of the data for this season were acknowledge, these findings should therefore be treated with caution. Finally natural daylight hours were reviewed for each office against their lighting efficient behaviours. The interesting finding from this external factor was that savings did not go up as daylight hours increased, again a unique pattern emerged for each individual office.

4.5 Classrooms

In 2014, lighting comprised 18% of all UK electricity use and consumed 58,000 TWh per year (Lighting Industry Association, 2014). Having recognised the need for verification and evolving improvement of building systems the 'European Committee for Standardization Technical Body CEN/TC 169 – Light and Lighting' is updating their documentation to include the 'Lighting Design Process' (LightingEurope, 2017). Of five stages within the 'Lighting Design Process', Stage 4 "Verification of the 'Lighting Design Process'" is key to the credibility of any business case to support lighting upgrades (Lighting Industry Association, 2014). As an example of the importance of lighting upgrades for overall energy consumption, in a school environment luminaires have a typical life expectancy of 11 years and a lighting capital expenditure (CAPEX) of £106/m^2 over a 30 year life for the building, compared to £66/m^2 for heating and £59/m^2 for ventilation (Karbasi, Marsh and Pitman, 2016). Importantly for Higher Education, the UK Government and Higher Education Funding Council for England (HEFCE) links English University funding to their Carbon Management Plan targets. This demonstrates the potential scale of energy, and financial, savings but predetermining when a lighting upgrade is necessary to make such savings, and what savings might be expected *a priori* remains an issue.

4.5.1 Performance Gap

The literature review defined and explained the performance gap. It is a measure of the difference between design assumptions and actual in field data. The performance gap, is dominated by studies that review newly constructed buildings rather than existing buildings. This current study aims to contribute to this growing area of research by exploring consultants' predictions of energy savings used in financing and supporting these projects prior to installation. It does so by calculating and assessing how retrofit upgrades to luminaires and controls in classroom areas perform in practice. This study focuses on classroom areas and provides further empirical evidence to the already established field of classroom lighting (Ramasoot and Fotios, 2008, 2009; Goven *et al.*, 2010; Drosou, Mardaljevic and Haines, 2015; Drosou *et al.*, 2016; Gentile, Goven and Laike, 2016) detailing the hours lighting in classrooms is switched on, compared to occupancy and room bookings. Calculating the lighting demand in existing buildings in the UK is a requirement of designers when retrofit works are undertaken to upgrade older systems (HM Government, 2010) but in the absence of in field data the predicted consumption of lighting is often based on prediction and model simulation. This section compares in field measurements against design assumptions to measure the performance gap.

4.5.2 Industry guidance

In the commercial sector the CIBSE 'Guidance TM22 Energy assessment and reporting method' is widely used in the UK to assess four (occupied) building types: offices, hotels, banks and agencies, and mixed use industrial, but there is no specific guidance for University buildings (CIBSE, 2006). The International Performance Measuring and Verification Protocol (IPMVP) method is adopted predominately in the United States (Borgstein, Lamberts and Hensen, 2016). Other benchmarking tools exist and in the UK the 'Carbon Buzz' project is a collaborative and anonymous database of each sector's actual energy use in relation to initial design predictions (CIBSE, RIBA and BRE, 2017). As a sector the performance gap in university buildings was calculated to be 85% for electricity consumption (kWh/m^2/year) when comparing the predicted energy use against actual energy use in practice through the 'Carbon Buzz' project (Menezes *et al.*, 2011). The Lighting Guide 5: Lighting for education acknowledges that there are two major factors for energy efficient lighting – the power consumption of the lighting and the hours it is used (CIBSE, 2011).

4.5.3 Objectives

A. to explore the predictions and assumptions by inputting the actual values of hours of operation into the carbon and power consumption calculations; and
B. to measure the performance gap of lighting in classroom environments
C. to identify interesting patterns of lighting use

4.5.4 Methods and buildings

The CIBSE TM22 method includes in Appendix A8 an Energy Tree Diagram, which is used as the basis for this study's assessment of lighting in thirteen classrooms in three university buildings. CO_2e saving predictions for calculating lighting installation energy over time, which includes parasitic load and controls, widely use the 'lighting energy numeric indicator' (LENI) measured in units kWh/m^2 per annum (HM Government, 2010; The Society of Light and Lighting, 2016). The carbon savings predictions that form the basis of this performance gap assessment for classroom lighting, are calculated using Equation 2.

$$\text{Annual operating hours} \times \text{Load factor x Predicted power consumption} =$$

$$\text{Total predicted power consumption per annum x } CO_2 \text{ conversion factor} = CO_2 \text{ per annum}$$

Equation 2 Adapted LENI and CO2 equation

Annual operating hours is the total hours of use (h), *Load factor* is a co-efficient based on industry assumptions (usually between 1 and 0.5), *Predicted power consumption* is the estimated power of luminaires, ballasts and parasitic load (kW), *CO_2 conversion factor* is the sum of generation (Scope 2) and transmission and distribution (Scope 3) factors, for example in 2016 respectively: 0.41205 + 0.03727 = 0.44932 kg CO_2e /kWh, and is extracted from published UK Government Greenhouse Gas Reporting Conversion Factors for the appropriate year of the project (Department of Energy and Climate Change, 2011b).

Equation 2 is extracted and adapted from the external consultants calculations used in these classroom lighting upgrade projects, they are based on the Carbon Trust formulae for calculating the business cases for retrofit projects (Carbon Trust, 2012). The designs and calculations used in these projects were carried out in 2012 and 2013, since then the LENI calculation has been further refined, nonetheless the original calculation is used for comparison purposes. For lighting projects Equation 2 includes two predicted terms: operational hours and power consumption and one predicted co-efficient: load factor. As these predictions are multiplied any error in the terms and co-efficient will skew the estimate of predicted energy consumption overall.

Buildings and CO_2 project data

The three buildings in this study were selected as they were identified as part of the university's carbon management plan and long term real estate strategy. Three areas of data collection will be identified as Humanities 1 (1st floor), Urban 2 (2nd floor), and Maths 1 (1st floor). Of the three buildings only Urban had the classrooms upgraded in 2013, the Humanities was costed and calculated but never carried out and Maths had upgrades completed by 2013 but excluded the classrooms. All classrooms are centrally bookable by any school, department, or society group and are accessible to all staff and students during the periods when the buildings are open. The classrooms have changing bookings which vary widely and are not solely occupied by one school or department but can be centrally booked by any group booking. The energy efficiency predictions for electricity consumption and reduction in CO_2 equivalent emissions for the three buildings are detailed in Table 16. These are the predictions as calculated from the individual projects.

	Location	Year	Annual operating hours	Load factor	Total predicted power – luminaires	Total predicted power consumption per annum	CO_2e conversion factor	CO_2e per annum
			(h)	(multiplier)	(kW)	(kWh)	(multiplier)	(tonnes)
Urban 2nd floor– Upgrade carried out 2013								
Estimate before	Current (2012)	2012	2394	1	27.93	66,867	0.0005246	35.1
Estimate after	T5 & absence & daylight sensors	2013	2100	0.7	8.7626	12,881	0.0005246	6.8
Predicted savings			*294*		*19.17*	*53,986*		*28.3*
Humanities 1st floor – Upgrade costed in 2012 but not carried out								
Estimate before	Current (2012)	2012	1680	1	14.66	24629	0.0005246	12.9
Estimate after	T5 & daylight sensors	2013	1680	0.7	6.08	7150	0.0005246	3.8
Predicted savings			*no change*		*8.58*	*17,479*		*9.2*
Maths 1st floor – Upgrade completed in 2013 but excluded classrooms								

Table 16 Power consumption predictions for classrooms in each building

4.5.5 Data collection

In each classroom monitoring area an environmental logger was installed at 1.5 metres from finished floor level on the vertical wall, as the students would mostly be sat down when the room was occupied. The HOBO™ UX90-005 occupancy/lights on (Passive Infra-Red (PIR) detector 5 metres), or UX90-006 occupancy/lights on logger (PIR detector 6 metres) was installed and this logger also recorded lights on/off with a photocell. The occupancy/lights on logger was configured to log occupancy events and return the light state every 1 minute as on or off. The photocell in the UX90-005/006 occupancy/lights on logger is triggered by the illuminance levels and can be calibrated on set up and at each data download with the lights on. The occupancy/lights on loggers cannot differentiate between daylight and artificial light, so data can be recorded as lights on when daylight reaches this threshold of toggling it on/off. To prevent this from happening the logger was placed in an area away from direct sunlight. The data were collected for six months and the data extrapolated for the full year as the university buildings are in constant use even in the summer months when several summer schools take place.

4.5.6 Results

Urban building – Measured lights on less than predicted

Six classrooms in the Urban building were studied on the 2nd floor and are shown in Figure 38. Median measured lights on hours was 1809 per annum (p.a.), median measured occupancy hours 746.9 (p.a.), median booking hours 1365 (p.a.). The predictions used 2100 operational hours (p.a.), based on these findings this represents a performance gap of -14%, when the measured lights on hours are used, the lighting is used for less time than predicted.

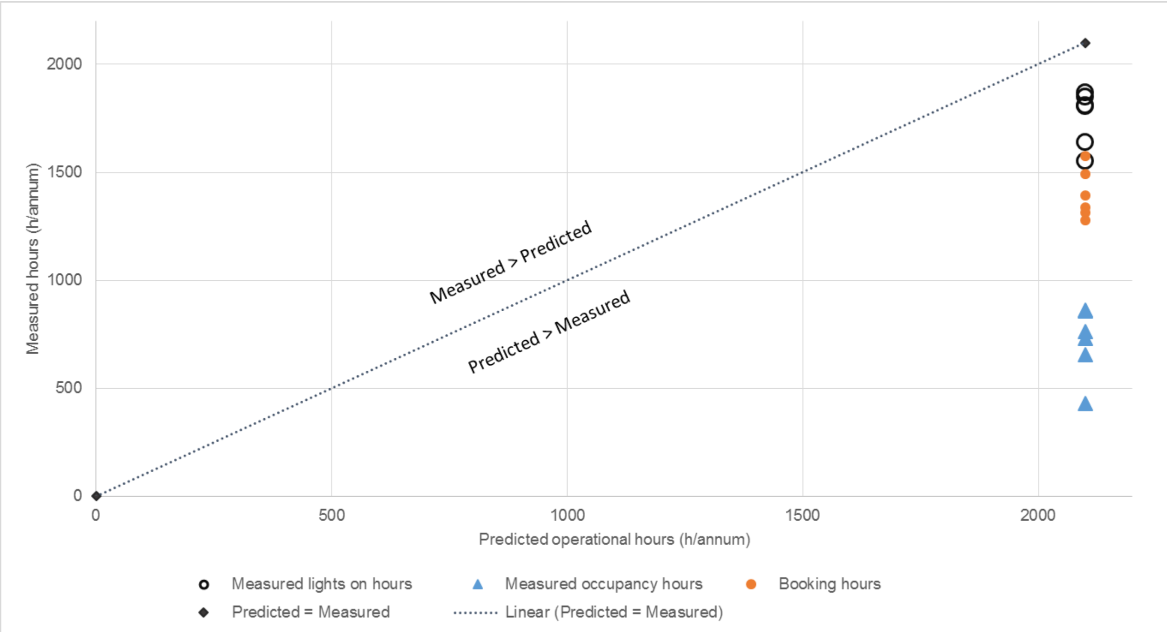


Figure 38 Predicted (2100 hours pa) and measured (hours pa) in the Urban Building

The predicted annual CO_2e and power consumption is compared to the measured values using the before and after process in Table 16. The measured savings are 3% more than predicted, these findings are conflicting with CarbonBuzz data for other University buildings where increased power consumption is the norm (van Dronkelaar *et al.*, 2016). These data indicate that the Urban building CO_2e and power consumption was calculated using overestimates of operating hours after the upgrade. Inputting the measured lights on hours into the original calculation for the after scenario, this project has saved more annual power, 1785kWh (p.a.), and annual CO_2e emissions, $1tCO_2e$ (p.a.), than originally predicted.

The patterns of lighting use as shown in Figure 39 indicate the lights being left on when the classroom is not in use and unoccupied, this pattern of behaviour is well established and acknowledged in industry literature (CIBSE, 2011) and the results here corroborate that position. There was a single classroom (north 3) where the measured lights on hours and booking hours were almost identical, although nobody was 'using' the room for the many hours it remained unoccupied with the lights on.

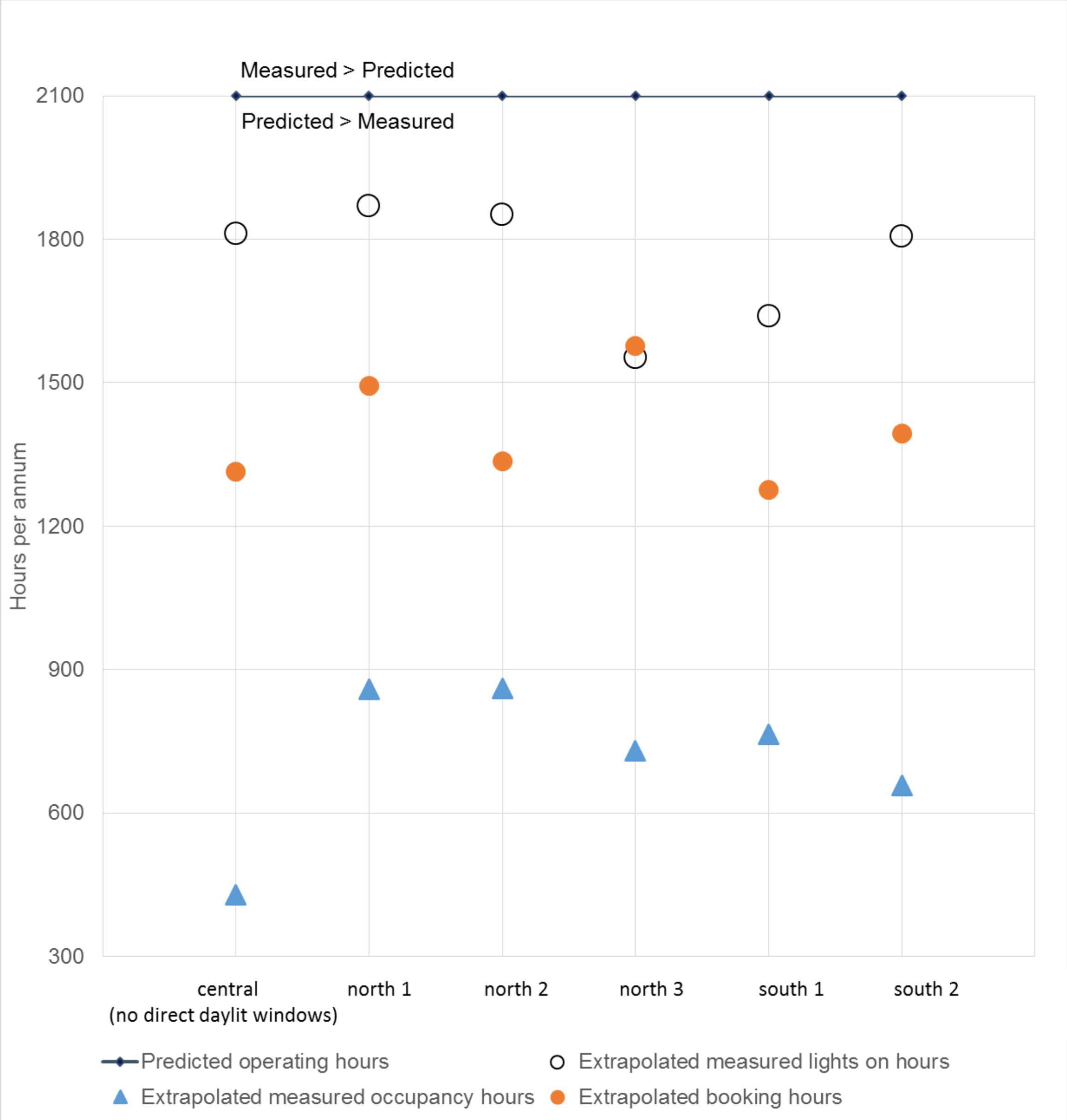


Figure 39 Patterns of lights on, occupancy and booking use hours (per annum) in the Urban building

Humanities building – measured lights on more than predicted

Four classrooms in the Humanities building were studied on the 1st floor and are shown in Figure 40. Median measured lights on hours was 2133 per annum (p.a.), median measured occupancy hours 1394 (p.a.), median booking hours 1629 (p.a.). The predictions used 1680 operational hours (p.a.), based on these findings this represents a performance gap of 27%, when the measured lights on hours are used, the lighting is used for more time than predicted.

The predicted annual CO_2e and power consumption was compared to the measured values using the before and after process in Table 16. The potential savings this measured are 11% less than originally predicted for this lighting upgrade that was appraised but not carried out. In the original assessment of the Humanities building, CO_2e and power consumption were calculated using underestimates of operating hours both before and after in the upgrade calculations. Inputting the measured lights on hours into the original calculation for the after scenario, this project - if it had been carried out, would have consumed more annual power, this would have reduced the savings by 1928kWh (p.a.), and annual CO_2e emissions, by 1tCO_2e (p.a.), than originally predicted.

The patterns of lighting use as shown in Figure 40 indicate the lights being left on when the classroom is not in use and unoccupied, a common finding. The two north facing classrooms both had measured lights on and booking hours (p.a.) that were closely related, and this finding is similar to the pattern of use in the north 3 classroom in the Urban building. Interestingly classroom 4 has more occupancy than bookings in Figure 40.

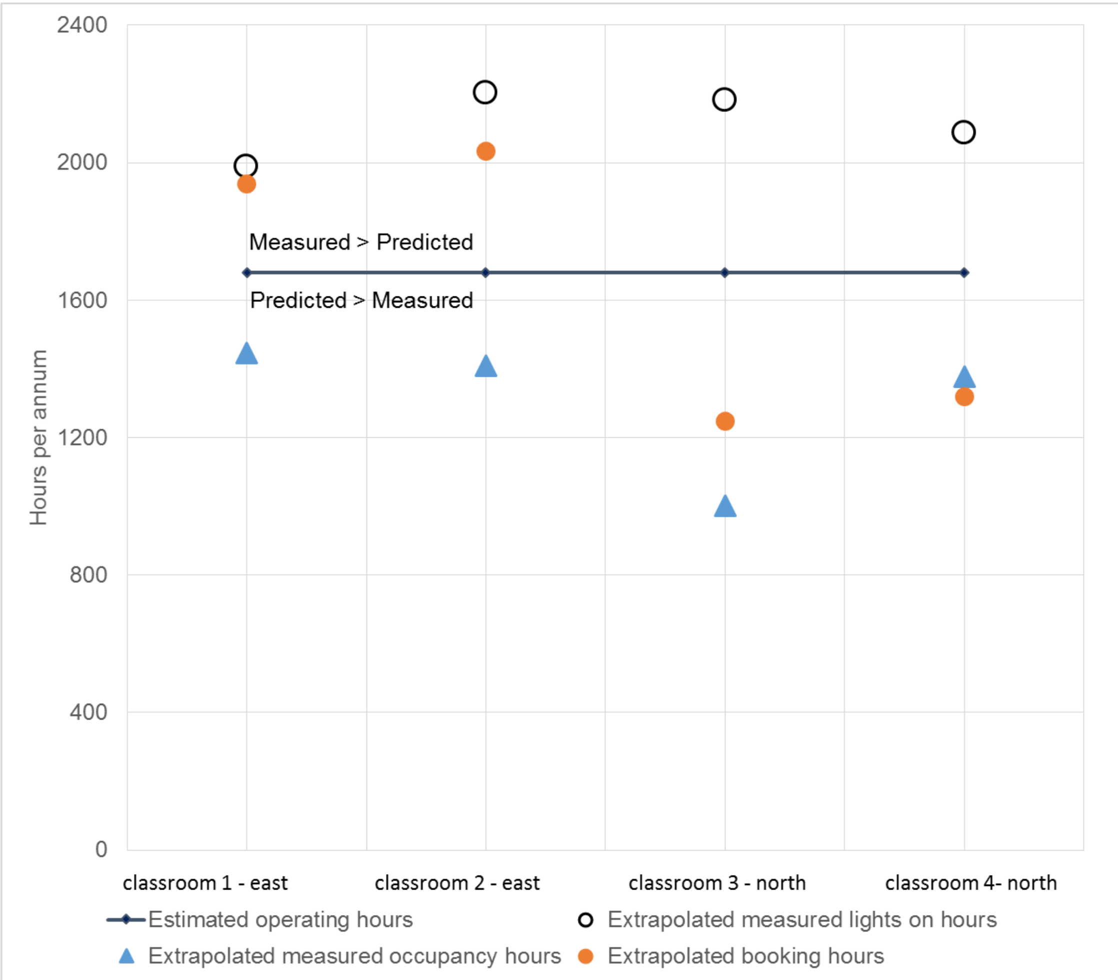


Figure 40 Patterns of lights on, occupancy and booking use hours (per annum) in the Humanities building

4.5.7 Maths building – Occupancy and booking

Despite the Maths building undergoing refurbishment and retrofit upgrades to corridor, office and communal area lighting in 2013 the classroom lighting was excluded from this upgrade project. The impact of piecemeal upgrades on users' experiences at the university has been highlighted elsewhere through qualitative case studies (van Someren, Beaman and Shao, 2017). Three classrooms in the Maths building were studied on the 1st floor and are shown in Figure 41. Median measured lights on hours was 2614 per annum (p.a.), median measured occupancy hours 1003 (p.a.), median booking hours 958 (p.a.). If the Urban building's prediction for 2100 operational hours (p.a.) is used – in the absence of designer's assumptions – as a baseline for comparison, based on these measurements this represents a potential performance gap of 24%, when measured lights on hours are used, the lighting is used for more time than anticipated.

As no CO_2e calculations were drafted for the Maths classrooms for upgrade it is not appropriate to theorise about consequences, however the Maths building does provide interesting patterns of use not found in the other two study buildings. The most surprising aspect of the data in Figure 41 is in the overlap of booking hours and occupancy hours. The patterns of lighting use as shown in Figure 41 indicate the lights being left on when the classroom is not in use and unoccupied, again this is a common finding. This mismatch between occupancy and lights on hours is seen across all three classrooms in this building, there is a clear indication that power savings could potentially be made. However as previously mentioned in the previous method and data collection sections, the environment loggers used in this study were triggered by illuminance levels. Despite every effort to not record daylight by placing the loggers where predominantly artificial light triggered a measurement, we cannot be certain that the lights on hours necessarily always reflect energy waste.

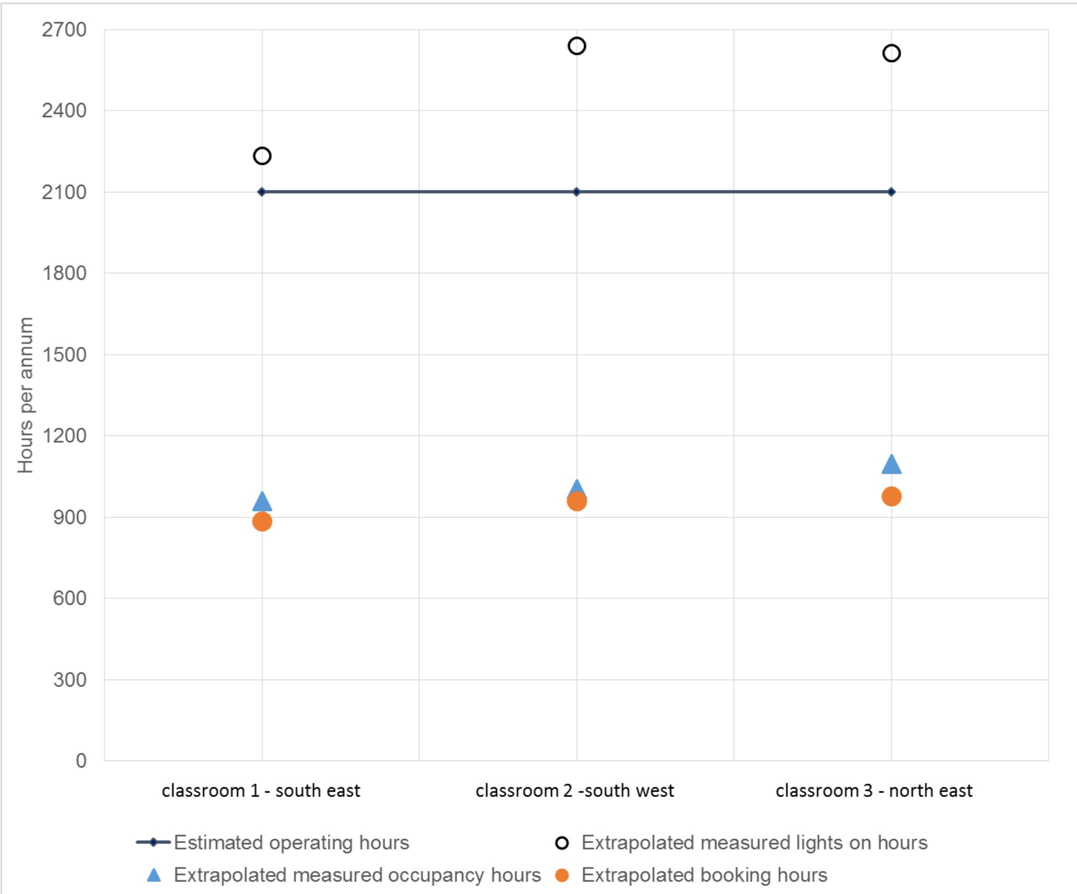


Figure 41 Patterns of lights on, occupancy and booking use hours (per annum) in the Maths building

The patterns in the three Maths classrooms were further investigated and a potential area for minimising waste was considered to be overnight when analysing the data, as this was a distinct time when daylight would not be influencing the measurements. The out of hours lighting use between 19:00 and 06:59 is shown in Figure 42. All three classrooms have wasted lights on hours and this is compared to the measured occupancy during those same periods and linearly extrapolated for the year.

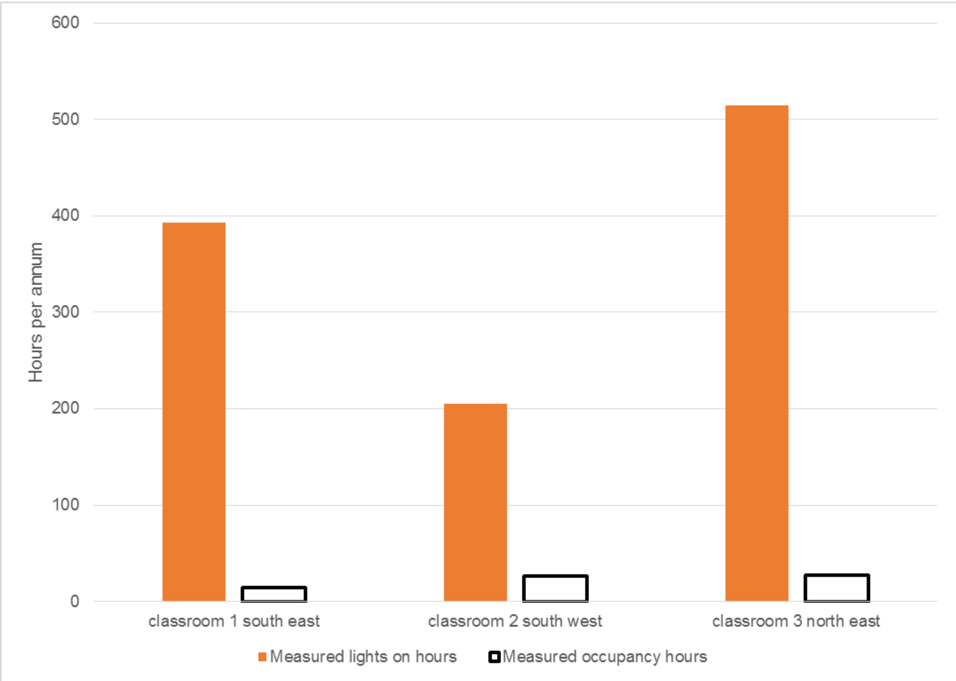


Figure 42 Out of hours (19:00-06:59) Maths building lights on and occupancy hours per annum

Wasted lighting in all classrooms

The final objective was to explore interesting patterns of lighting use. Across all thirteen classrooms studied the trend of wasted lighting use was prevalent, as shown in Figure 43. The dark solid circles indicate lights on, the grey triangles occupancy and waste is identified as being the difference in those two variables. The wasted hours of lighting when the classroom is not occupied but the lights are on totals 13,885 hours for the thirteen classrooms, the equivalent of 1.5 years in hours. Two further interesting patterns occur, the first where lights on (dark solid circle) and booking hours (outlined circle) are similar in 3 classrooms: Urban north 3, Humanities east 1 and Humanities east 2. The proposed reasoning for this is based on observing the porters in these buildings monitoring the communal areas regularly. The second pattern is where occupancy (grey triangle) and booking hours (outlined circle) are similar in 4 classrooms: Humanities north 2 and all three Maths classrooms southeast 1, southwest 1 and northeast 1. This second pattern provides the opportunity to consider other methods of lighting control. It is recommended that classroom lighting controls be based on using campus access cards, much like a hotel room to activate the ability to switch on and off, thereby avoiding waste and maintaining user control.

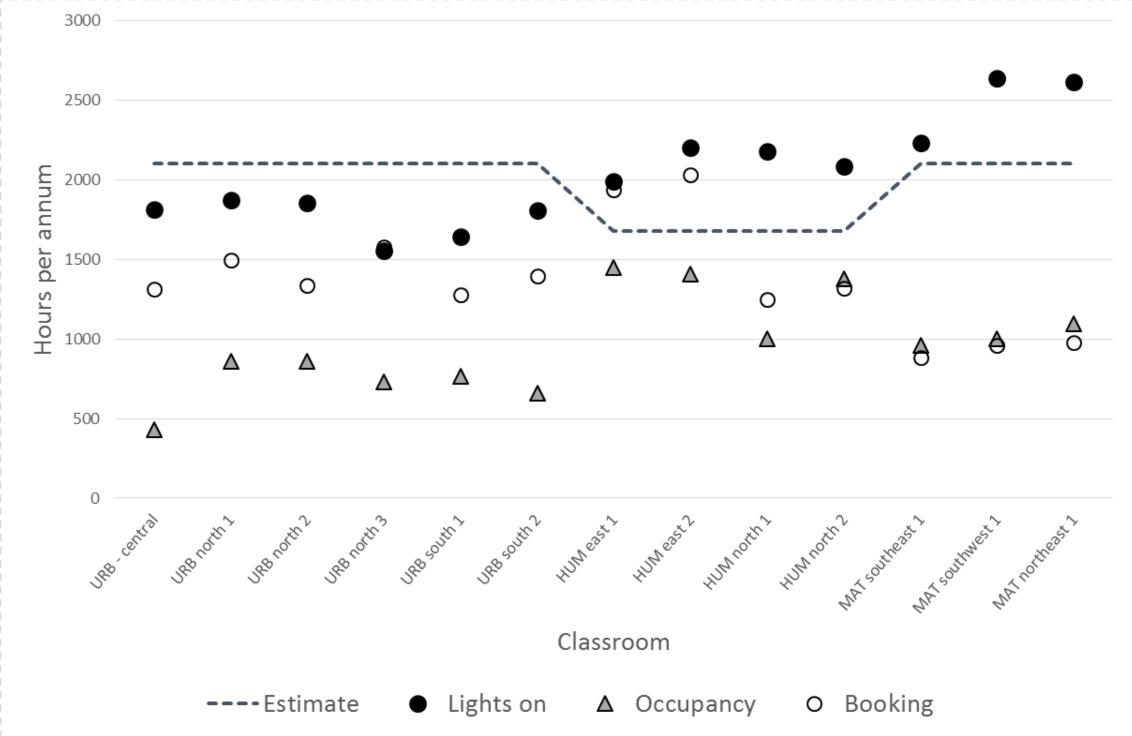


Figure 43 Patterns of lighting, booking and occupancy hours of use per annum

4.5.8 Discussion

Despite the classrooms in the upgraded Urban building being fitted with photocells and absence detection from the measured data it would indicate that these were not performing to their full potential. The LightingEurope (2017) paper which details commissioning, verification and operation and maintenance if carried out in practice has the potential to narrow the gap between lights on hours and occupancy hours. The inputs used in the LENI calculations, Table 16, by the external consultants in these feasibility studies were based on assumptions and best guess estimates, and the unreliability of these methods is congruent with other performance gap research showing that consultant's thermal modelling input assumptions were highly variable (Imam, Coley and Walker, 2017). As we have demonstrated, the estimated operational hours can easily be replaced by actual data collected in practice. The use of widely available environmental loggers provided insightful and practical inputs to calculations that would otherwise be based on assumptions about unknown variables.

Integrating these environmental loggers into common use enables Energy Managers and Project Managers in all sectors to collect field measurements rather than relying on assumptions. Using environmental loggers can provide an additional tool to support decision making in energy efficiency projects. The use of the HOBO™ loggers in lighting applications enables commissioning engineers to reduce the performance gap between the lights on hours of use and occupancy patterns. It is proposed that the closer the lights on hours are to the occupancy hours in these buildings, the greater the savings in annual electricity consumption and carbon dioxide emissions.

4.5.9 Management factor & Load factor

It is worth noting that a significant element of the CIBSE TM22, Energy assessment and reporting method, calculation comes from the management factor which is not explored in depth here and yet which also affects the accuracy of predicted energy savings. This term is understandably ambiguous as each mechanical and electrical service will have different requirements in a building. In lighting terms this encapsulates the additional complexity of commissioning, dimming, daylight, hold on time, contextual elements involving school schedule, types of occupant and operation, times of year and overarching policies on energy management. The load factor in the LENI calculation is not benchmarked or validated by evidence and remains another ambiguous estimation for external consultants and designers, this is often used as a crucial co-efficient for promoting the justification for automated controls over manual lighting controls.

4.5.10 Limitations

The HOBO™ loggers used in this study were agreed for installation with the Building Managers and Energy Manager as they could then be subsequently utilised for other applications. They were relatively low in cost and this justified using them in classroom areas where they were liable to tampering and even theft. However, the loggers are limited in their operation such that the occupancy hours are likely to be more accurate at recording occupancy when occupants are in the direct spatial vicinity of the logger, hence the recorded occupancy hours may underestimate the amount of time the classrooms were occupied. It is for this reason that the actual lights on hours were used as part of the calculations for assessing the performance gap in classroom lighting. The occupancy does however give another separate opportunity to analyse the data for time of day analysis, this would provide insights for other mechanical and electrical systems, such as heating to determine the profiles in term time and out of term periods. The calculations for CO_2e and power consumption estimates relied on the assumption that the sensors would be more efficient at switching off the lights than a manual switch and routine operation by say the security staff member walking around at the end of the day. Since the study was limited to 6 months of data (the loggers were redeployed to other locations) it was not possible to give a full year of data. The extrapolation of six months of data to a full year is also another aggregation that limits the contribution of this study.

4.5.11 Conclusions

This study aimed to explore the predictions and assumptions by inputting the actual values of hours of operation into the carbon and power consumption calculations. Firstly the input parameter for predicted operational hours ≠ occupancy hours ≠ lighting on hours: the terms are not analogous for measured lighting use across the three buildings studied. The impact the hours of use had on carbon and power consumption calculations was not substantial in the two classroom upgrades studied in the Urban and Humanities buildings. Another objective was to measure the performance gap of lighting in classroom environments, for the two buildings with consultant's calculations these were -14% and

27% for the Urban and Humanities buildings, the potential performance gap for Maths classrooms was estimated to be 24% higher. These findings are comparable to CarbonBuzz data in higher education buildings (van Dronkelaar *et al.*, 2016). The final objective of this study was to identify interesting patterns of lighting use. The out of hours lighting use in the Maths building from this retrospective study demonstrated that savings could be found by revisiting the lighting upgrade in the Maths building and potentially using absence controls.

This study provided original empirical evidence on lights on hours, occupancy hours and booking hours in classrooms which was previously unknown and found that neither of these are synonymous with operational hours. These results suggest that there is a valuable distinction between lighting on hours and occupancy hours, a parameter not captured in the current 'Energy assessment and reporting method'. The performance gaps calculated between the original estimates and predictions based on actual measured data are different however this did not materially affect the CO_2e and power consumption savings. As the research into performance gaps has previously found the difference between design estimates and actual performance data can be up to 85% in University buildings (Menezes *et al.*, 2011). There are still many unanswered questions about the management factor, used in the LENI calculation, and load factor, used in TM22, both can lead to conceivable variance in measured annual power consumption and would be suited to further in field studies with empirical evidence. Taken together, these findings support the use of environmental loggers and recommendations to use empirical evidence from field data in energy efficiency upgrade projects. There is abundant room for further progress in utilising small unobtrusive and relatively inexpensive environmental loggers across all building services which can be implemented prior to upgrade works or energy efficiency retrofits.

4.6 Corridors

The UK Government and Higher Education Funding Council for England (HEFCE) links English University funding to their Carbon Management Plan targets as previously explained. In 2009, industry sponsor, a UK University committed to the target of reducing its carbon emissions by 35% against the 2008/2009 baseline and in February 2017 achieved this target (Hodgson, 2011; Sustainability Team University of Reading, 2017). In the first six years of this University's carbon management programme, lighting retrofit projects made up 12% of the total carbon energy efficiency projects and the nine lighting upgrades cost a total of £810,532 and achieved savings of £164,951 per annum (p.a.) and 800 tCO_2e (p.a.) (Fernbank, 2013). The 30 teaching and learning buildings on the main University campus amount to 122,000m^2 of Gross Internal Area (GIA) floor space, and communal areas total 21% of this space (25,300m^2). Corridor and communal areas are not defined as usable floor space in the context of a building that is primarily used for teaching and learning with additional academic offices (RICS, 2015). The electricity consumption in these transient corridor spaces is predominately electrical lighting and this is a substantial floor area to illuminate. The purpose of this study was to investigate, over a six month period, whether the lighting within the corridor areas of three different University buildings was being used efficiently.

4.6.1 Decision Making

The decision making surrounding energy efficiency installations involves consideration of many factors, including financial incentives, carbon reduction and routine maintenance and management of upgrading older systems. A difficulty estates and facilities teams face is in convincing budget holders and decision makers that new energy-efficient systems will save money and reduce carbon dioxide emissions in practice. Faced with this difficulty, most researchers investigating decision making in the built environment have utilised the Multiple Criteria Decision Making (MCDM) method, where multiple inputs are ranked, or Analytic Hierarchy Process used in group decision making (Kracka and Zavadskas, 2013; Fouchal *et al.*, 2016). In the absence of actual data, estimates are used for the calculations, based on assumptions and discussions with building occupants but the accuracy of these estimates has not been examined. The lack of credibility in these estimates leads to doubt by the decision makers, or worse still the estimates go unchecked.

We suggest that the 'PreMortem technique' proposed by Klein could be adopted by built environment designers. A prospective hindsight approach is used to describe and imagine weaknesses in the early design stage, the reasons and adaptations to mitigate failure are then discussed (Klein, 2007).

As an example:

- *The assumptions used for the hours of operation for a University building corridor are 10 hours a day, 5 days a week, 48 weeks of the year: a total of 2400 hours annually.*
- *Other corridor calculations have estimates of use for only 42 weeks of the year, and yet others with 8 hours per day not 10 hours.*

There are no indications within the calculations as to why these differences are so large – as previous researchers have pointed out, these assumptions survive unchallenged (Menezes *et al.*, 2012).

Lighting upgrades are relatively simple projects but it is critical to anticipate where the weaknesses are in the assumptions and how pivotal these might be in relation to the outcome metrics: Return on Investment (ROI), simple payback, annual electricity consumption, carbon dioxide equivalent emissions and savings.

4.6.2 Objectives

The objectives of this study were:

A. to discover any interesting patterns of lighting on use and occupancy;
B. to explore the predictions and assumptions by inputting the actual values of hours of operation into the carbon and electricity consumption calculations; and
C. to measure the performance gap of lighting in corridor environments

The key contribution of this work is to measure the performance gap in corridor lighting by taking a retrospective approach and analysing three buildings lighting use by recording actual occupancy and lights on data. This will allow for evaluation of the accuracy of the energy efficiency calculations commonly used by energy managers for decision making. The metrics for assessing the use of corridor lighting in practice against project carbon and electricity saving estimates provides insights that could also be used in other mechanical and electrical installations in buildings, not just lighting.

4.6.3 Materials & Methods

The CIBSE TM22 method in Appendix A8: Energy Tree Diagram is used as the basis for this study's assessment of four different lighting areas in three university buildings. The data collected include in-depth 1 minute resolution of corridor lighting on time, corridor occupancy, vertical corridor illuminance and building level electricity metering where available. Monitoring of occupancy is based on a PIR sensor for a limited zone of the corridors studied.

4.6.4 Building Descriptions

The three buildings in this study were selected as they were identified as part of the university's carbon management plan and importantly the long term real estate strategy. All three buildings had corridor lighting assessments from the university's external consultants, in house project managers and sustainability team. Between them, the three buildings contributed four corridor areas of data collection and will be identified as Humanities 1 (1st floor), Urban 2 (2nd floor), Urban 3 (3rd floor) and Maths 1 (1st floor). Two buildings Urban and Maths had upgrades completed by 2013, the financial payback periods for the Humanities lighting upgrade was considered unviable and therefore the decision was made that this building's corridor lighting would not be upgraded at the time.

Field information

The University has closure dates each year where the buildings are closed and not accessible without prearranged authorisation from the campus security team. For the period considered, the closure dates were 24 December – 3 January and over the Easter period, including Maundy Thursday through to Easter Monday. The buildings in this study are closed by security staff between 9 and 10pm and access is gained by cleaning staff who usually enter at 5.30 or 6am. During closure periods and outside of normal working hours the buildings are only accessible by staff and students who hold authorised access permissions, otherwise in all other cases the buildings are accessible by staff, students and arranged visitors. The buildings are all fully operational and used during the UK summer period in July, August and September for other courses and all students have full access during this time. All four locations are accessible to all staff and students during the periods when the buildings are open. The corridor locations – which are outside of classrooms – were specifically chosen to represent corridor spaces outside classrooms which are not solely occupied by one school or department but can be centrally booked by any group booking.

4.6.5 Data Collection

Environment Loggers

At each corridor monitoring area 2 loggers were installed at 1.5 metres from finished floor level on the vertical wall of the corridor. As previously detailed the HOBO™ UX90-005 occupancy/lights on logger and the HOBO™ U12-012 light intensity environmental loggers were installed at each site to measure vertical illuminance.

CO_2e saving predictions

As previously discussed the method most widely used for calculating lighting installation energy over time, which includes parasitic load and controls, is the 'lighting energy numeric indicator' (LENI) measured in units kWh/m^2 per annum (HM Government, 2010; The Society of Light and Lighting, 2016). The carbon savings predictions that form the basis of this performance gap assessment for corridor lighting, are calculated using Equation 2 however the corridor is calculated on a per metre rather than metre squared basis. As per the previous section, Equation 2 is extracted from the external consultants calculations used in these corridor lighting upgrade projects and they are based on the Carbon Trust formulae for calculating the business cases for retrofit projects (Carbon Trust, 2012). The designs and calculations used in these projects were carried out in 2012 and 2013, since then the LENI calculation has been further refined, for differentiating daytime, night time and parasitic consumption, nonetheless the original calculation is used for comparison purposes.

For lighting projects Equation 2 includes two predicted terms: annual operational hours and total predicted power (electricity) consumption and one predicted co-efficient: the load factor. As these predictions are multiplied any error in the terms and co-efficient will skew the estimate of predicted energy consumption overall. The load factor is usually between 1 and 0.7, it is an estimated coefficient based on assumptions that takes into account parasitic load and whether the control system achieves electricity savings when it is dimming, switched off through absence detection, or daylight detection. In the absence of specialist sub-metering data and simultaneous recording of the lights at a dimmed level or at a lower load, the load factor remains routinely based on assumptions rather than evidence provided by lighting manufacturers (Caple, 2016). The CO_2e conversion factor is extracted from published UK Government Greenhouse Gas Reporting Conversion Factors for the appropriate year of the project (Department of Energy and Climate Change, 2011b). The CO_2e electricity factor is the sum of generation (Scope 2) and transmission and distribution (Scope 3) factors, for example in 2016 respectively: 0.41205 + 0.03727 = 0.44932 kg CO_2e /kWh. The corridor study examines the accuracy of the predicted term annual operating hours.

Lighting Controls and field information

The lighting controls operating in each of the four corridors is described in Table 17.

Study Location	Humanities 1		Urban 2 & 3	Maths 1
Lighting Control	Schneider Electric Timer CCT15720 IHP1C	Ex-Or Standard Series LightSpot MS1500P	CP Electronics MWS3A-PRM PRM switching, adjustable head, IP40, microwave, presence/absence detector & GEFL PIR	Ex-Or LR15F LightSpot Long Range 15m Microwave Detector - flush
Type	Timer	Ultrasonic passive photocell	Microwave & Passive Infra-red with photocells	Microwave with photocell
Installation date	2009 (not upgraded)	2009 (not upgraded)	2013	2014
Presumed Commissioning settings	8am – 8pm Monday to Saturday	Time out from last presence 20 minutes	Time out from last presence 20 minutes	Time out from last presence 10 minutes
Commissioning	Manually: Options for seasonal settings, daylight saving time (British Summer Time), holiday periods for each day of the week	Manually: 6 different controls on the side of the fitting: 2 dials and 4 switches that determine the set parameters for the sensitivity and on/off settings of the controls for both motion and light	Handset: No ability to receive data from these sensors via the handset so the present settings are not known	Handset: Ability to receive data from these sensors via the handset and then transmit new parameters to the sensors

Table 17 Lighting Corridor Controls Field Data

4.6.6 Data structure & Data procedures

The data produced by the HOBO™ loggers was downloaded each month using the HOBOware software, the light on calibration for the U90-005/6 loggers took place at each installation and reinstallation in situ. Where incomplete days of data were recorded, for example at the beginning of the study when a logger was installed at 13:00 hours on Tuesday, the whole of Tuesday's data was omitted as the study aimed to capture complete hours of operations over a 24 hour period. Using the HOBOware software the data was aggregated to count the total number of hours the lights were recorded as switched on and occupied each day. The average illuminance each hour was also aggregated, these summative datasets were exported as a Microsoft Excel file.

Energy Efficiency Predicted Project CO_2e Calculations

The energy efficiency predictions for electricity consumption and reduction in CO_2 equivalent emissions for the three buildings are detailed in Table 18. These are the predictions as calculated from the individual projects. The annual operating hours that is being adjusted in this study is the 'after' set of figures highlighted in pale blue in each case.

	Location	Year	Annual operating hours (h)	Load factor	Total predicted electricity – luminaires (kW)	Total predicted electricity consumption per annum (kWh)	CO_2e conversion factor (kg CO2e /kWh)	CO_2e per annum (tonnes)
	Humanities 1 – Upgrade not carried out							
Estimate before	Current T8, timer and presence sensors	2012	1680	1	28.8	48,384.0	0.0005246	25.4
Estimate after	Upgrade option LED & presence sensors	2013	1680	0.7	4.8	5,644.8	0.0005246	3.0
Predicted Savings			no change		24	42,739.2		22.4
	Maths 1 – Upgrade carried out in 2014							
Estimate before	Current T12 no switches	2013	8222	1	4.41	36,259	0.0004836	17.53
Estimate after	Upgrade option T5 lamps and ballasts	2014	8222	0.7	2.13	12,259	0.0004836	5.93
Predicted Savings			no change		2.28	24,000		11.6
	Urban 2 & 3 – Upgrade carried out in 2013							
Estimate before	Current T12 manual switches	2012	8760	1	12.12	106,160.3	0.0005246	55.7
Estimate after	T5 & presence daylight sensors & dimming	2013	2100	0.5	8.10	8,500.8	0.0005246	4.5
Predicted Savings					4.02	97,666.2		51.2

Table 18 Electricity consumption predictions in corridors for each building

The load factor changes as outlined previously in Equation 2 are based on assumptions provided by lighting manufacturers. The load factor assumes lower loads due to photocells, dimming controls and other control options after upgrade.

4.6.7 Results

4.6.8 Humanities 1

Corridor lights on and occupancy patterns

The original calculation in Table 18 for predicting the operating hours for Humanities 1 assumed and 'estimated after' 1680 annual operating hours in total, based upon 8 hours per day, 5 days per week and 42 weeks per year. The Humanities 1 building had two control systems (timer and ultrasonic sensors) operating for similar lights on hours, the lights on median annual value from the four areas is 3994 (h/annum) and lights on standard deviation (SD) 111 (h/annum), the data from the four areas are displayed in Figure 44 with standard deviation error bars. The occupancy in the four corridor data collection areas is shown alongside the predicted value of operational hours in Figure 44, with an occupancy median value of 1547 per annum and occupancy SD of 302 (h/annum).

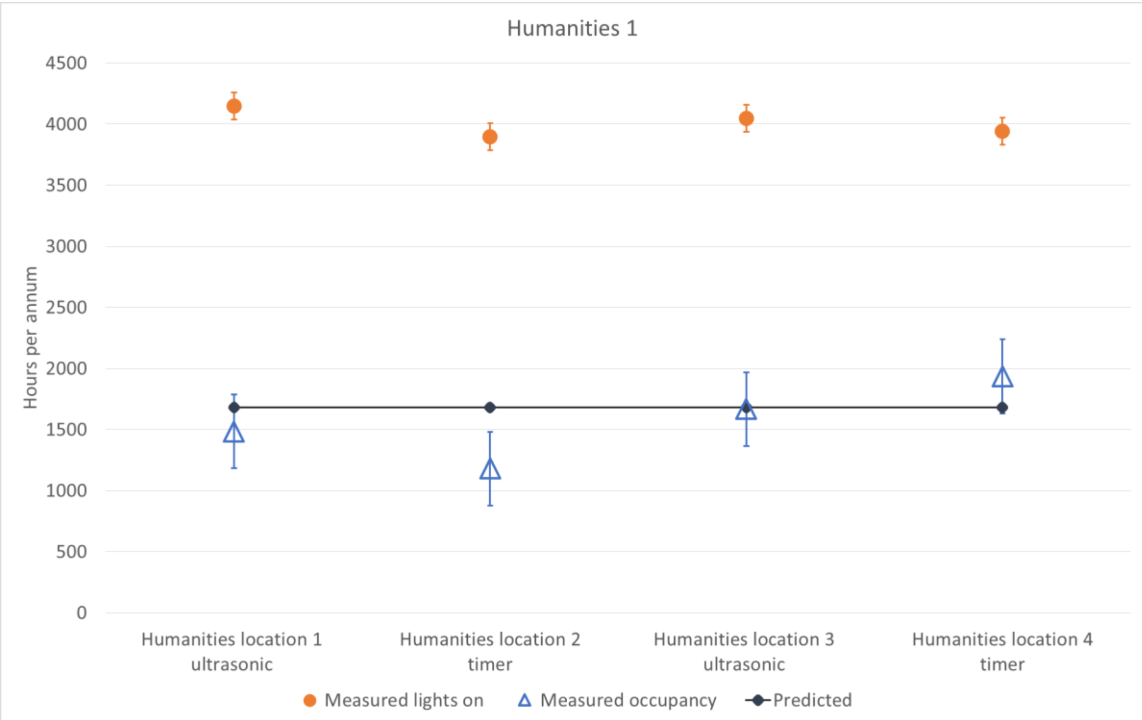


Figure 44 Predicted operational hours and measured hours per annum in the Humanities 1 Building

The predicted assumption has no weekend or working between 08:00-09:00 hours and 17:00-20:00 hours and no occupancy for 10 weeks of the year. Building users were accurate in providing their own occupation period as the median value is only 133 hours per annum lower than the predicted value of 1680. However, this original prediction omits the arrival of the cleaners at 05:30 hours each morning during the working week and students' union groups and other societies making use of the classrooms (with prior agreement) until 20:00 hours on some working week evenings. The heuristics, or rules of thumb, used in the assumptions could be perceived as overoptimistic in their major underestimation of the actual patterns of lights on hours which are 138% higher than predicted operational hours. Operational hours is used as a proxy for occupancy hours which is in turn used as a proxy for lights on hours.

A key finding of this study is that operational hours ≠ occupancy hours ≠ lighting on hours: the terms are not analogous

The patterns that emerged from the data was that the hours of occupation extended to more realistically being 08:00-20:00 hours each weekday as shown in Figure 45.

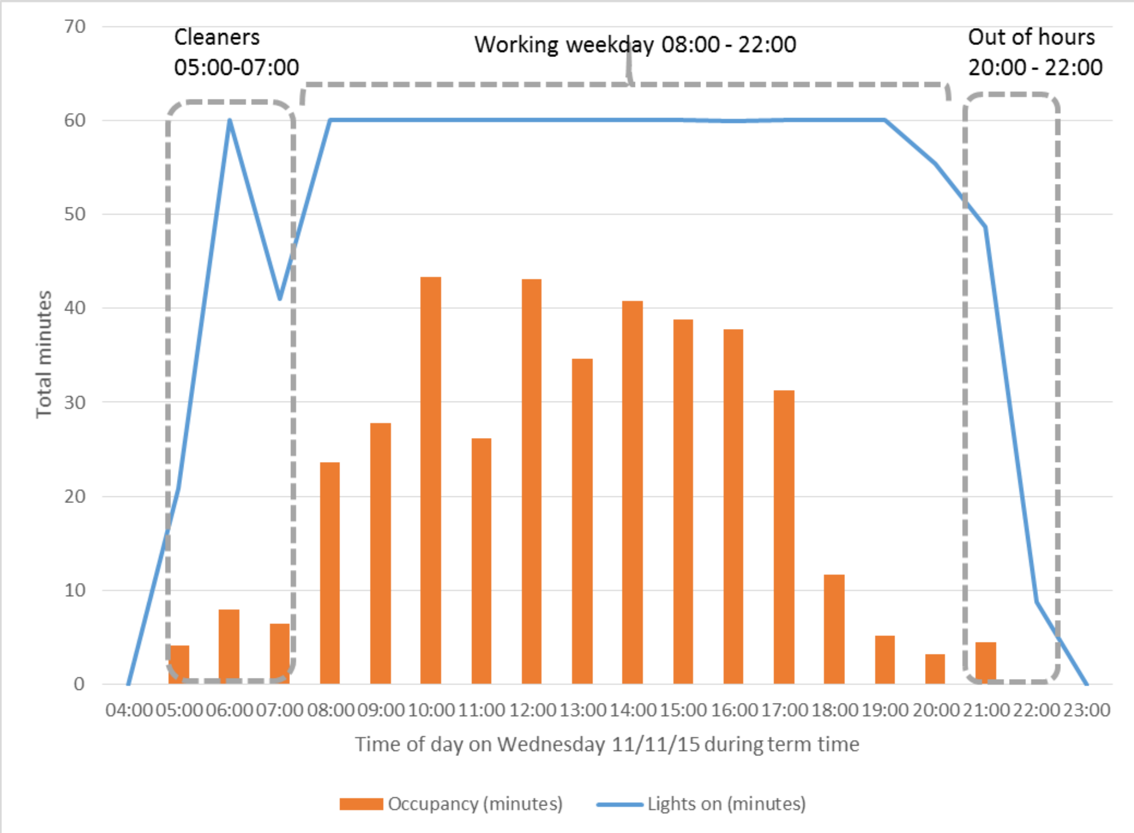


Figure 45 Typical term time weekday lights on and occupancy profiles: Humanities 1 corridor at location 1 where installed ceiling lighting is controlled by ultrasonic sensors (rather than the timer)

The pattern supports the conclusion that the timer settings of 08:00-20:00 hours are rational as a design solution for the half of the lighting system luminaires that are linked to the timer, however this does not account for the settings including Saturday. The occupancy proportions according to time of day, working day and weekends are divided as: mean working hours Monday – Friday 08:00-20:00 hours 89%, non-working hours 20:00-08:00 hours Monday – Friday 9%, and the remaining 2% was weekend occupancy. The combined control methods used in this corridor satisfy the out of hours use 20:00-08:00 hours and weekend use with the ultrasonic sensor and the timer 08:00-20:00 hours could be further adjusted to Monday-Friday only and to be switched off over the closure periods to consume less electricity. It is proposed that the large discrepancy between lights on hours and occupancy hours in Figure 44 and Figure 45 can be reduced by shortening the hold on time after someone has vacated the corridor area. The 'Lighting Design Process' (LightingEurope, 2017) Stages 3 Commissioning, Stage 4 Verification and Stage 5 Operation and Maintenance are iterative and can take place consistently until the gap is narrowed to reduce operating costs, electricity consumption and CO_2e emissions.

4.6.9 CO_2e emissions and electricity consumption

The predicted annual CO_2e emissions and electricity consumption is compared to the measured values using the before and after process in Table 18 and is shown in Figure 46. The measured values are 138% higher than predicted, these findings are consistent with CarbonBuzz data for University buildings which have shown up to a 150% increase in recent performance gap analysis (van Dronkelaar *et al.*, 2016).

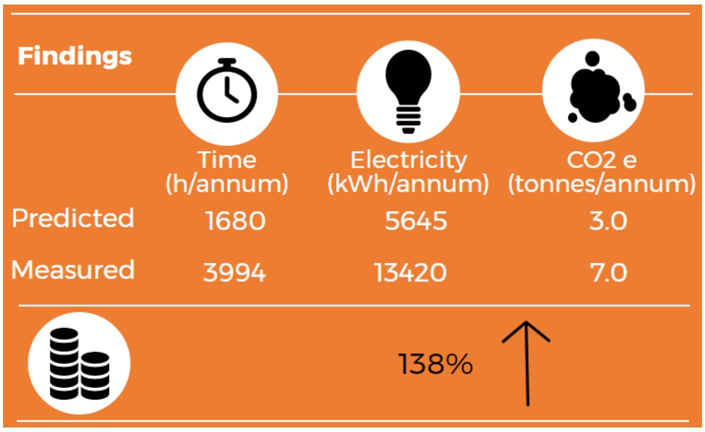


Figure 46 Humanities 1 CO2e emissions and electricity consumption analysis

Another important finding was that although this building did not have the lighting upgraded in 2013, with the measured data available for total annual hours on, almost 4000 hours p.a., the calculations can be revisited for both the 'estimated before' and 'estimated after' calculations in Table 18. If only the annual hours of use are changed the before gives a measured total of 60.4 CO_2e p.a. (tonnes), and after upgrade with LED lighting gives a total of 7.1 CO_2e p.a. (tonnes), saving 53.3 CO_2e p.a. (tonnes) compared to the predicted 22.4 CO_2e p.a. (tonnes). What is surprising is that the decision making surrounding this project lead to it being deemed unviable at the time due to its payback periods. Using the Pre-Mortem technique for this project if the designers and project managers had imagined weaknesses in the early design stage they might have picked up on the appropriateness of the assumptions in the predictions. Reasons and adaptations to mitigate failure at the time were not explored as this project was put on hold, it now has the potential to save much more than first expected using measured values.

4.6.10 Maths 1

Corridor lights on and occupancy patterns

The Maths building was part of the lighting energy efficiency upgrades in the Carbon Management Plan. The corridor lighting upgraded was completed in 2014 with microwave sensors, the corridors on the first floor where this study was located have a mixed use of academic offices and centrally bookable classrooms. The original calculation in Table 18 for predicting the operating hours for Maths 1 assumed an 'estimated after' upgrade of 8222 annual operating hours in total. The median annual lights on value from the three areas is 2683 (h/annum) and lights on standard deviation (SD) 416 (h/annum), these are displayed separately in Figure 47. The occupancy in the three corridor data collection areas is shown alongside the predicted value of operational hours in Figure 47, from the three areas a median value of 831 per annum and SD of 354 (h/annum) are calculated.

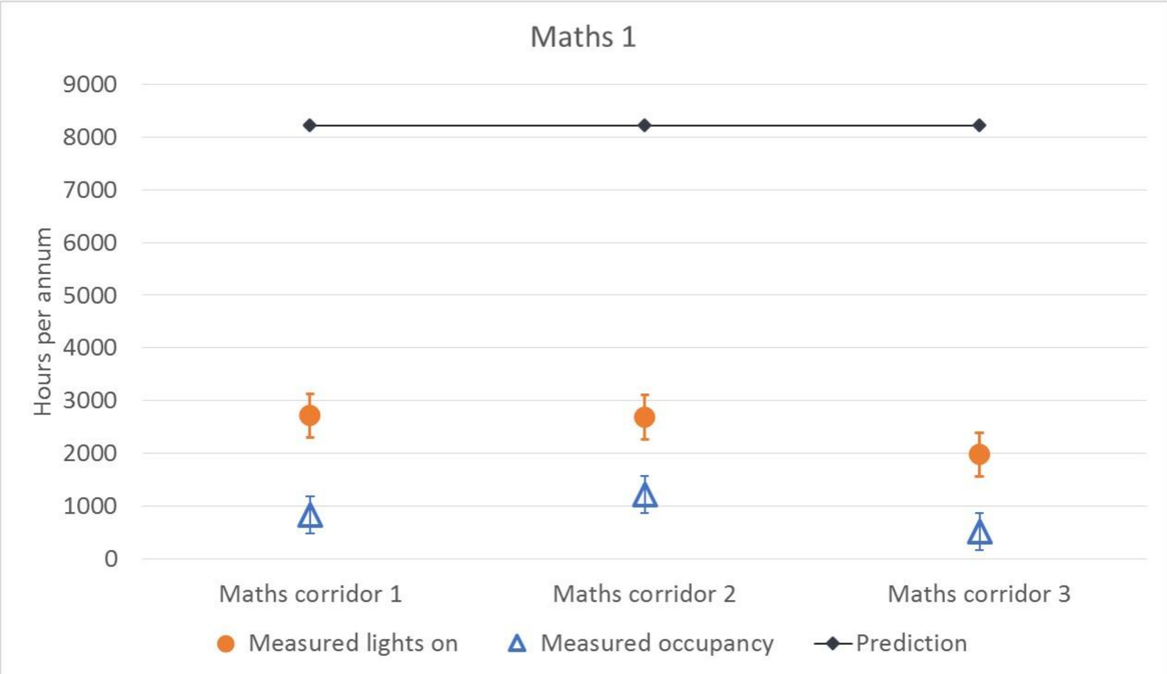


Figure 47 Predicted operational hours and measured hours per annum in Maths 1 Building

The predicted 8222 annual operating hours was calculated from survey data where prior to the retrofit some of the corridor lights did not have switches and remained on constantly, some were on for up to 80% of the year. Lights on for 24 hours a day 365 days of a year = 8760 annual hours; the prediction assumes 22 days in the year the corridor lights are off. The actual patterns of lights on hours after the corridor lighting retrofit are 67% lower than predicted operational hours. Operational hours is used as a proxy for occupancy hours which is in turn used as a proxy for lights on hours which supports the previous building's analysis. The patterns that emerged from the data are shown in Figure 48, which shows continual occupancy from 06:00 – 20:00 hours and out of hours occupancy from 20:00 – 22:00 hours.

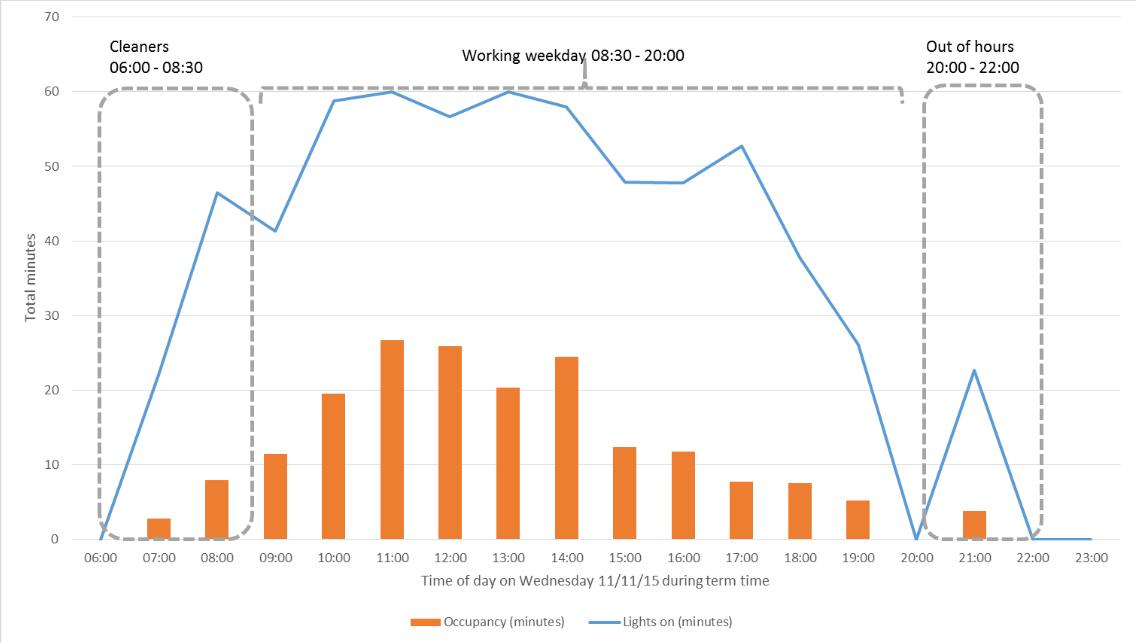


Figure 48 Typical term time weekday lights on and occupancy profiles: Maths 1 corridor location 2 microwave sensor

The pattern of lights on and occupancy during the study period are aggregated each week from the three corridor loggers and shown in Figure 49. The study period began during an undergraduate break in the academic calendar in early November 2015. Median lights on use is calculated by taking the median value from the total daily lights on use across the seven days of the week from the three data collection corridor locations. The identical calculation is used for occupancy and both are displayed alongside each other in Figure 49. The highest daily median lights on value is 12.60 hours at week 12 prior to the Easter holidays during weeks 13-15. Non-term times at week 45 when the study started, weeks 52-53 over Christmas and a drop in occupancy at week 7 for reading week can be seen in Figure 49. It is proposed that the difference between the median lights on hours and occupancy hours is the time delay when the corridor has been vacated to the lights being switched off. The lights were fully commissioned to complete the upgrade process in 2014, the study took place in 2015 only one year after retrofit completion. In the lighting design process if stages 3-5 (LightingEurope, 2017) are iteratively explored for reducing the performance gap this study generates the hypothesis that the lights on hours and occupancy hours would be much more closely aligned.

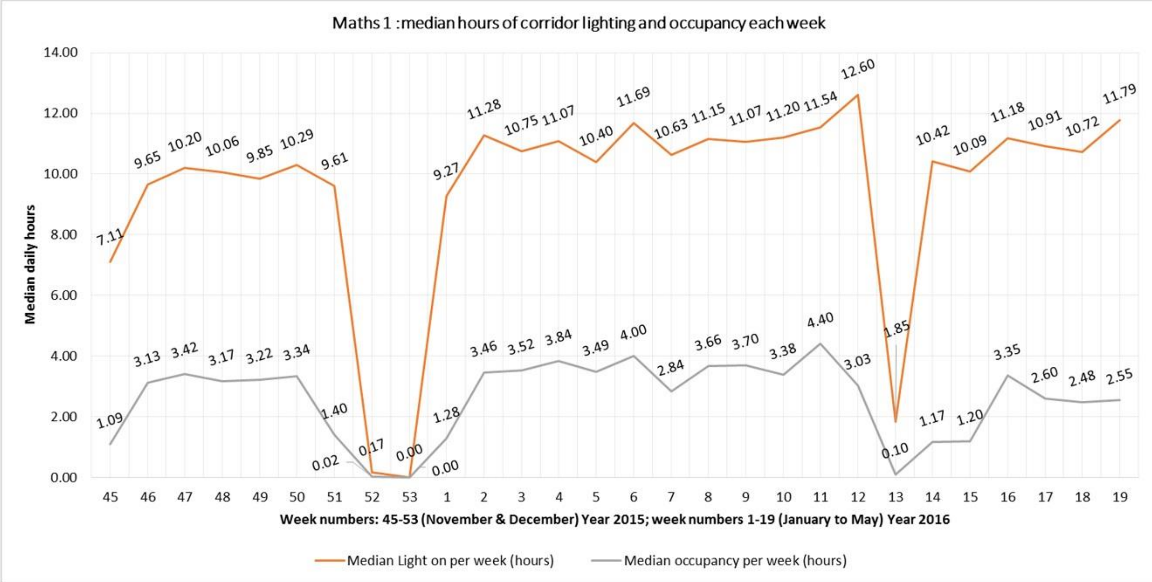


Figure 49 Maths 1 median hours corridor lights are on and median occupancy each week

CO$_2$e emissions and electricity consumption

The predicted annual CO$_2$e and electricity consumption is compared to the measured values using the before and after process in Table 18 and is shown in Figure 50. The measured values are 67% less than predicted, these findings are paradoxical with CarbonBuzz data for University buildings where increased electricity consumption is the norm (van Dronkelaar *et al.*, 2016).

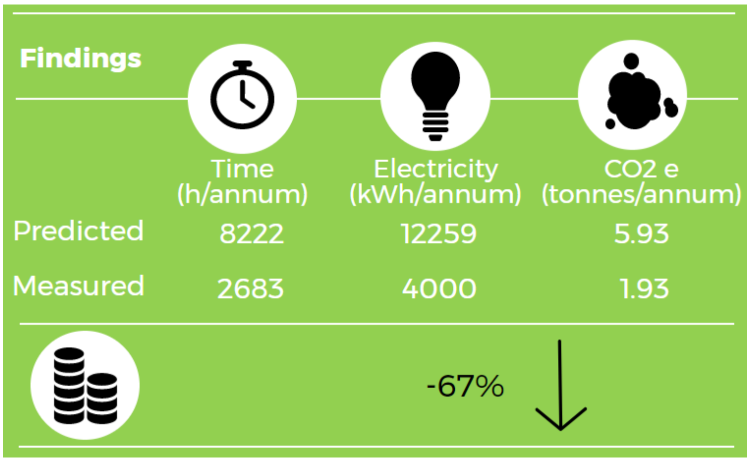


Figure 50 Maths 1 CO2e and electricity consumption analysis

Maths 1 has been calculated using overestimates of operating hours both before and after the upgrade. Inputting the measured lights on hours into the original calculation for the after scenario, this project has saved more annual electricity and annual CO$_2$e emissions than originally predicted.

4.6.11 Urban 2 & Urban 3

Corridor lights on and occupancy patterns

The corridors on the second floor (Urban 2) accessed mainly centrally bookable classrooms and some shared post graduate offices. Four corridor locations surrounding a central staircase access point were monitored on the second floor. The consultant's assumptions for the Urban 2 and 3 corridor retrofit lighting project were predicted to be an 'estimate after' 2100 operational hours annually after the retrofit in 2013 (10 hours per day 5 days per week, 42 weeks per year). The commissioning of the infrared and microwave sensors after the retrofit of new lighting was set to 20 minutes of hold time where if no presence was recorded the lights linked to that sensor would automatically switch off. The corridors on the third floor (Urban 3) accessed single occupancy offices for academics and administrative staff offices. A key element of logging corridor data in the two different locations in the one Urban building was the difference in the use of these two floors. It was anticipated that the occupancy and lights on hours would be quite different between Urban 2 and Urban 3, however without empirical evidence to support this, this study sought to find out if there was such a difference. The lights on median annual value from the four areas in Urban 2 is 2964 (h/annum) and lights on standard deviation (SD) 287 (h/annum), the data from the four area are displayed in Figure 51Figure 51.

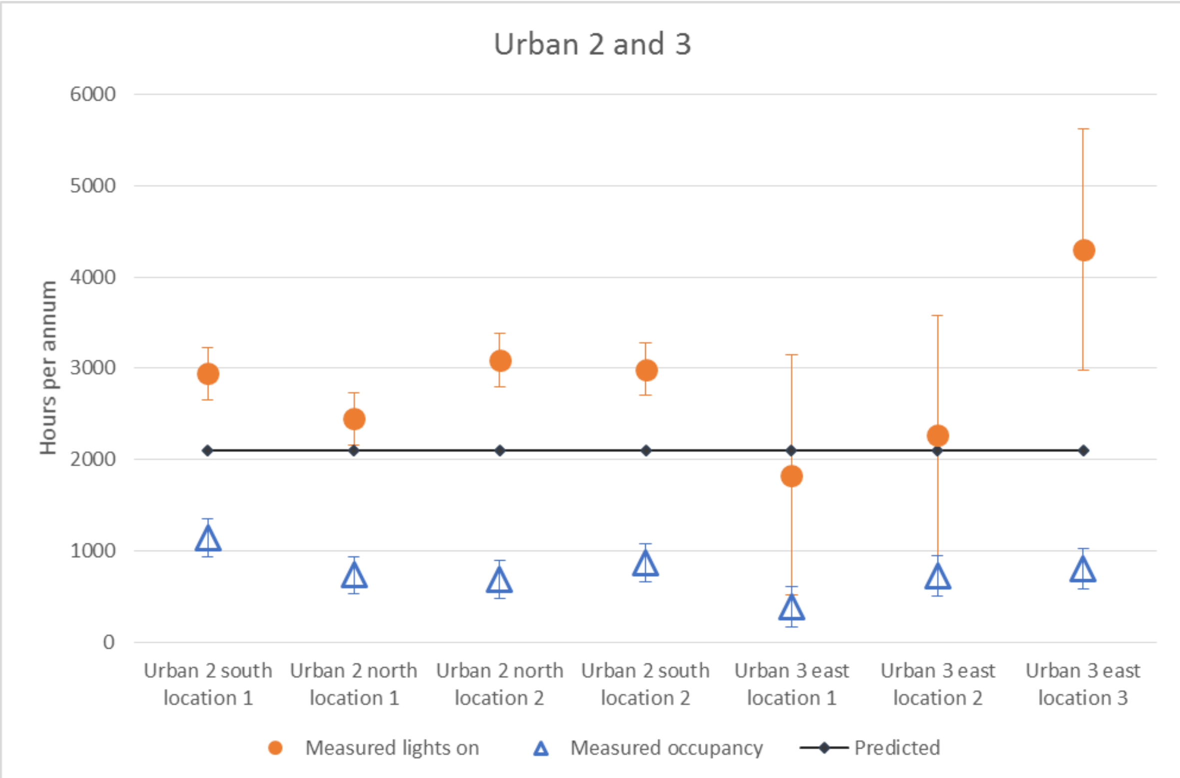


Figure 51 Predicted operational hours and measured hours per annum in the Urban Building

The lights on median annual value from the three Urban 3 corridor locations is 2,267 (h/annum) and SD 1317 (h/annum), standard deviation is indicated by the error bars shown in Figure 51. The high standard deviation in Urban 3 lights on suggests the hypothesis of highly varied office hours kept by the academic staff on this floor. The occupancy is also shown in Figure 51, with an occupancy median value of 804 (h/annum) for the four corridor areas in Urban 2 and 725 (h/annum) for the three corridor areas in Urban 3, the respective SD are 207 (h/annum) and 220 (h/annum). The assumptions used in the calculations for estimating the operating hours of lighting after the retrofit were 2100 (h/annum) for both Urban 2 and Urban 3. However, as envisaged the Urban 2 location had a higher footfall from students due to the classrooms on the second floor and was almost 800 hours in addition to those predicted in the original calculations.

Investigating the patterns of lights on use (rather than occupancy) for both Urban 2 and Urban 3 on the different building floors, Figure 52 illustrates the very different patterns of lights on use between the 2nd and 3rd floors in the Urban building on Wednesday 6th May 2015. It should be noted that rather than continuing to show lights on and occupancy patterns together this figure instead illustrates only lights on data for comparing the two corridor locations. The Urban 3 corridor has lights on from 06:00- 15:00 hours, however the lights remain on in the Urban 2 corridor at some level almost continuously throughout the night. In the Urban building 3 standalone vending machines are sited underneath one of the PIR sensors, it is proposed that this triggers the corridor lighting on out of hours in this location between 20:00-06:00.

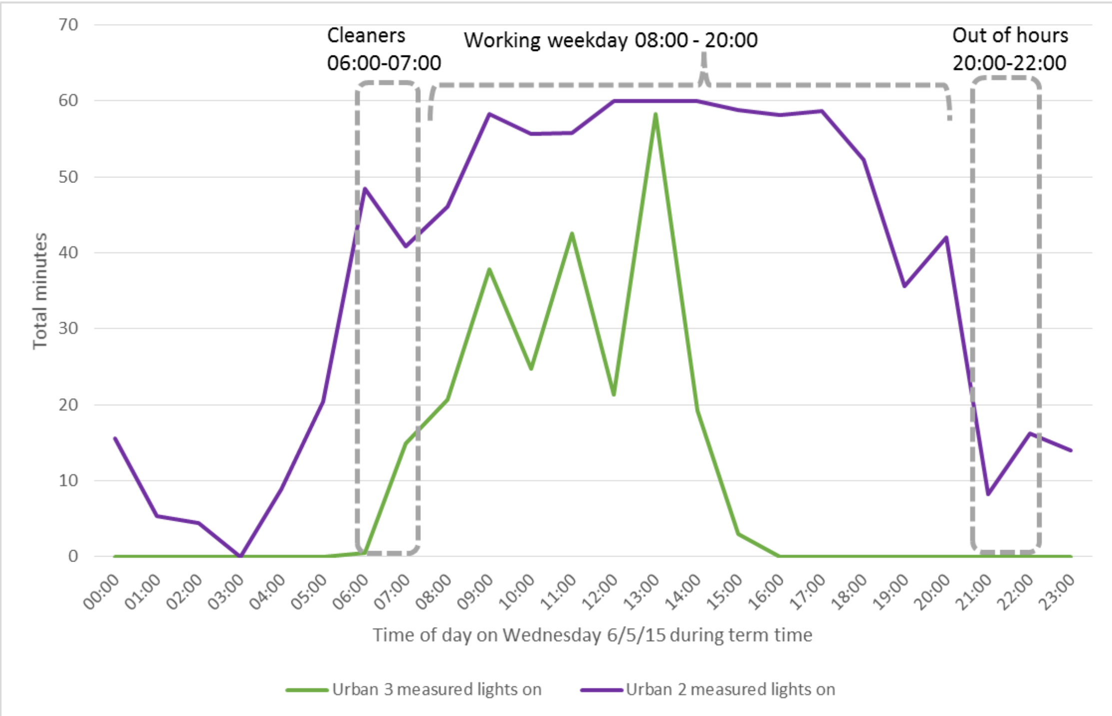


Figure 52 Typical term time weekday lights on for Urban 2 and Urban 3 corridor profiles

4.6.12 CO_2e emissions and electricity consumption

The lighting upgrade in the Urban building in 2013 was part of the wider Carbon Management Plan and anticipated carbon dioxide savings of 51.2 tonnes of CO^2 equivalent, Table 18.

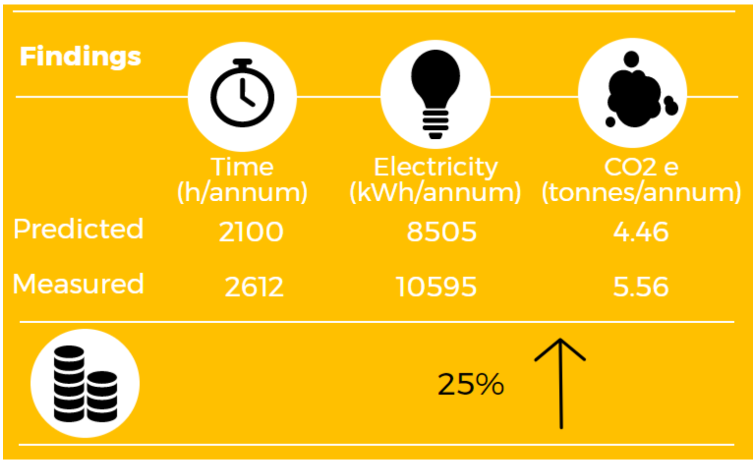


Figure 53 Urban 2 & Urban 3 CO2e and electricity consumption analysis

The original estimates were based on estimated operational hours of 2100 per annum for both floors, the calculation was split so that half of the annual hours were taken from the measurements from Urban 2 (2nd floor) and Urban 3 (3rd floor), the combined calculations for annual hours, electricity consumption and CO_2e emissions are shown in Figure 53. The measured values are 25% more than predicted, these findings are consistent with CarbonBuzz data for University buildings where increased electricity consumption is the norm (van Dronkelaar *et al.*, 2016).

4.6.13 Comparison across the three study buildings

The predicted operational hours, measured lights on hours and measured occupancy hours across all three buildings are plotted in Figure 54. What is striking about the values for annual hours in Figure 54 is the large variance between buildings in predicted operational hours. The heuristics, or rules of thumb, used by the external consultants in the predicted operational hours have a large variability and error compared to actual measured values. Overall, these results across all three buildings consistently show that operational hours ≠ occupancy hours ≠ lighting on hours. This finding needs to be tested on further lighting retrofit studies in other locations to verify if this is also seen in different building sectors or use types but the consistent pattern observed here suggests that, at the very least, estimates of operational hours based on indirect evidence of occupancy hours may not be reliable and should be viewed with caution.

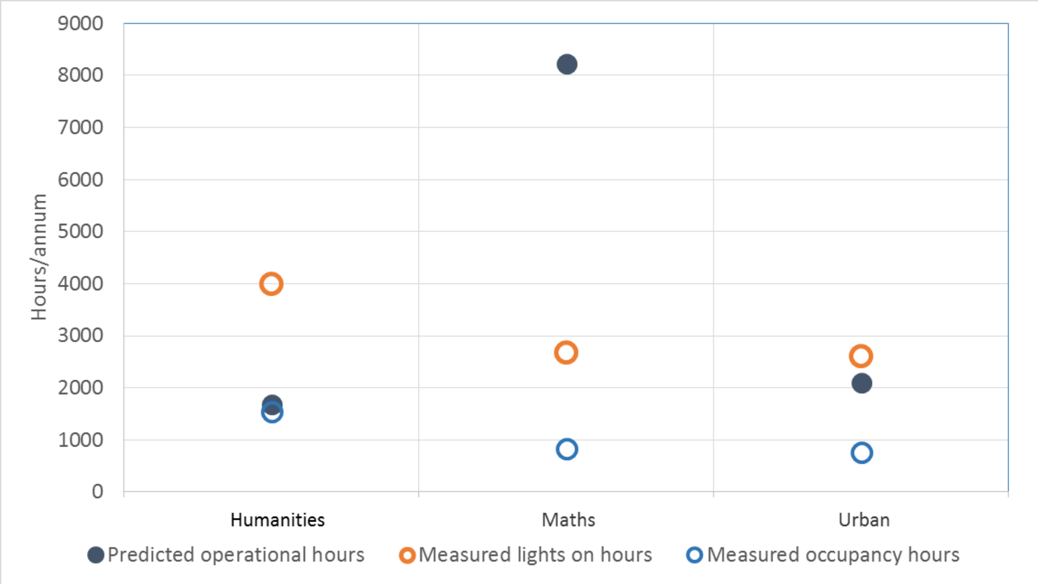


Figure 54 Annual hours of lighting and occupancy across three buildings

For reporting the performance gap in percentage terms to follow the convention of other performance gap researchers (Bordass, Leaman and Ruyssevelt, 2001; Menezes *et al.*, 2012; van Dronkelaar *et al.*, 2016) the final comparison of predictions vs. actual data are displayed in Figure 55.

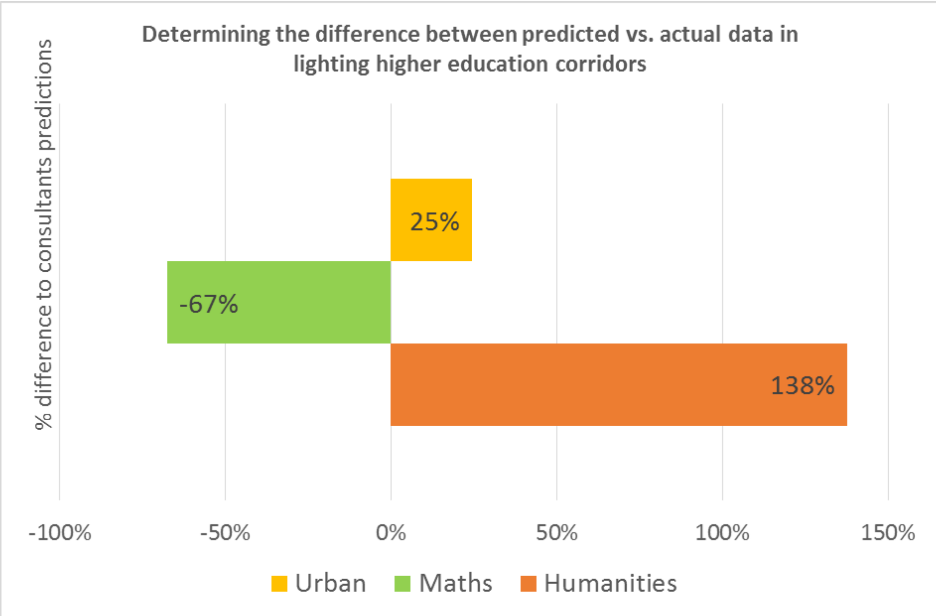


Figure 55 Determining the difference between predicted vs. actual data in lighting higher education corridors

4.6.14 Discussion

Two key findings arise from this corridor lighting performance gap study. Firstly the input parameter for predicted operational hours ≠ occupancy hours ≠ lighting on hours: the terms are not analogous for measured lighting use across the three locations studied. Secondly in the context of lighting retrofits the lights on hours of use were found to be -67%, 25% and 138% different from designers' and external consultants' predictions. The findings are comparable to CarbonBuzz data in higher education buildings (van Dronkelaar *et al.*, 2016). The novel findings from this retrospective study are that further savings could be found in revisiting the lighting upgrade in the Humanities building as this upgrade was not carried out, the input parameters used in this project were grossly underestimating the annual lighting hours. For the two lighting retrofit projects that were completed in the Maths and Urban buildings, further savings can be accrued for Maths given this measured data and with iterative verification of commissioning the Urban building has the potential to narrow the gap between lights on hours and occupancy hours. The inputs used in the LENI calculations, Equation 2, by the external consultants in these feasibility studies were based on assumptions and best guess estimates, this is congruent with other performance gap researchers who found that consultant's thermal modelling input assumptions were highly variable (Imam, Coley and Walker, 2017). The operational hours can easily be replaced by actual data collected in practice. The use of widely available environmental loggers provided insightful and practical inputs to calculations that would otherwise be based on unknown assumptions.

Integrating these environmental loggers into common use enables Energy Managers and Project Managers in all sectors to collect field measurements rather than relying on assumptions. Using environmental loggers can provide an additional tool to support decision making in energy efficiency projects. The use of the HOBO™ loggers in lighting applications enables commissioning engineers to reduce the performance gap between the lights on hours of use and occupancy patterns. It is proposed that the closer the lights on hours are to the occupancy hours in these buildings, the greater the savings in annual electricity consumption and carbon dioxide emissions. This can be achieved through following stages 3, 4 and 5 in the 'Lighting Design Process' (LightingEurope, 2017) with regular re-commissioning and dramatically shortening the time delay to switch off.

4.6.15 Management factor & Load factor

An important element of the 'Energy assessment and reporting method' (CIBSE, 2006) calculation comes from the management factor – this is the same as the load factor in the LENI calculation– which is not explored in depth here as this was outside the scope of our study. This term is understandably ambiguous as each mechanical and electrical service will have different requirements in a building. In lighting terms this encapsulates the additional complexity of commissioning, dimming, daylight, hold on time, contextual elements involving school schedule, types of occupant and operation, times of year and overarching policies on energy management. The load factor in the LENI calculation is not benchmarked or validated by evidence and remains another ambiguous estimation for external consultants and designers, this is often used as a crucial co-efficient for promoting the justification for automated controls over manual lighting controls. A further study building on this research is being carried out in corridor locations where manual controls are in operation to investigate the load factor co-efficient.

Limitations

The HOBO™ loggers used in this study were agreed for installation with the Building Managers and Energy Manager as they could then be subsequently utilised for other applications. They were relatively low in cost and this justified using them in corridor areas where they were liable to tampering and even theft. The loggers are limited in their respective situations of deployment in so far as the occupancy hours are only in the direct vicinity of the logger so it is likely that the recorded occupancy hours underestimate the amount of time the corridors are occupied. It is for this reason that the actual lights on hours were used as part of the calculations for assessing the performance gap in corridor lighting. The occupancy does however give another separate opportunity to analyse the data for time of day analysis, this would provide insights for other mechanical and electrical systems, such as heating to determine the profiles in term time and out of term periods. The calculations for estimates relied on the assumption that the sensors would be more efficient at switching off the lights than a manual switch and routine operation by say the security staff member walking around at the end of the day. This provides an opportunity to assess what the hours of lights on use and occupancy are for manually operated corridor lighting which is part of a future study. Since the study was limited to 6 months of data (the loggers were redeployed to other locations) it was not possible to give a full year of data. The extrapolation of six months of data to a full year is also another aggregation that limits this study.

4.6.16 Conclusions

This corridor study aimed to measure and assess how automatic lighting controls in corridor areas performed in practice, in comparison to consultants estimates of energy savings. The lack of continuity in how the operational hours were originally conceived as the basis of these calculations shows how the TM22 method has still not permeated the consultancy sector which provided these calculations. This study provided original empirical evidence on lights on hours and occupancy hours in corridors which was previously unknown and found that neither of these are synonymous with operational hours. These results suggest that there is a valuable distinction between lighting on hours and occupancy hours, a parameter not captured in the current CIBSE TM22 'Energy assessment and reporting method'. The performance gap analysis determined the difference between predicted and actual measurements for lights on hours ranging from -67% to 138%. As the research into performance gaps has previously found the difference between design estimates and actual performance data can be up to 85% higher in University buildings (Menezes *et al.*, 2011). There are still many unanswered questions about the load/management factor, used in the LENI calculation and CIBSE TM22 respectively. This can lead to conceivable variances in measured savings and would be suited to further in field studies with empirical evidence. The analysis of lighting on use and occupancy patterns undertaken here has extended our knowledge of including both out of hours occupancy and weekend working into corridor lighting use, yet none of these were taken into account in the predictions calculated by designers. Taken together, these findings support the use of environmental loggers and recommendations to use empirical evidence from field data in energy efficiency upgrade projects. There is abundant room for further progress in utilising small unobtrusive and relatively inexpensive environmental loggers across all building services which can be implemented prior to upgrade works or energy efficiency retrofits.

Chapter 5 Prompt study

The prompt study builds on the work of previous EngD graduate Dr Richard Tetlow who presented his pilot study in his thesis (Tetlow, 2014). The previous work showed there was a significant link between the office occupants forgetting to switch off their office lighting and this 'post completion error' event being directly based on the light state of the manually controlled corridor lighting. It found that when the corridor lights were switched off, the office lights were more likely to be switched off too on exit. Tackling the link between habit and design, the prompt study sought to capture in field measurements to determine whether office occupants were prompted to switch off, or conversely leave their office lights on, by the difference in illuminances between office and corridor on exiting their offices. Unfortunately the pilot study light intensity logger failed to record the illuminance during this study. The choice architecture and nudge concept was introduced in the literature which was applied to a post completion error problem of lighting waste, illustrated in Figure 56. We identified and defined waste as the events when someone exits their office leaving the lights on. As illustrated in introducing the thesis outline, the prompt study had the following objective:

- To determine if there was a relationship between office lights being left on, or switched off, and the difference in vertical illuminance between office and corridor on exit

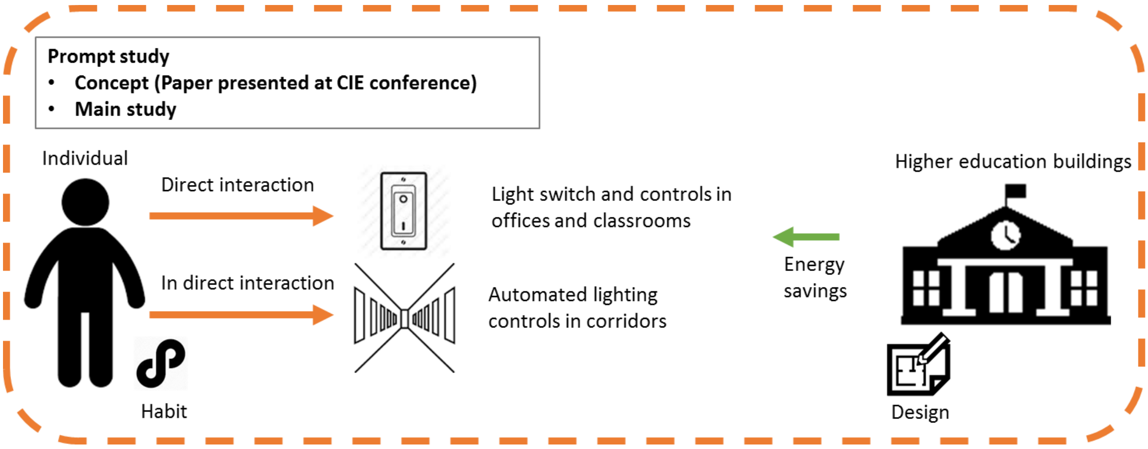


Figure 56 Prompt study

The concept of this prompt study was presented as a peer-reviewed paper (van Someren *et al.*, 2015). In what follows, I have adapted the content of that conceptual paper to locate this study in the context of previous research and this thesis. The following section will then focus on the hypothesis and questions that were explored. The results will then be reported outlining the research, sample size, methods of analysis and major findings. The major findings will be discussed in relation to how this prompt study informs professional practice and knowledge. To conclude this chapter I will argue for designing for sustainable habits and importantly suggest how to apply habit design to prompt people to save energy rather than taking away control from the end user.

5.1 Why prompt?

Why prompt? Many of the behaviours and habits carried out in the built environment by end users go largely unseen, and even if they are obvious they are difficult to measure or quantify. In the earlier literature review at chapter 2, I introduced the Fogg Behaviour Model and applied this to having the ability to control one's environment. Additionally the Fogg Behaviour Model presented the idea of a trigger being required for the new behaviour where the motivation and ability threshold had been reached. This trigger, or cue as it is more commonly termed in psychology, is what the prompt is based on. By applying the prompt study concept to individual offices we sought to find out if end users failed to switch off their office lights as a direct result of the corridor light state and lack of threshold illuminance difference between the office and corridor. Individual offices were chosen as office end users had complete control over their environment and can form long term habits. Lighting offers an interesting opportunity to explore how inherent lighting design and illuminance levels can play a part in whether the end user either remembers to switch off the lights, when exiting their office or accidentally leaves their lights on, leading to waste.

5.1.1 Automation vs individual control

How can we influence people to waste less lighting energy when they are not occupying a space? There are three progressive methods used today:

- Automatic controls; we purposely started this research with the intent to seek a people rather than purely technology based solution;
- Behaviour change; implies that you have performed undesirable actions, campaigns and gamification are good at producing short term awareness but lack long term commitments; competitions favour a prior starting point of the most unsustainable practices;
- Nudges and cues; we change the environment so that we subtly prompt people to act differently.

With the lighting industry growing and automation controls a key feature of upgrades little attention is given to how people form habits in lighting behaviours surrounding these new technologies. The lighting sector claims that lighting makes up 18% of UK electricity and that this could be reduced to 4 or 6 % with controls and energy efficient lighting (Lighting Industry Association, 2014). The guidance for lighting in higher education helpfully acknowledges that the Building Regulations stipulate conformity in areas of efficient lamps and gear, however the industry authors point out that an inefficient luminaire can still be accepted for Part L compliance (CIBSE, 2011). They go on to explain that up to 60% of the building will need automated controls to conform to Part L retrofit targets and that both these and efficient luminaires are necessary for preventing energy waste (CIBSE, 2011). The "killer variables" identified and defined by Leaman & Bordass (1999) found clusters of topics across their multiple studies which included (without ranking): personal control, responsiveness, building depth, and workgroups. It is clear from other research that the unintended consequences of automated lighting in offices could lead to more energy waste than less due to end user behaviour (Pigg *et al.*, 1996). The prompt study therefore focussed on individual personal control in office spaces.

5.1.2 Holistic design

Lighting spaces separately by task is industry convention. In higher education applications, best practice guidance suggests 300 lux for classrooms (up to 500 lux for evening classes), staff offices at 300 lux and corridors at 100 lux (CIBSE, 2011). Our previous work highlighted the neglect and frustration end users felt by occupying spaces that were subject to piecemeal upgrades of say just one area such as corridors, rather than all offices and corridor spaces (van Someren, Beaman and Shao, 2017). These piecemeal upgrades could lead not only to different illuminance levels but different colour temperatures and other unintended effects. The industry guidance recognises that entrance areas will serve as a transitionary space between outside and inside (CIBSE, 2011) however we postulate this could also occur once the building occupant is adapted to the indoor environment in an office.

5.1.3 Waste and post completion error

How can we waste less by design (default) rather than by control? The following figure outlines how the environment could be cuing or nudging end users to energy waste or energy savings.

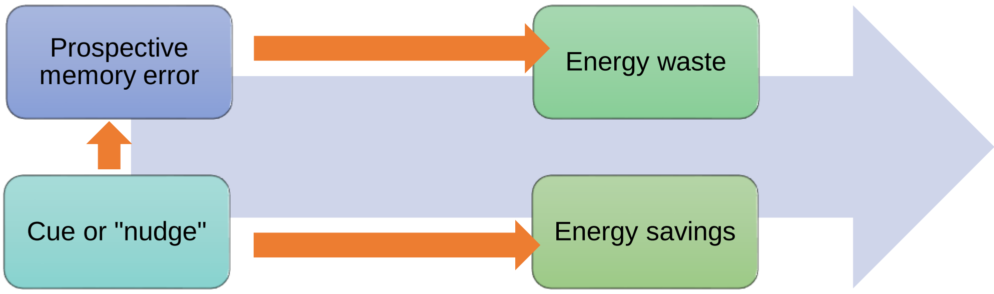


Figure 57 Outline of source of anticipated energy savings (reproduced from van Someren et al., 2015))

The concept put forward proposed that over illumination in corridor areas led to an inherent prospective memory error (where you intend to carry out an action but forget), due to a lack of contrast between the office (lit) and corridor (over lit), Figure 57. The cue or nudge from the corridor was also proposed to act on energy saving opportunities which could be made where at a lower threshold level the corridor lighting could in fact nudge people to remember automatically to switch off the manual office lights. This concept was an original contribution to knowledge in the lighting field as it synthesised cross-disciplinary topics and applied them in a new way.

5.1.4 Implications for industry, design and end users

The impact of this prompt study on industry, design and end users could hold valuable insights into how people form habits around their lighting behaviours. For industry the implications could assist with supporting end users in retaining the killer variables of personal control and responsiveness, leading to possible worker productivity, more usable manual control design and wellbeing improvements. The retention of control would support energy managers in decision making and specifying manual controls rather than moving towards expensive automated controls that are not welcomed, wanted, commissioned or designed appropriately for end users. The study could also open new research areas in design practices for interlinking lighting areas which have conventionally been kept apart for energy efficient behaviour based outcomes. Finally for the end users, this study could support sustainable behaviours, habits whilst retaining personal control. The prompt study contributes to knowledge by carrying out empirical work not done before and in addition builds on and continues an original piece of work.

5.2 Hypothesis and objectives

This study specifically investigates the hypothesis that if the corridors are overlit a person leaving their office or classroom is less likely to switch off the overhead lights on exit, an error of prospective memory, because a dark corridor should serve as a reminder of the presence of overhead lights in the office. There is little evidence detailing the transition between lit environments internally when we move around our indoor spaces. This work explores the relationships between lighting in corridors and offices as interrelated spaces rather than as separate entities for design (and behaviour). We propose methods of 'prompting' or 'nudging' prospective memory to support energy efficient behaviours and habits in building users and facility managers through appropriate human-centred design and choice architecture, Figure 57. This is in contrast to full automation of energy-using systems which would exclude user participation and control.

- To determine if there was a relationship between office lights being left on, or switched off, and the difference in vertical illuminance between office and corridor on exit

5.3 Prompt research design

The prompt research design was really quite simple in practice and based on the principle of collecting data simultaneously in the office and corridor location in the immediate vicinity of the office. The research design was carried out over six months in order to capture as many events as possible when the lights were switched off or left on, when the occupant exited. Illuminance, luminance, measurement of brightness and perception of lighting is such a complex field that the prompt study used the very approximate and basic measurement of vertical illuminance as a proxy for ambient brightness. This simple design clearly has its own limitations and therefore the light state, on or off, was used and time of day for the light switching events to further develop the models and concepts.

5.3.1 Sample size and data collection

Participants were recruited directly through email based on their building and location. There were a limited number of loggers available at any one time. Therefore it was practical to deploy the corridor loggers in locations where two or three office occupants were situated and willing to participate.

There was a limited response rate from occupants for participating in the prompt study. The request for participation email outlined that downloading the data would need to be carried out every 28 days and that the loggers would be in place for up to six months. It also explained that ethical approval was favourable for the study and included the ethical requirements with briefing and consent forms.

5.3.2 Data collection

Three data points were collected from location, via two loggers deployed in the office and in addition two loggers in the corridor. The loggers were the identical loggers used in the waste avoidance chapter and it was the same data used in the prompt study however at a different resolution and for a different purpose.

An indicative layout of the office, corridor and loggers is shown in Figure 58.

Figure 58 Diagram of logger set up in prompt study

5.3.3 Data tidying

The data tidying process involved first checking the data to ensure that no erroneous points had been recorded, for example removing the instances where weekend lights on hours were recorded where no occupancy was recorded in the prior period, this happened in a limited number of cases as the lights on logger is triggered by a threshold illuminance, presumably from daylight. Data cleaning and mining has been suggested to take 80% of the effort for extracting the most valuable 80% of data, which determines the findings (Dasu and Johnson, 2003). A necessary step to take millions of minute by minute data points and compress this into a meaningful dataset involves data tidying. The data were first merged in the proprietary HOBOware software and then exported as an MS Excel file after filtering for minute level data as lights on time, occupancy time and light intensity. This was carried out for each office and corridor on an individual basis, pairing the office and corridor logger locations. The dataset for the prompt study use the minute by minute data rather than the aggregated hourly, daily and weekly data in the prior waste avoidance studies. Data tidying was necessary for the prompt study as I needed to extract all of the events that met the following rules. A flowchart is the optimal way of presenting the set of rules applied to the excel datasets and is shown in Figure 59, starting at "Office lights are on".

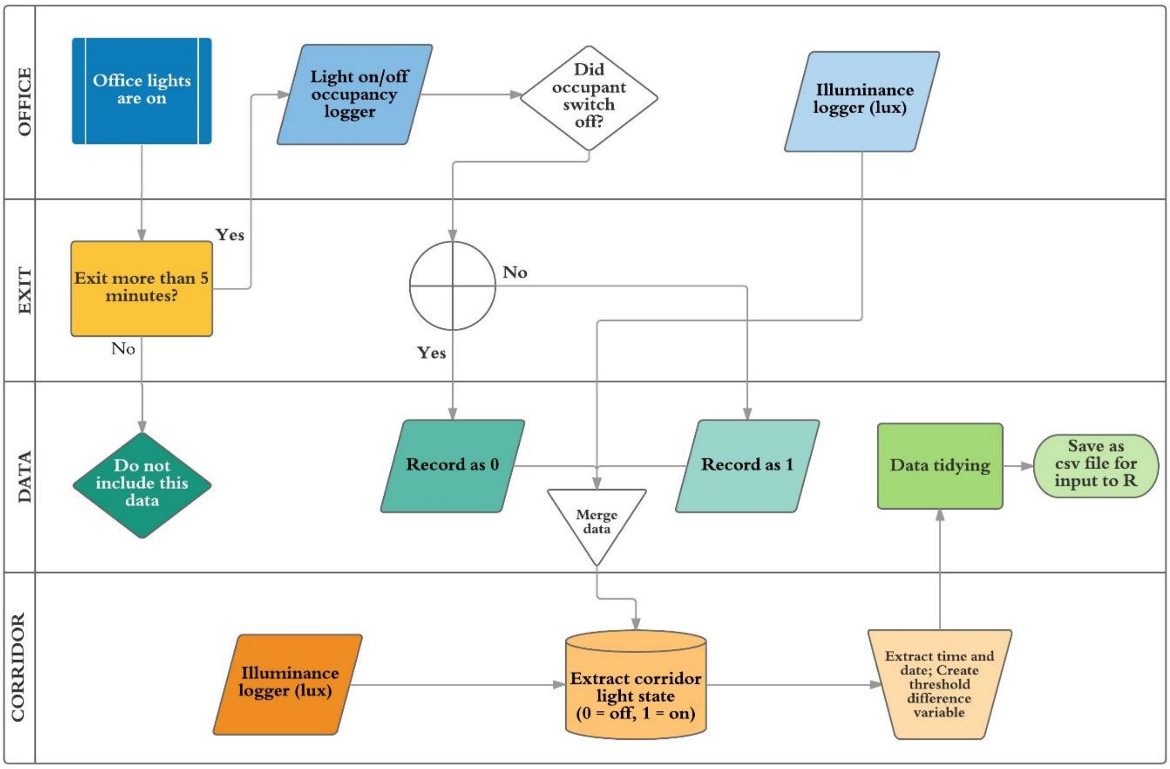


Figure 59 Prompt study data tidying flowchart of rules applied in MS Excel

As previously outlined there were a small number of missing values for the illuminance levels in offices and corridors. In the Maths and Humanities corridors where missing values occurred the 'on' illuminance level was taken from another date where the lights were on; the same applied for the 'off' state for illuminance levels as there was a lack of natural daylight interfering with the measured illuminance levels. In contrast in the offices with missing illuminance values these were not replaced as they had varying levels of light due to natural daylight and blind state throughout the study period.

The tidying of each dataset was a process carried out on the ten offices for their pairs of office and corridor logger locations as shown in Figure 59. The ten datasets were individually saved and exported as both an MS Excel file and a comma separated variable (csv) file. For importing into the free open source programming software 'R' the csv files were used as R has more powerful statistical analysis tools than MS Excel.

5.4 Data analysis

The analysis presented used chi square χ^2 analysis and takes the previous prompt study analysis a step further by including binomial logistic regression and supplementary statistical tools for assessing these models.

Given the hypothesis stated earlier the following parameters are applied:

Dependent variable: Binary (0 or 1) lights being switched off = 0, or left on = 1

Independent variables: Continuous (scale, e.g. time of day) or binary (e.g. corridor light state 0 = off, 1= on)

Common Applications: Regression is used in this study to look for significant relationships between two or more variables. It can also be used to predict a value of one variable given values of the others (Karadimitriou and Marshall, 2016).

The head() function in R is used to display the raw data below:

```
head(alloffices)

##     Office     lightstate officelight datetimeoffice     time officelux
## 1 Office 1 Lights left on           1 16/12/14 15:40 15:40:00     138.0
## 2 Office 1 Lights left on           1 18/12/14 09:28 09:28:00     177.4
## 3 Office 1 Lights left on           1 18/12/14 09:29 09:29:00     169.5
## 4 Office 1 Lights left on           1 18/12/14 10:30 10:30:00     193.2
## 5 Office 1 Lights left on           1 18/12/14 12:40 12:40:00     224.7
## 6 Office 1 Lights left on           1 18/12/14 12:41 12:41:00     232.6
##   corridorlight corridorlux thresdiff hour thresdiffabs building month
## 1             1       201.0      63.0   15         63.0    urban    12
## 2             1       201.0      23.6    9         23.6    urban    12
## 3             1       201.0      31.5    9         31.5    urban    12
## 4             1       208.9      15.7   10         15.7    urban    12
## 5             1       208.9     -15.8   12         15.8    urban    12
## 6             1       208.9     -23.7   12         23.7    urban    12
##   catthresdiff       cathour chrontime officelightint officelightnum
## 1            B     afternoon  15:40:00              2              2
## 2            A early morning  09:28:00              2              2
## 3            A early morning  09:29:00              2              2
## 4            A  late morning  10:30:00              2              2
## 5            A  late morning  12:40:00              2              2
## 6            A  late morning  12:41:00              2              2
```

5.4.1 Plotting the missing data

The output is a combined graph of missing values summated across each variable as shown in Figure 60.

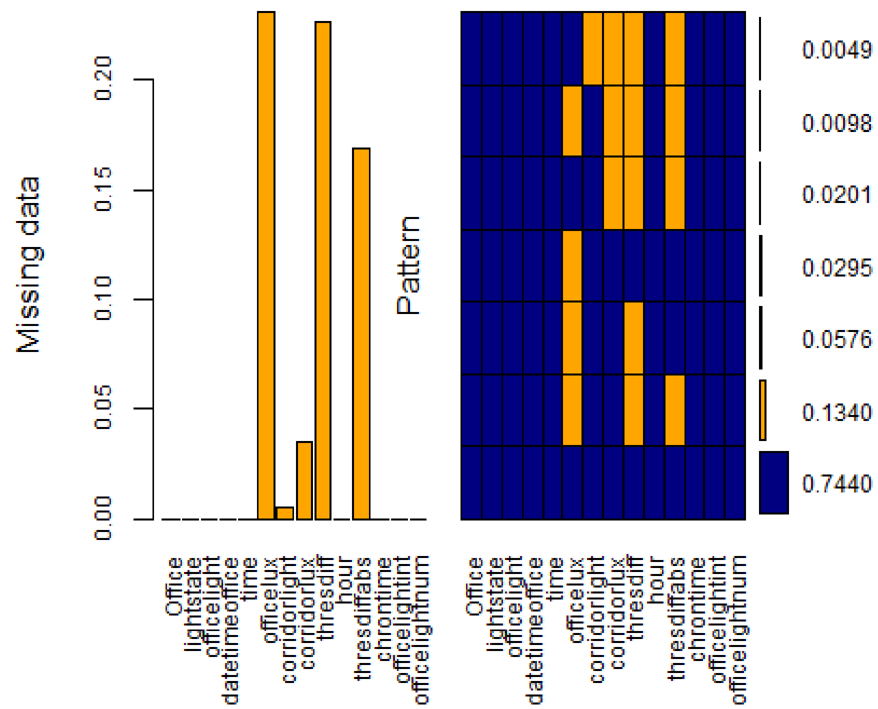


Figure 60 Missing data graphs

From the graphs in Figure 60 we see that 74.4% of data is complete across all variables. Because the threshold difference variable (thresdiff and thresdiffabs) is derived from both office lux and corridor lux levels it is not surprising that these are showing missing values based on our previous explanation. The same is true of other variables (officelight and all time related variables) that are in different R types of data such as factors rather than numbers or integers for statistical analysis.

5.5 Prompt findings

5.5.1 Plotting the data

The first step in analysis is to plot the data. The exploratory data analysis plots explored what the outcomes were against our hypothesis variables. The first plot in Figure 61 shows the proportion of office light states against the time of day as a factor by hour, the scale of the rectangle is the number of observations at each hour. The red indicates the office light state as 0 - off, the teal colour is light state as 1 – on.

Time of day

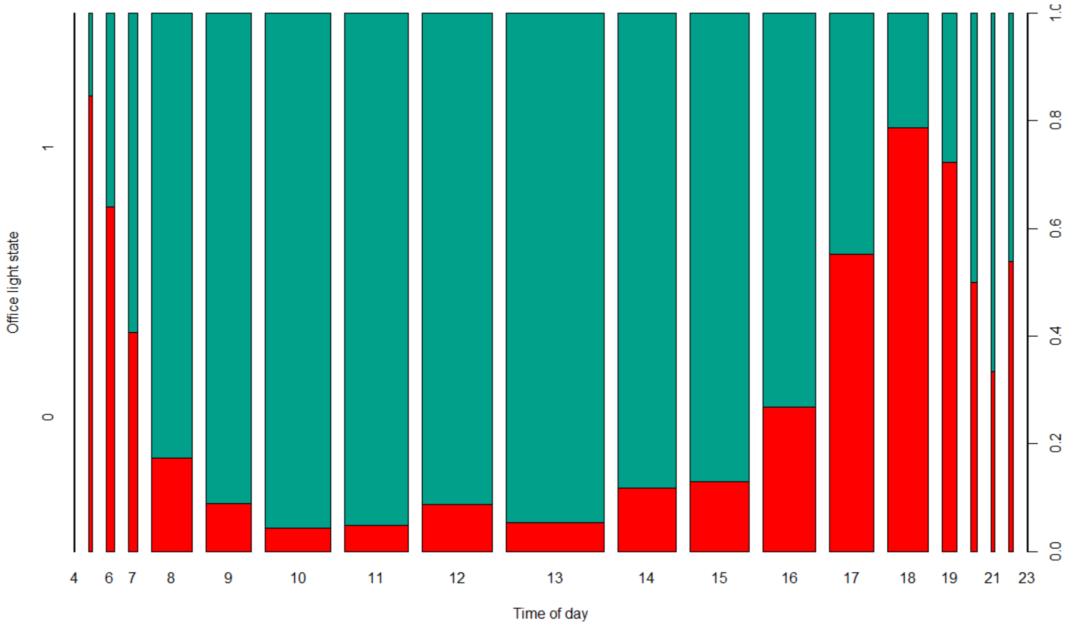


Figure 61 Proportion of office light states against the time of day as a factor by hour

The first plot in Figure 61 shows that the lights are left on most frequently in the time of day period 13:00-1359, the next most frequent time slots for waste are actually 10:00 to 11:59, and not 12:00-12:59 which was unforeseen. Another surprising finding was the time of day for switch-off after 19:00 hours does not behave in the same manner as the switch-on profiles predicted by Hunt (1980), figure taken directly from the paper, Figure 62.

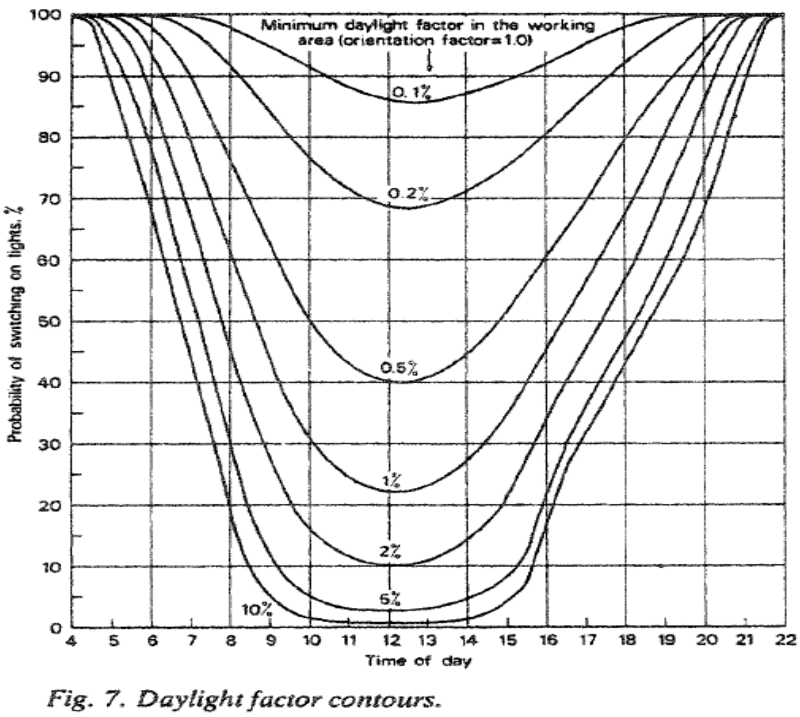


Figure 62 Hunt's (1980) prediction curve for time of day

The expected findings would have assumed a parabolic curve for the light state against time of day. However the decrease in lights being switched off after 19:00 is different to those expected and predicted by Hunt (1980). Other lighting researchers have look at switch-on probabilities (Hunt, 1980; Fabi *et al.*, 2014) and switch-off probability based on the amount of time someone is absent (Reinhart 2004, Figure 3(c)), but this is an original finding based on the combination of the switch-off data and time of day analysis.

Corridor light state

The second plot in Figure 63 shows the relative proportion of data collected for the office light state and corridor light state on exit. The red is used to identify when the office lights have been switched off, teal represents the lights left on. This suggests that we can reject the null hypothesis that the corridor light state is having no impact on the office occupant to switch off on exit.

Figure 63 Proportion of data collected for the office light state and corridor light state on exit

The second exploratory data analysis plot in Figure 63 shows that there is indeed a difference in the outcome of the occupant either switching off their lights or leaving them on. There is a difference in proportion for the occupant's actions on exit and this varies alongside corridor light state. Following on from the exploratory data analysis statistical analysis was conducted using binomial regression. This was carried out using both the full dataset on variables where this is appropriate and the reduced dataset omitting missing values.

Time of day as a category

The third plot in Figure 64 involves three variables plotted alongside each other, again 1 indicates lights on, 0 lights off. Where:

00:00-9:00 "early morning" erlm;

09:01-12:00 "late morning" ltmr,

12:01:13:00 "lunchtime" lnch,

13:02-17:00 "afternoon" aftr,

17:01-23:59 "evening" evnn

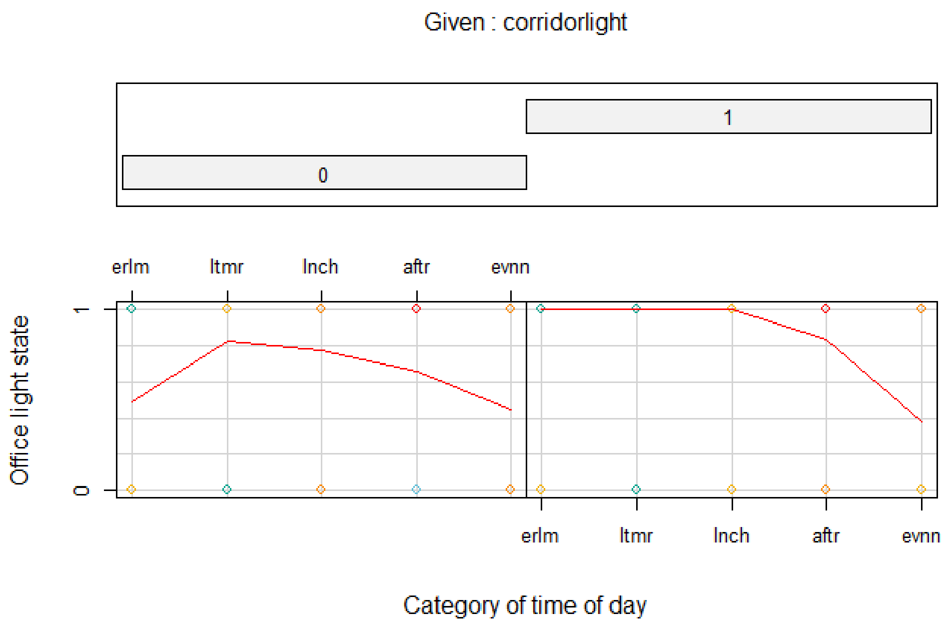


Figure 64 Office light state, corridor light state and time of day

Figure 64 shows how the time of day and corridor light state is affecting the switch off for the office light state dependent variable. In all of the corridors automated lighting was present regardless of the minimal access to daylight in the three Urban corridor areas, the remainder in the Humanities and Maths buildings did not have direct daylight. The final exploratory data analysis plot reveals differences in individual office participant's habits relating to their switch off behaviours, Figure 65. It should be noted this dataset was a subset of the data whereby the conditions were met for the lights being switched on whilst the office occupant was present in their office (as described in Figure 59). It is therefore important to point out this does not reveal the energy efficient behaviours of those participants who regularly used their offices with the lights off (Office participants 1, 2 and 3 as discussed in Chapter 4).

Individual offices

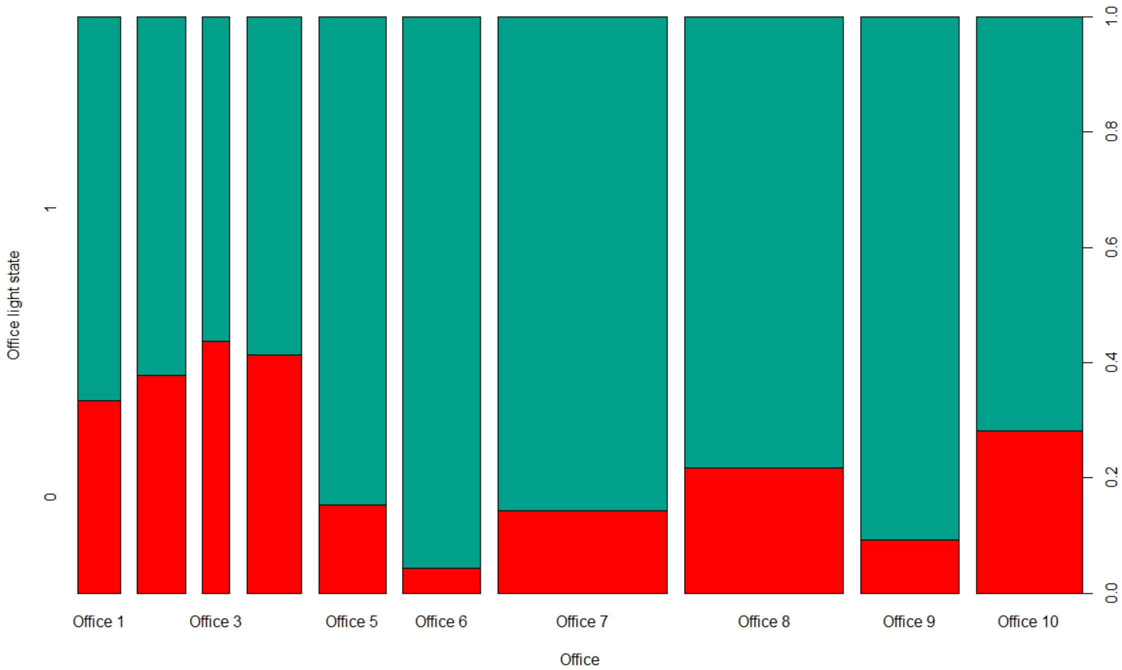


Figure 65 Individual offices and the switch off proportions for leaving the lights on (1) or switching the lights off (0)

There are a number of additional factors that could be influencing the light saving behaviours (0 in red), or lights being left on (1 in teal). If the office is over-illuminated this could be altering the environmental cue to switch off. The occupants of the Urban building have already reported their dislike of the installed ceiling lights in Chapter 3 user experiences, office 1, 2 and 3 are different participants to the interview participants.

5.5.2 Generalised linear mixed models with random effects

The first analysis model will look at the whole dataset to see if the office light state is being influenced on exit. This was where office light state was used as a predictor based on the response to the other variables measured. The variables measured in the first model were corridor light state – on or off and the time of day. Summary data statistics are shown as an output with random and mixed effects.

Time of day

Model 1 with the predictor variables of corridor light was modelled with a new variable where the time of day was separated into hours, this new variable was labelled categorical time (cathour in the model).

There are two fixed effects, the corridor light (corridorlight) state and the hour of the day (cathour). In addition there was one random effect accounted for each office (1|Office), because the data is dichotomous (0 = off, 1=on) a binomial logit analysis was applied.

```
Family: binomial  ( logit )
Formula: officelight ~ corridorlight + cathour + (1 | office)
```

The prompt study design implicitly assumed that multiple measures were taken from each participant (office). For each event where the occupant left their office for over 5 minutes and the light was previously on prior to exit, there were multiple opportunities for them to switch their light off or leave it on. This principle violates the independence assumption, where multiple events from the same occupant cannot be regarded as independent from each other. Every office occupant has a slightly different habit relating to their switching behaviour, and that is an idiosyncratic factor that affects all outcomes of switch off or leaving the light on, thus rendering these outcomes inter-dependent, rather than independent (Winter, 2014). The way this was dealt with in the regression model was to add a random effect for the office participant. This resolved the non-independence by assuming a different "baseline" light switching behaviour for each office participant.

```
Fixed effects:
                                  Estimate Std. Error z value Pr(>|z|)    
(Intercept)                        1.11207    0.29304   3.795 0.000148 ***
corridorlight1-0                   0.55061    0.18359   2.999 0.002707 ** 
cathourlate morning-early morning  1.55751    0.22446   6.939 3.95e-12 ***
cathourlunchtime-late morning     -0.09639    0.30901  -0.312 0.755097    
cathourafternoon-lunchtime        -1.71967    0.27243  -6.312 2.75e-10 ***
cathourevening-afternoon          -2.19995    0.19362 -11.362  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Table 19 Model 1 generalised linear mixed model results for corridor light and category hour

The generalised linear model - Table 19, model1 - shows the standard errors and p-values for each category of time of day, as fixed effects. The significant results are indicated by the significance codes alongside the p value. This suggests that for the participants of our study there was a significant difference in their lights switching behaviour on exit based on the corridor light state being on (in the model this is written "corridorlight1"). This suggests the null hypothesis where there is no relationship between office light switching behaviour and corridor light state can be rejected. The time of day and corridor light state suggest the time periods between early morning and late morning, lunchtime and afternoon and, afternoon and early evening combined with corridor light state are having a significant impact on whether the occupant switches off or leaves their light on in their office.

Threshold illuminance

A second generalised linear model - Table 20, model2 - repeats the first model however this dataset is reduced as the missing values where illuminances are missing are omitted. Categorical data points were created for each difference in threshold value at the following intervals:

0-50, "A"

50-100, "B"

100-250, "C"

250-500, "D"

500-5000, "E"

The reason the categories were chosen was because a relatively even number of data points needed to be binned in each category otherwise the model would not run.

```
Fixed effects:
                 Estimate Std. Error z value Pr(>|z|)    
(Intercept)        1.3283     0.1873   7.091 1.33e-12 ***
corridorlight1-0   1.0274     0.2387   4.305 1.67e-05 ***
catthresdiffB-A   -0.4195     0.2511  -1.671  0.09477 .  
catthresdiffC-B    1.2284     0.1843   6.666 2.63e-11 ***
catthresdiffD-C    0.9662     0.2010   4.807 1.53e-06 ***
catthresdiffE-D    1.1898     0.4517   2.634  0.00844 ** 
```

Table 20 Model 2 generalised linear mixed model results for corridor light and category hour

Table 20, model 2 results show the standard errors and p-values for each category of threshold difference as a fixed effect. The significant results are indicated by the significance codes alongside the p value. This suggests that for the participants of our study there was a significant effect of the corridor light state on lights switching behaviour on (in the model this is written "corridorlight1"). This suggests the null hypothesis where there is no relationship between office light switching behaviour and threshold illuminance can be rejected. The threshold difference suggests there are different office light state outcomes according to the threshold differences of C-B, D-C and E-D. The most important value to review is the -0.4195 estimate in categorical threshold difference between B-A, this is the only value where there is a change in relation to light state in the opposite direction to the remaining categories of threshold difference. Substantial caution must be applied to these findings as we outlined in the research design that the simplistic assumption of using the vertical illuminance as a proxy for ambient brightness was a key limitation. The study was seeking proof of concept in a field setting and this finding merely suggests that further studies using more sophisticated techniques for measuring brightness might be worthwhile.

5.5.3 Limitations

There are a number of limitations to the prompt study findings. Despite collecting data from 10 offices for 6 months, the remaining data is not distributed evenly. This results in potential problems in regression modelling as some light states have so few counts. For example when the proportion of corridor light states is considered in Table 21, there are limited events (counts) when the occupants leave their offices with the corridor lights off.

		Office 1	Office 2	Office 3	Office 4	Office 5	Office 6	Office 7	Office 8	Office 9	Office 10
Corridor light off (0)	0	7	98	3	13	9	4	24	6	1	70
Corridor light on (1)	1	46	1	46	76	167	122	375	327	169	101

Table 21 Proportion of corridor light state counts by office

There could be other factors influencing switch off patterns, time of day is not the only factor: meetings appointments, hunger, natural daylight availability and circadian rhythms could also impact the behaviours of occupants. These findings may be somewhat limited by the fact that no manual light switching was present in the corridors, this restricted the ability to gather more data under the circumstances where the corridor lights were lowered. A way of temporarily manipulating the corridor lighting would be to use the emergency lighting, however this could only be sustained temporarily without the occupants becoming concerned. Another strategy could remedy the lack of data by fixing the illuminance levels in the corridor at a lower state (a) and higher state (b), and running month by month changes alternating between the two states (a,b,a,b,a,b) however a lack of maintenance staff to carry out the temporary changes meant that this not was possible in field. The observations from this study nonetheless support the hypothesis that there is indeed an influence on light switching behaviour being linked to the corridor light state, time of day and threshold illuminance difference, this supports the Fogg Behaviour Model (2012) and use of nudges in lighting with cues.

If the light switching behaviour is related to corridor light state and illuminance then it does suggest that differences between illuminance in interlinked spaces could be an area to study further, especially given the design criteria for differences in illuminances by task.

Chapter 6 Findings and Conclusions

The sixth and final chapter collectively discusses the results from chapters two, three, four and five. The findings are discussed in relation to publications and contributions to original knowledge. The research is critiqued in relation to the original research problem, aims and objectives to reach conclusions. The main findings from the research are summarised to include the impact of this research to the industry sponsor and the implications for the wider industry. Limitations of the research are discussed alongside recommendations and future work

This engineering doctorate investigated energy reduction through post occupancy evaluation and designing for habits. The main aim of the thesis was to explore how habit and design are interlinked in lighting use and occupancy. This aim was accomplished by completing six inter-related studies that addressed the individual objectives. The thesis proposed that by understanding users' needs and patterns of behaviour better lighting design would follow that could lead to energy savings. Key findings are summarised against each of the objectives.

The literature in chapter 2 explored energy efficiency on a large scale, reviewing: metering, feedback, behaviour change and gamification as areas that could not answer the questions asked in this research. Design and post occupancy evaluation were found to be the most applicable areas for reducing carbon emissions in lighting higher education spaces. The literature surrounding habits and design demonstrated this was a growing area with an opportunity to explore mixed methods research in higher education lighting controls and occupancy. It was anticipated that by focussing on the end users, their experiences of light and lighting, and collecting hours of use data for lighting and occupancy that a contribution could be made to how lighting and occupancy are designed in higher education. The literature highlighted gaps in relation to post occupancy evaluation through interview data and performance gap analysis. A further gap was found through interdisciplinary examination of the literature connecting design, habits, lighting and post-completion errors through prompts.

Objective 1: Explore end users experiences by applying qualitative methods of semi-structured interviews.

Chapter 3 presented the views and experiences of post graduate students and staff in relation to the campus wide energy reduction strategies. The pilot study findings were developed into the main study questions and focussed on the academic teaching staff. The users' experiences study was published in Lighting Research and Technology, one peer reviewer questioned the sample population and we pointed out that we explicitly sought not to corroborate the previous findings by focussing on building managers, designers and energy managers. Instead we provided new insights from the end users, the occupants. It is difficult to deliver criticism to facilities managers, however the feelings of neglect, frustration and adaptive behaviours were honestly and thoughtfully expressed by the participants. The piecemeal upgrades have left most end users feeling neglected and frustrated, they have adapted by using their own desk lamps and uplighters to combat the negative feelings of poor office lighting. The type of blinds and lack of a view from classrooms when these are used, lead to lecturers perceiving that their students sometimes struggled to concentrate in these classrooms. An original contribution to industry was made by providing some of the first qualitative work in lighting. Another researcher has supported the idea of more qualitative work in lighting being required to incite change and better understanding (Kelly, 2016). Motivated by these findings the facilities team adopted post occupancy evaluation use of interviews and the lighting specification was re-written. The results of this work was discussed in relation to design problems, management of window cleaning and importantly compared the user's conceptual model to the designer's conceptual model of how the control interfaces worked in field. In order to change working practices and design better spaces the occupier's needs must be included in the conversation rather than excluded. Further qualitative lighting research is required to provide a richer and deeper understanding of our lighting systems from different viewpoints and experiences. Future work could focus on the most vulnerable of occupants, those users with disabilities and could include porters, security and cleaners into the discussion as they all carry out daily work in our lit environments.

Objective 2: discover any interesting patterns of lighting on use and occupancy in offices

Objective 3: measure the performance gap of lighting in classroom and corridor environments

Objective 4: look at external factors to see if they influenced lighting, occupancy and wasted lighting in offices;

Chapter 4 comprehensively analysed post occupancy evaluation data for lighting and occupancy hours of use in offices, classrooms and corridors. Lighting upgrades were not carried out in offices therefore exploratory data analysis, time of day analysis and external factors were instead studied, fulfilling objectives 2 and 4. The post occupancy evaluation of lighting use and occupancy in offices revealed distinctly different patterns in each office occupant's patterns of behaviour. This finding corroborates previous single occupancy office lighting researcher's findings, that show very different patterns of use in each office (Lindelöf and Morel, 2006). The time of day analysis again showed the different switching patterns and occupancy profiles across the 24 hour time period. These results did indicate that there were active and passive users of the light switch, which supports Reinhart's findings (2004). The statistically significant differences in lighting and occupancy between buildings and size of office was not expected. This has two implications, firstly the building and its occupants seem to have an intrinsic pattern of lighting and occupancy. It would therefore be inappropriate in the circumstances of upgrading the office lighting to apply a single hours of use figure (as per the classroom and corridor assumptions) to the office occupants in different buildings. If upgrades were carried out this could reveal dramatic differences in the performance gap when measured in practice against design assumptions. It is therefore suggested that choosing appropriate baselines for each office accounting for different buildings would be the most reasonable method for calculating any upgrade savings.

These varying baselines could then provide the sample set from which to build a more realistic set of assumptions for hours of lighting use and occupancy.

The classroom findings satisfied objective 3 and revealed a limited performance gap between the design intent and practice however substantial savings could still be made over and above those estimated. The thirteen classrooms collectively had wasted over 13,000 hours of lighting, representing 1.5 years of waste. The identified electricity savings that could be made are significant and it was suggested that a different approach to the classroom light switch design could be the practical step required to achieving the savings in practice. The industry sponsor was grateful for the insights provided as classrooms represent one of the most crucial elements to get right for a higher education provider. Being seen to be wasteful can be detrimental to the reputation of the university. An interesting finding from the classroom study was that little difference was found in CO_2e emissions and energy consumption, despite these being the key metrics of performance that energy efficiency decisions are based upon. The hours of use for lighting, occupancy and booking all showed different patterns and none can be taken as a proxy for the other when making design assumptions about in field uses.

Objective 3 was completed by providing performance gap analysis for corridors, the most neglected area of empirical lighting studies. The key contribution to this field was in relation to the corridor lighting hours of use not being synonymous with occupancy or hours of operation as stated in the CIBSE guidance. As some of the first empirical findings relating to corridor lighting use in field this represents perhaps the greatest opportunities for findings further savings though continuous commissioning and verification of lighting control settings. Both the classroom and corridor studies were written up as original research journal papers and submitted to the International Journal of Low Carbon Technologies and Frontiers in Mechanical Engineering, respectively. Many more future studies could be carried out in all of the study areas to build a body of knowledge to act as a benchmark for finding energy savings. By using the simple method of deploying small unobtrusive loggers to record hours of use, a rich and detailed picture of a person's habits relating to their light switching patterns can be formed, similar patterns can be found for classroom and corridor lighting use. As a result of these findings the industry sponsor is proposing to upgrade the corridor lighting in the Humanities building as the upgrade can deliver a substantial CO_2e reduction in emissions. The lighting industry continue to push automated controls as the most effective was to save energy and yet in all of the corridor areas studied none was commissioned to its optimum level to achieve robust savings.

Objective 5: determine if there was a relationship between office lights being left on and the difference in vertical illuminance between office and corridor on exit.

The final objective concluded the six empirical studies. The prompt study found there was a significant relationship linking the office light being switched off, or left on, by the occupant as a direct consequence of (i) the corridor light state, (ii) threshold difference in illuminance (between corridor and office) and (iii) the time of day. The prompt study built on the pilot study of another EngD student and sought to capture the long term light switching habits of single occupancy offices. The findings presented need to be taken with caution and further studies undertaken to confirm the results. If these findings are corroborated then it could lead to a rethink in the different illuminance levels between corridor and office spaces.

The limitations of the six inter-related studies have shown that further qualitative work must be produced in lighting to develop designs that are usable. This will only be achieved through validation of multiple sources, by including other built environment users. The equipment limitations have already been outlined and if budget and circumstance allow then deploying at least two or three types of the loggers into each space perhaps on different time scales will verify the findings by triangulating the data. This would lead to a far greater quantity of data as big data analysis tools were already required in the office study. The nature of in field study, as opposed to laboratory study, is that you collect slightly imperfect data as each iteration of the study is naturally different to account for place, layout, use, access and design. Despite these limitations this engineering doctorate research has successfully achieved its main aim of exploring how habit and design are interlinked in lighting use and occupancy. Key contributions were made in the form of three peer reviewed journal papers and a conference paper. Five specific objectives were fulfilled, generating new insights that contributed to the industry sponsor, industry and thesis aims. The research has explored post occupancy evaluation using two methods. Both methods are capable of finding energy savings to reduce carbon emissions. Furthermore, the research has supported the notion that energy saving habits can be formed through the design of our spaces by cueing or nudging people through light. Collectively, the results of this research has demonstrated how the gap between design intent, practice and experience can be reduced to provide a better working environment whilst reducing energy consumption.

Recommendations to industry

- Use POE interviews with end users rather than relying on building managers to understand how the space is actually used, spreadsheets only tell you so much.
- Include people with disabilities, cleaners, security staff and more vulnerable users in your design process rather than shying away from asking difficult questions.
- Keep an open mind that a designer's mental model is not necessarily the same as the end user's mental model of how something works
- Test control panels with the end users at the very beginning of the design process to see if the vulnerable users find it useable.
- Designer's assumptions are also subject to bias, anchoring and automatic thoughts, challenging these assumptions at the beginning of the project should be openly encouraged.
- Carbon emissions metrics do not necessarily reflect waste.
- Continual commissioning on an annual basis will keep the dynamic performance gap in check
- The lighting load factors should be set to 1 unless otherwise proven with in field data as evidence of real savings directly linked to a) minimising the time and b) dimming to reduce the load has yet to materialise.
- Over illuminating a corridor might have unintended consequences for office lights being left on when someone leaves their office.
- In corridors set the hold on time down to the minimum rather than the maximum 20 minutes
- Window cleaning directly impacts the occupants in times of cost saving and had the unintended consequences of staff feeling neglected and using more lighting, therefore FM teams should not value engineer this out of their budget.
- The O&M manuals produced by contractors and consultants should directly mark explicitly which sensor is installed where and what commissioning settings have been used rather than lazily including every product ever made, a hand written note is not good enough.
- Commissioning engineers should change the handset settings for commissioning each sensor where appropriate in day lit areas rather than lazily applying the 'same' settings throughout a corridor space, again noting this in the O&M manual.
- Loggers need to be used before, during and after commissioning to actually see if the changes have occurred. In a setting where biological research is carried out this is critical.

Future Work

1. Vulnerable users
2. Control factors/Load factors
3. Plastics

Vulnerable users represent some of the most forgotten people and yet we know that if we design for the most vulnerable user, everyone benefits through better design.

Control factors and load factors are meaningless without data and evidence from practice. In field studies with metering data directly on the light source to detect when it is 'dimming' and using different commissioning strategies i.e. turning off due to daylight, turning off due to absence, would actually build a dataset and picture of when these discounting factors can be applied. In the absence of any data 1 should be used rather than assuming the controls 'save'.

Plastics represent the biggest threat to the ocean and ecosystem and with regular re-fits of lighting the vast majority of this must go to landfill as it is not currently in an easily recyclable format. Recycled versions and using sustainable materials all could limit the plastics used as LEDs do not emit heat in the same manner as CFL bulbs.

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Appendix A: Pilot study interviews, questions and format

Qualitative Methods PYM0QQ

Project Submission Form

Name: Kate van Someren Email Address:k.vansomeren@reading.ac.uk

GENERAL TOPIC AREA – Attitudes towards climate change

Project Title: Investigating post graduate psychology student's energy use and energy feedback systems in the University of Reading's Whiteknights campus buildings.

Project Summary (maximum 250 words):

AIMS: To investigate the factors affecting post graduate psychology student's energy saving decisions within the University of Reading's Whiteknights campus buildings and whether energy feedback will influence energy use.

METHODS: Semi-structure in-depth interviews conducted with 6 participants (volunteers) from the Psychology MSc or PhD programmes. The sample may include post graduate participants from the Clinical Languages School. The interviews will be audio-taped and transcribed verbatim.

Will interviews be conducted individually or in groups (circle your answer)?

Individually In groups of ……….. participants (specify)

Have you attached an information sheet (circle answer)? Yes / No

Have you attached a consent form (circle answer)? Yes / No

Have you attached a topic guide (circle answer)? Yes / No

Qualitative Interviews Conducted with Reading University Student Participants by MSc Students for PYM0QQ Assignment

Investigating post graduate psychology student's energy use and energy feedback systems in the University of Reading's Whiteknights campus buildings.

Topic Guide

1. What are your experiences of energy saving devices at the University of Reading's buildings?
    a. Have you seen other students/staff saving or using energy?
    b. What about the media?
2. What was your view about energy saving before you joined the UOR, if any?
3. What were your perceptions of the UOR energy savings in the built environment on campus?
4. What information was provided to you about operating the buildings when you started your course?
5. How influenced do you feel by other people's energy behaviour & habits?
6. Do you feel support or pressure to save or use energy at the UOR?
7. How and when did you make your decision about energy saving or energy use at UOR?
8. What types of energy feedback systems do you know of?
    a. What do you think would be the most effective energy feedback system?
    b. Please give examples
9. Do you have any plans to change your energy use or behaviour at UOR?
10. Do you have an understanding of the energy use and costs involved in your own research?
    a. Does this influence your research grant proposals?
    b. Could it influence them in future?
11. If you could demonstrate your energy behaviour, do you think this could influence your future employers?

Format for interview:

1) Explain why the interview is taking place
2) Consent forms/info signed – reiterate that the transcripts are made anonymous & a copy of the transcript can be provided if they choose)
3) Ask how much time the interviewee has
4) Any questions they may have before the interview commences
5) Check that they are ok with the interview being audiotaped
6) Run through checklist of forms (ethics/participant info sheet/consent form (2 copies of each one for interviewee the other for interviewer)
7) Record interview time/date/place
8) Commence interview
9) End interview and thank the interviewee for their time and participation in this study

Appendix B: Main study interviews, questions and format

Semi-Structured Interviews to be conducted with University of Reading Staff

Investigating light switching behaviours, energy use and relative light levels in the University of Reading, Whiteknights campus buildings.

Topic Guide

1. What are your experiences of automatic lighting devices at the University of Reading's buildings?
    a. For example some corridors are fitted with sensors and dimmers, have you noticed any of these lighting changes in campus buildings?
2. Specifically focussing on the corridor and circulation spaces, what actions do you think take place in these areas?
    a. Within the URS building do you consider the orientation of the building to be a factor in its light use?
    b. How do you perceive the level of daylight in the corridor areas?
    c. Focussing on your work environment, please tell me more about the levels of daylight, artificial lighting quality and improvements that you think could be made?
3. Do you have any views about energy saving behaviours or practices?
4. Please describe some of the lighting habits and patterns of behaviour that you go through on a normal day specifically focussing on when you first arrive and again when you leave your workplace
    a. Does this change during the seasons?
    b. Does this change when the clocks change from GMT to BST?
    c. What about the time of year in your work calendar, are there particular busy periods?
5. Have you experienced a lighting control switch in a university building that you have had particular difficulty in using because of its complexity or poor design?
6. How do you perceive the dimming function of the corridor lights?
7. What about the sensitivity of the detector, is there any delay in it switching on or off?
8. Have the corridor light changes made you change anything in your normal pattern of behaviour, e.g. when you are locking your office at the end of the evening?

Format for interview:

10) Explain why the interview is taking place
11) Consent forms/info signed – reiterate that the transcripts are made anonymous & a copy of the transcript can be provided if they choose)
12) Ask how much time the interviewee has
13) Any questions they may have before the interview commences
14) Check that they are ok with the interview being audiotaped
15) Run through checklist of forms (ethics/participant info sheet/consent form (2 copies of each one for interviewee the other for interviewer)
16) Record interview time/date/place
17) Commence interview
18) End interview and thank the interviewee for their time and participation in this study

Appendix C HOBO logger manuals